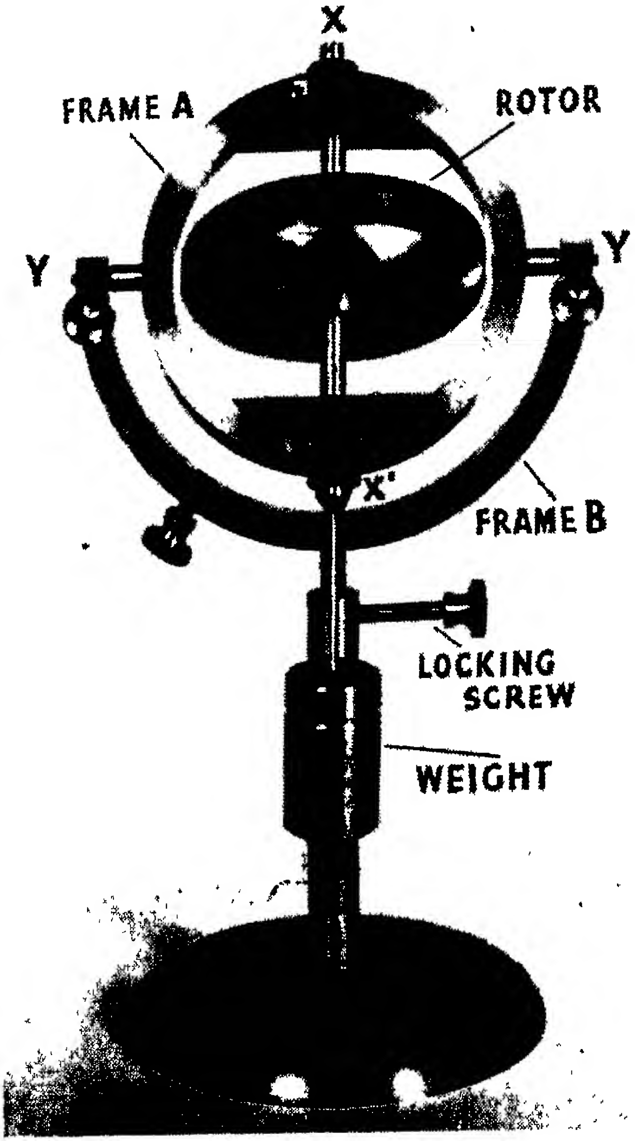
THE GYROSCOPE

AND ITS APPLICATIONS



A two-framed demonstration model gyroscope. See text for explanation.

THE GYROSCOPE
AND ITS APPLICATIONS

Edited by

MARTIN DAVIDSON, D.Sc., F.R.A.S.

In three sections—

SECTION I: GENERAL THEORY
by Dr. M. Davidson

SECTION II: MARINE APPLICATIONS
by G. C. Saul, A.I.N.A., F.R.A.S.

SECTION III: AERONAUTICAL APPLICATIONS
by J. A. Wells, A.F.R.Ae.s.
and A. P. Glenny, B.Sc.

HUTCHINSON'S SCIENTIFIC AND TECHNICAL PUBLICATIONS
LONDON : NEW YORK : MELBOURNE : SYDNEY

ERRATA

Angular momentum and *moment of inertia.* There are different methods of expressing these units, but for angular momentum as on page 18 line 19 and elsewhere *read* $lb.ft^2/sec.$ *instead of* lb.ft./sec. and for moment of inertia as on page 32 and elsewhere *read* $lb.ft^2$ *instead of* lb.ft.

Page 20, line 22 from bottom, *for* pp. 16-17 *read* Fig. I. 2.

On page 34. 19th line from bottom, *for* ft.pd.sec. *read* $lb.ft^2/sec$ and 4th line from the bottom *for* ft.pds. *read* $lb.ft^2/sec^2$.

Page 52 line 11 from bottom, *for* 0.701 *read* 0.7071.

Page 53 first line, *for* $\sqrt{25} \times 0.866$ *read* $\sqrt{(25 \times 0.866)}$.

Page 54 line 27, *for* being *read* is.

Page 57 line 19, for $d\alpha$ read $d\alpha/dt$.

Page 58 line 11 from bottom and page 59 line 18, *delete* (28).

Page 64 lines 12 and 14, for V read v.

Page 64 line 19 from bottom, *for* 0.0000242 *read* 0.00000242.

Page 64 equation (58) *for* sec^2 *read* sec^3.

Page 65 Fig. I. 23 caption, *for* 15′ *read* 15°.

Page 186 line 15, *for* local *read* load.

Page 195 Fig. III. 35, at end of caption, *for* inversely *read* directly.

Page 214 Fig. III. 49 caption, *for* $cycles^2$ sec. *read* cycles/sec.

Page 256 (Glossary) *for* Syphon *read* Sylphon.

Made and Printed in Great Britain by
Cheltenham Press Ltd., Cheltenham and London.

PREFACE

The purpose, scope and plan of this book are explained in the Introduction, but may be briefly summarised here. The purpose is to explain the theory of the gyroscope and to describe its practical applications in a manner understandable by all with any interest in the subject. The scope embraces all aspects that are not barred by security reasons from a book written in wartime. The plan of the book is to expound the general theory in Section I and to describe the marine applications in Section II, and the aeronautical applications in Section III ; the Appendices following Section I give more elaborate explanations of various points not strictly necessary to a general understanding but useful and important to serious students.

In the preliminary discussion with the publishers of their suggestion that I should undertake the general editing, it soon became apparent that no one man could write the whole, and we have been fortunate in getting together an able team whose collaboration has left nothing to be desired. Each author, whose name is attached to the Section for which he is responsible, is a specialist in his subject, as will be evident to any careful reader.

Many acknowledgments are due to various outside helpers, without whose assistance the book would have been impossible. Dr. H. Cousins, who was associated with Brennan in his early work, read the MS., and all sections of the book owe much to the unstinted assistance and loan of illustrations by those other pioneers, the Sperry Gyroscope Co. Ltd. Similarly thanks must be expressed to Messrs. S. G. Brown & Co. Ltd., of Acton ; Messrs. Brown Bros. Ltd., of Edinburgh ; to the Ministry of Aircraft Production ; Ministry of Information ; The American Office of War Information ; and H.M. Stationery Office. Appreciation should also be expressed of the work of Mr. W. H. Johnson, who proposed this book and has kept a steady hand on all concerned in its production.

THE EDITOR.

January, 1946.

CONTENTS

CONTENTS—*contd.*

CONTENTS—*contd.*

SECTION III—AERONAUTICAL APPLICATIONS

By J. A. WELLS, A.F.R.Ae.S., and A. P. GLENNY, B.Sc.

INTRODUCTION

Most of us know the gyroscope if only as one of those fascinating toys that we buy for the youngsters and hand over to them only when we have worn it out by playing with it ourselves. Many of us also suspect, if we do not know, that the gyroscope has other applications, that it is used in some mysterious way on ships that navigate the seas and fight the world's battles and on aircraft that go a long way towards winning wars. We have also heard that gyroscopes have been suggested and even used with a very poor degree of success on some freak vehicles intended to travel on land.

The purpose of this book is to explain what the gyroscope is, how and why it works and how and why it has affected the science of marine and aerial navigation and made a ship and an aircraft instruments of precision like the gyroscope itself, rather than erratic tools in the hands of a whimsical human being.

A gyroscope is a heavy wheel on an axle mounted in a special frame which in ordinary applications gives to the axle ability to move in any direction. When rotating at a sufficiently high rate of speed the gyroscope will take up a position from which it may only be shifted quickly by the application of a considerable force. If the gyroscope is big enough the efforts required to shift it rapidly may be beyond human scope. If, therefore, a big enough gyroscope be rigidly installed in an aeroplane or a ship that aeroplane or ship may be induced to refuse to budge under the influence of air pockets or gales or under the buffeting action of the waves. These applications have both been tried but hope for immunity from air or sea sickness proved to be too dearly bought, and at the moment this kind of stabilising application of the gyroscope is not popular.

It is an interesting fact that the most important applications of the gyroscope to-day are on the water and in the air. Afloat it provides a compass that knows nothing of magnetic variations, and by elaborate coupling of such a compass to a ship's steering gear it holds the ship on a steadier course than could any human helmsman. Without the gyroscope modern naval gunnery would be either much more complex than it is at present (impossible as this may seem) or it would be comparatively crude and simple.

Much the same applies to aircraft, only perhaps more so. But for the gyroscope some of the large cities of the world would be much healthier and safer places to live in than they are or have been. Without the gyroscope there would be no "George"—that automatic pilot that takes our planes exactly where the human pilot wants them to go, without requiring any physical effort on his part, and without the gyroscope our aircraft bomb and gunsights would have been far less serious matters than they were to the gentle Hun !

The next time, therefore, that you pull the string of your son's gyro top so as to show his friends how you cannot help but balance it very cleverly on the blade of a knife or the point of a pencil, pause to think that but for this amusing toy you might not be alive to enjoy it.

The gyroscopes described in this book are very different from the simple little things costing a few shillings and operated by a piece of string. Some of them rank among the highest precision instruments known to man and some of them attain the highest speeds of any rotating mechanism in use. Their driving and bearings have provided and continue to provide problems engaging some of the best brains in the world. This effort is not being expended for nothing and this book goes a long way towards answering the eternal questions : How and Why ?

The book is divided into three main sections, each of which has its chapters. The first section deals with the theory of the gyroscope. Of this section the first part is purely elementary and general talk which should be read and can be understood by anyone wanting to acquire the broadest knowledge of this subject. It is primarily intended for those who have no knowledge of the dynamics of the gyroscope. Later on this section becomes rather more advanced and is intended to appeal to those who want to know a little more (and how much it is !) and they will need some ordinary mathematical groundwork on which to base their understanding. The section does, however, stop short at the really advanced dynamics of the gyro which, to be thoroughly understood, demands a good background of mathematical knowledge and will take the student a long way into applied mathematics. Some of these aspects are treated in Appendices at the end of the section.

Section II deals with the marine applications of the gyro, the commonest of which is, of course, the gyro compass, and its applications. The Editor appreciates full well that a deep understanding of the implications of the gyro involves a certain knowledge of modern navigation, but it is not the function of this book to teach navigation but merely to explain the practical applications of the gyro to it. After the navigational other marine applications are described, such as the use of the gyro for stabilising ships and torpedo direction control.

Section III deals with the aeronautical applications and is perhaps the one of widest practical interest at the presnt time. There are very few large aircraft in the air to-day that are not largely dependent on the gyro for their navigation, although the gyro compass as such is not used in the air. Nevertheless the navigator, deprived of the services of his gyro instruments to supplement his magnetic compass, is apt to find himself and his aircraft in a very awkward position. Similarly the bomb-aimer without his gyro will lose much of his accuracy, and even the air-gunner is now coming to rely on it more and more for his deadliness.

While all the sections are to some extent naturally interdependent, each section is complete in itself. For this reason the numbering of the chapters and of the illustrations has been made complete in each section, but to assist in identification of the figures, each one is printed with the figure number proper prefaced by the number of its section—a step that hardly seemed necessary for the chapters.

It was intended to add a fourth section giving a brief outline of some past or potential applications of the gyroscope on land. Some enthusiasts think that by installing a gyroscope the ordinary motor car may be made to run on two wheels like a bicycle, which is true enough, but it must be admitted that hitherto the disadvantages of the system have heavily outweighed any possible merits. And although the gyro railway train may run on one rail instead of two, it is generally considered easier to provide a second rail than to fit a gyro to the individual cars or coaches. Although these possibilities have been explored and the appropriate apparatus has actually been built, the ultimate lesson of experience has been that the experiments are not worth development into commercial or serious applications. It has been decided, therefore, with some regret, that the proposed Section IV was hardly justified.

It is not claimed that the book constitutes an exhaustive treatise on the gyro in theory and practice. Such a treatise would indeed constitute not a book but a library, and there are already several books, each considerably larger than this and each devoted to one aspect or one application of the gyro. The present aim is to offer to those interested a reliable *introduction* to the theory and a general survey of the practical applications of present-day importance. For some notable omissions of descriptions of these applications, security reasons or failure of the appropriate Government Departments to respond to invitations to collaborate are not so much an excuse but the actual reason.

SECTION I—GENERAL THEORY

CHAPTER 1

THE GYROSCOPE (GENERAL)

In the Introduction it has been pointed out that the gyroscope has very important applications in ships and aircraft and in other ways, and that the purpose of the present book is to explain what a gyroscope is and how it works. Many of our readers have probably experimented with toy gyroscopes* when they were young, but perhaps they have grown too old or if not too old then too proud to be seen using such gyroscopes now. Nevertheless, if they want to understand properly some of the elementary principles developed in this Section, they must be prepared to carry our a few simple experiments, not necessarily with an elaborate or expensive gyroscope, but with the ordinary toy gyroscope which they may have purchased for their boys. Although the following chapters will describe exactly how a gyroscope behaves (and to a novice its behaviour often seems very extraordinary) readers will want to know *why* it behaves in this way, and they will also want to predict what it will do under certain varying conditions. One word of advice before proceeding with the present Section may not come amiss to some who prefer theory to practice and who are prepared to accept the statements of others without investigation : "Never be afraid of experimenting ; as far as possible test things out for yourselves." It is true that this advice is not always easy to follow, but in the case of the gyroscope no serious difficulties will be encountered.

How it got its name

The word *gyroscope* received its name about the middle of the 19th century when Foucault, the French Academician, devised an instrument to demonstrate the diurnal rotation of the earth, and the name *gyroscope* was given to the apparatus. The word is derived from two Greek words, *gyros*, a circle, and *skopeo*, I view, and was a very appropriate term to apply to an instrument which enabled one to see the earth's rotation, relative to a revolving wheel more or less stable in direction with reference to the distant heavenly bodies. This rotation was thus demonstrated beyond possibility of doubt.

Although Foucault's instrument, the essential feature of which was a disc rotating with high speed, was used in 1852, it is known that something similar to the gyroscope was in existence in 1816-7. In addition, we must give the credit to an Englishman, or more correctly, a Scotsman, for suggesting the use of the instrument for demonstrating the rotation of the earth. In 1836 Mr. Edward Sang, an engineer, read a paper before the Royal Scottish Society of Arts, and suggested an experiment with an instrument similar to the gyroscope, by which the rotation of the earth could be shown. It is amazing that no one seems to have

*This simple form is often known as the single-framed gyroscope possessed sufficient imagination to carry out the experiment until 1852 when Foucault applied the principle, though there is no proof that he was aware of Mr. Sang's suggestion. We can only deplore the fact now that our country does not claim the honour of being the first to make use of such a simple piece of apparatus for demonstrating the earth's rotation. A little more imagination and enterprise would have obviated this failure.

Precession

The word "precession" will be used frequently in this book and the reader must understand what the term implies. The simplest illustration of the phenomenon is found in the case of the ordinary spinning top.

When a top is spinning on a rough surface and its toe is fixed in one spot, it frequently slopes from the vertical position, and in these circumstances the head of the top moves comparatively slowly in azimuth, describing a figure which is practically a circle. If we imagine a line joining the toe to the centre of the head, this line traces out an inverted cone in space, the lower end of the toe being the apex of the cone. The azimuthal motion of the spin axis of the top is known as *precession* and many applications of this phenomenon are found in different spheres. As will be seen later, precession is important in connection with a certain movement of the earth.

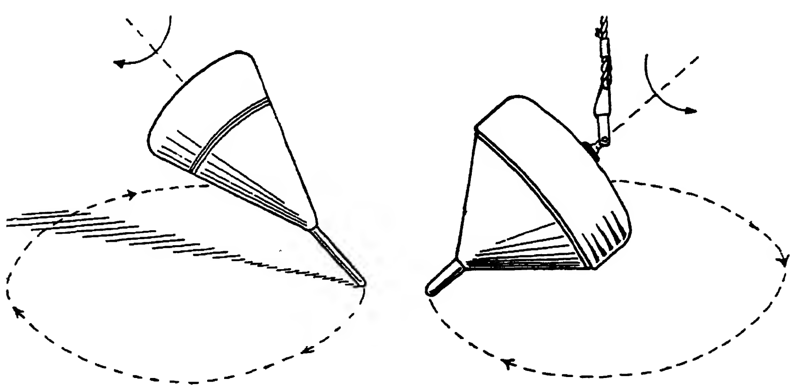


Fig. I.1 (a). The top on the left which is spinning on its point precesses in the same direction as its spin.

Fig. I.1 (b). The top on the right which is suspended by a string precesses in a direction opposite to that of its spin.

If we look at the top from above, the direction of its precession will always be found to be the same as the direction of its spin. Suppose now that the toe is placed on a fairly smooth surface; it will trace out an approximate circle on this surface and this will be described in the direction of the rotation of the top (see Fig. I. 1a). If, however, the top is spun and suspended by a string attached by means of a swivel to its head, the toe and axis will move round in a direction contrary to that of the spin of the top when viewed from above (see Fig. I. 1b). This interesting experiment illustrates the precession of the earth which takes place in a direction opposite to that of its rotation or spin.

A definition of precession specially adapted for simple gyroscopic phenomena will be given when some experiments with a gyroscope have been described.

Experiments with a simple gyroscope

The simplest form of a gyroscope consists of two distinct parts (see Fig. I. 2). First of all there is a wheel which has a heavy rim, heavy at least for its size, and which is free to spin about its axle. The axle is mounted in a frame, and wheel and axle can rotate in this with the minimum of friction. In the toy gyroscope the rotation or spin is effected by means of a piece of string, and although there is a very decided limit to the length of time that the wheel will spin even under the most ideal conditions—reduction of friction to a minimum—this form of gyroscope can be used to illustrate many very important dynamical principles. The following experiments should be tried and the observations carefully noted.

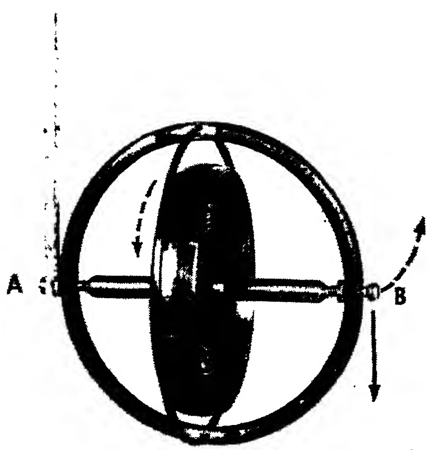


Fig. I. 2. A single frame gyroscope when supported at A will precess as shown at B by the dotted arrow, due to the pull of gravity shown by the vertical arrow.

Experiment 1. Spin the wheel and hold the gyroscope by the frame in any position. Carry the whole apparatus round in a circle, taking care that the axle points to the same direction in space, or in other words, that the plane of the wheel does not alter its original direction. No resistance will be experienced in doing this, and so far as this experiment is concerned, no difference will be experienced in carrying the gyroscope round if the wheel is not rotating.

Experiment 2. Spin the wheel again and then turn the apparatus so that the axle changes its direction in space. For instance, if one set screw B in the frame is at the top, turn it upside down so that this screw is at the bottom. Although the instrument may be only a toy, a distinct resistance is felt in tipping it over, and it behaves as if it resented any interference with the plane of the spinning wheel. It will be found that this resistance decreases as the speed of the spinning wheel decreases and finally disappears completely when the wheel stops spinning. Actually when it is spinning slowly no force opposing the change of direction of the axle will be felt, but in theory such force exists until the wheel ceases to spin. If two or more gyroscopes of different sizes are available and are used, it will be found that the heavier the wheel, the greater the resistance with the same rate of spin, as might be anticipated.

Experiment 3. Spin the wheel again and, for convenience in the experiment, make the direction of spin the same as that of the hands of a clock, when you look on the spinning wheel from above, say A. Place this end A of the frame on a small pedestal or, what may prove more convenient, attach a piece of twine to this end, tilt the gyroscope a little out of the vertical, and release it. If it is spinning with sufficient speed it will not fall out of the twine but the whole apparatus, frame and wheel, will start moving round in a circle the centre of which is the point of attachment of the twine to the set screw in the frame. As it continues to move round it will slowly descend, and if allowed to continue descending long enough, it will probably fall out of the twine. If it is picked up and replaced in the original position it will repeat the process but will move round in the circle more quickly than before and it will also descend more rapidly. The direction of motion of the gyroscope round the point of attachment A is anti-clockwise viewed from above, this direction and that of the spinning wheel being indicated by arrowheads in the figure.

Experiment 4. Spin the wheel again in the same direction and suspend the end B of the frame on the string or place it on a support. On releasing the frame it will move round on the pivot at B but in a direction opposite to that in which it moved previously. The same phenomena are repeated, the descent of the gyroscope and the increase in the speed with which the frame moves round, etc., and the only difference is in the direction of this motion. This can always be determined by means of the following simple rule :

For convenience hold the gyroscope when the wheel is spinning in a vertical or approximately vertical position so that the direction of the spin, looked at from above, is obvious. When the end of the gyroscope is placed on a support the whole apparatus will move round this point in the same direction as that of the spinning wheel.

The weight of the gyroscope tends to turn it round a horizontal axis through its point of support, and would do so if the wheel were not spinning. When the wheel is spinning, instead of the gyroscope turning round this axis, its motion takes place round a vertical axis through the point of support, and *precession* occurs, a simple definition of which is as follows :

When a torque (see p. 22), equivalent to up and down forces, is exerted on the axle of a gyroscope, the motion of the ends of the axle of the gyroscope takes place, not in the direction of the forces as occurs when the wheel is not spinning, but in a direction at right angles to this direction.

The reasons for the precession of the gyroscope will now be considered.

Momentum

Those who have an elementary knowledge of mechanics know the meaning of the word "momentum." The momentum of a body in motion is measured by multiplying its mass by its velocity, each being expressed in proper units. As the English system will be adhered to throughout the present book, we shall measure mass in pounds and velocity in feet per second. In these circumstances the product of mass by velocity is the momentum of the body at the time, measured in pounds feet per second (1 lb.ft/sec.). If we wish to find the momentum of a body of mass 100 lb. which is moving with a velocity of 20 ft. per sec., it is only necessary to multiply 100 by 20 and the result is the momentum, 2,0C0 lb.ft./sec.

Moment of momentum or angular momentum

The moment of momentum or the angular momentum of a body can be best explained by a simple illustration. Imagine a weight attached to the end of a rope which is then twirled round so that the rope is taut. If the size* of the weight is small in comparison with the length of the rope, so that it practically dwindles to a point, though retaining its mass, the angular momentum of the weight is measured by the product of the momentum and the length of the rope, provided the rope is practically horizontal at the time. This angular momentum is measured round a vertical line drawn through the operator's hand. If the rope is not horizontal the angular momentum is the product of the momentum and the horizontal distance from the weight to the vertical line through the operator's hand. If r is the length of this perpendicular and m and v are the mass and velocity respectively of the weight, the angular momentum can be expressed in the form mvr. Thus if the mass of the body is 100 lb., its velocity 20 ft./sec. and r is 8 ft., the angular momentum is 16,000 lb.ft./sec.

Conservation of angular momentum

The following important principle will now be enunciated but no proof will be given because a full proof is rather outside our present scope. The principle is exemplified in a number of phenomena well known to the reader, and reference to a few of these will be made. It is known as the Conservation of Moment of Momentum and it must be thoroughly understood before we can proceed to deal with further problems connected with the gyroscope. The principle is as follows:

In any system of particles, whether rigidly connected together or not, the total angular momentum of the system relative to any point fixed in space remains constant, provided no external forces act on the system, internal forces only being considered. A similar result holds good for the centre of inertia even though this point be not fixed in space.

Illustrations of the principle

A familiar illustration of this principle is seen when a child on the end of a rope swings round a vertical pole. When the rope is extended to the utmost the speed of the child is relatively slow, but as the rope coils round the pole and shortens, it will be noticed that the child's speed increases rapidly. This homely illustration will be used to show the implications of the above principle.

When the child starts swinging, the moment of momentum or angular momentum round the pole is measured by the product of the mass of the child, its speed, and its distance from the pole, the latter being the length of the line drawn from the child at right angles to the pole. We can write this angular momentum in the usual form mvr, and the principle states that this remains constant so long as the system is unacted on by forces external to itself. A difficulty arises at this point because it is impossible in ordinary terrestrial experiments to isolate a system

*The reason for this assumption will be explained in Chapter 3.

so completely that it is unacted on by external forces. Thus, in the above illustration, the child is acted on by the resistance of the atmosphere, and there is also some friction at the pole. For this reason the illustration can be considered only approximately correct but it is good enough for the present purpose.

Returning to the rope coiling up on the pole, it is obvious that r is continually decreasing while m, the mass of the child, remains the same. Now the principle of the conservation of angular momentum states that the angular momentum of the system remains constant during this coiling of the rope, because this is not due to an external force. If an outsider assisted with hurrying or retarding the motion of the child, this would be an external force and the principle would be vitiated, but as this does not occur, the expression mvr retains the same value throughout. As has been shown, r decreases and m remains constant, so it is necessary that v should increase if mvr is to retain the same value throughout the operation. Hence the velocity of the child increases.

Another illustration is seen when a performer stands on a horizontal disc capable of rotating about a vertical axis through its centre. If the performer carries a heavy weight in each hand and suddenly extends his arms horizontally when the disc is spinning, the rate of rotation immediately decreases. If he drops his arms to his sides the rate of rotation will at once increase again. In the first case when the weights were held extended some distance from the centre of the disc the angular momentum due to these weights was increased owing to their greater distance from the centre. The original angular momentum of the system was due to the rotation of performer and weights and also to the disc. Forces producing the movements of the performer, such as extending his arms, are merely internal forces, so that the principle is not vitiated. Hence when the part of the angular momentum due to the weights was increased there was an immediate response on the part of the rotating disc to preserve the total original angular momentum unaltered, and this was done by slowing down the rate of rotation.

There is an interesting application of the principle in the solar system. The moon is largely responsible for the production of tides and it is known that the friction of these tides, more especially in a few of the shallow seas, is responsible for slowing down the earth's rate of rotation, If we imagine the earth-moon system to be uninfluenced by any other heavenly bodies (which is not true but we can regard the system as nearly isolated for our purpose) the angular momentum of the earth and moon round a line through their common centre of gravity, known as the barycentre, is constant. If, however, the earth's rate of rotation is slowing down, then the earth's contribution to the angular momentum by its rotation is diminishing, and to maintain the constancy of the angular momentum of the system the moon must increase her angular momentum. To do so she recedes from the earth, though the amount of the recession is very small—on the average about 5 feet a century.

Angular momentum about different lines

Readers are conversant with the law of the parallelogram of velocities and forces, and, as is shown in Chapter 3, this law also holds for angular velocities and angular momenta. The angular momentum of a system about a line in any direction can be resolved about a line in any other direction in the same way as a force can be resolved. Suppose we calculate the angular momentum of a gyroscope about a line drawn from the instrument to a star, given the mass of the wheel, its dimensions, and rate of spin, and, to simplify the problem, we can imagine that this line coincides with the axle of the wheel. If the axle is tilted so that it no longer points towards the star, the angular momentum about the line from the gyroscope to the star will be less than it was originally. The principle of the conservation of angular momentum states that it would be the same, provided no external forces acted on the system. Of course the muscles of the hand are responsible for an external force in the present case and hence the principle is vitiated.

Why the axle of the rotor tends to maintain the same direction. We can now see why the axle of the spinning wheel tends to maintain the same direction with reference to some object fixed in space, the nearest approach to which is one of the "fixed" stars. (Incidentally no stars are fixed ; they are all moving rapidly, some with speeds of hundreds of miles a second, but they are so far away that this speed dwindles into insignificance in comparison with the immense distances, and we can regard them as fixed for our present purpose.) If the axle of the gyroscope did not point in the same direction (assuming that no external forces acted on it) the principle of the conservation of angular momentum would not be true, because the system would be able to alter its position in such a manner that the angular momentum about a fixed line would not be the same. It is obvious, therefore, from the fundamental principle of the conservation of angular momentum, that the axle of a gyroscope tends to remain in the same position in which it was placed, provided no external forces act on it, and this explains why a resistance is felt when the axle is forcibly tilted to different directions in space.

The single-framed gyroscope with which the experiments have been carried out (see pp. 16-17) is not very convenient for illustrating the tendency of the axle of the spinning wheel to maintain a fixed direction in space, but it can be used if certain precautions are taken. Attach a piece of string to the frame in such a way that the axle of the wheel is horizontal. The greater the accuracy one secures in balancing the apparatus so that the axle is horizontal, the greater will be the success of the experiment. Spin the wheel and suspend the gyroscope with the string attached to the frame ; it will be seen that the axle either points in the same direction or if not that it moves very slowly round in a horizontal plane. If the point of attachment of the string is moved slightly so that one end of the axis is higher than the other, precession will start, and the greater the difference in the heights the greater is the rate of precession. It will be found that it is difficult to hurry on the precession ; any attempt to do so in a horizontal plane is resisted as if the gyroscope had determined to set its own pace and resented any interference, and the gyroscope will move in a vertical plane. Precession takes place for the same reason as in the previous experiments when the vertical through the point of support of the apparatus did not pass through its centre of gravity.

It has been shown that the rate of precession increases as the gyroscope continues spinning and the reason for this will be given later. We may anticipate what follows by stating that the rate of precession is in inverse ratio to the angular velocity of the spinning wheel, other factors remaining the same. Hence if the rate of spin of the wheel is diminished by friction about the spin pivots, the rate of precession must increase. If friction about the spin pivots could be entirely eliminated, but the friction about the precession axis remained, the gyroscope would still fall, but the rate of precession would not alter. This is due to the fact that the horizontal component of the angular momentum increases proportionally with the torque about the horizontal axis.

Convention regarding direction of spin

When we speak of angular momentum about a line it must be remembered that there must be some convention about the direction of spin. For instance, if we decide to call the angular momentum positive when the spin is opposite to the direction of the hands of a clock, as we look down on the spinning body, obviously a spin in the opposite direction will produce negative angular momentum. The necessity for the two signs will be clearer from an example.

Take the illustration of a performer on a rotating disc. Suppose it is rotating anti-clockwise and while it is doing so the performer turns on the disc in an opposite direction ; it is clear that he is deducting from the angular momentum of the disc about a fixed line through its centre at right angles to its plane. In fact, if the disc were rotating slowly and the performer were turning in the opposite direction, even supposing that the disc were fairly heavy but had not a considerable angular momentum, it would be possible for him to neutralise the angular momentum of the disc. If, on the other hand, he turned in the same direction as the disc in its rotation, he would add to the angular momentum of the system.

We imagined that the wheel was spinning in a clockwise direction when viewed from above. When the axis AB is horizontal the spin, regarded from the point of view of an observer from above, is neither clockwise nor anti-clockwise as the plane of the wheel is vertical. When A drops a little the direction of the spin is anti-clockwise—a fact which can be better appreciated by imagining that BA has dropped very far and is nearly perpendicular to the horizon. Once the gyroscope passes the horizontal position in its downward course, the direction of the spin of the wheel is reversed as viewed from above, and hence the angular momentum of the wheel actually detracts from the original angular momentum.

Why a gyroscope descends

When precession has been established the gyroscope would cease to fall if friction at the precession pivots could be entirely eliminated or if the friction were counteracted by any means—say by a follow-up motor. In the cases which have been considered this elimination or counteraction of friction does not take place, and the dissipation of energy at the precessional pivots, owing to friction, occurs. The fall of the gyroscope provides the energy required to overcome the friction at the precessional pivots.

We have seen that a certain amount of resistance is experienced when we try to tilt a gyroscope so that the axis of the spinning wheel changes direction. It must not be imagined from this that if a gyroscope is set spinning and a very small force is applied to try tilting it that this force will be ineffective. The slightest force will alter the direction of the axle but of course the smaller the force the longer the time required. It has been shown that the primary effect of this force is not to change the direction of the axis in the line of the force, but to cause precession provided the apparatus is free to precess. At this stage it would not be advantageous to deal with formulae connecting the magnitude of the applied force, the angular momentum of the wheel, the rate of precession, etc. It will be better for the reader first of all to acquire a very clear idea of the simplest form of gyroscope such as has been described, and the reason for precession. More complicated gyroscopes will be considered later and these must be understood before proceeding to the Sections which deal with the application of the gyroscope to marine and aerial problems.

Rules for Precession

A summary of the behaviour of a gyroscope is given below and the reader may require this for reference on various occasions. He should understand it thoroughly before proceeding to more difficult portions of the book.

When the gyroscope is precessing there is a force acting through the centre of gravity of the apparatus—the force of gravity. Other forces could be used, and in fact it was suggested in one case that the force of gravity should be counteracted and the free end pressed upwards to show that precession would take place in the opposite direction. We shall give the name "torque" to the moment of this force for the present —a word which means "twisting" and about which more will be said later. When the torque is applied by the force of gravity and an equal and opposite reaction at the support, it tends to turn the gyroscope about a horizontal line or axis through its point of support. When precession occurs it takes place about a vertical axis through the point of support, and the following rule should be understood.

If a free gyroscope is acted on by a torque in a plane through the gyro axis, then that axis will precess in another plane which is perpendicular both to the plane of the spin and to the plane of the torque.

Thus, a torque was applied in a vertical plane through the axis. The plane of the spin of the wheel was vertical when the axis was horizontal, and a plane at right angles to both of these is horizontal. The precession takes place in this plane.

The horizontal position of the axis has been taken to make the explanation clearer, but its position is immaterial.

Applying the rule regarding the conservation of angular momentum while the gyroscope is precessing, the following rules can be deduced from it and will be simpler to apply than the rule about the conservation of the angular momentum of the system on various occasions.

(1) Consider one of the two forces producing the torque, say at the end B of the axis AB. Represent this force in direction by a line marked with an arrow. Turn this line through 90° in the same direction in which the wheel is spinning. The arrowhead will then indicate the direction of precession of that end of the gyroscope (see Fig. I. 2).

(2) An alternative rule can be used which will sometimes be found more convenient than (1). Suppose forces are applied to the casing, parallel to the axis or perpendicular to the plane of the wheel. Represent one of these forces by a line and rotate it 90° in the direction of the spin. The direction of the line will then give the direction of movement of the point of the casing to which it is now attached.

If the gyroscope is held in the hand and a torque is applied to the frame, this torque is due to two forces acting at each end of the frame, and for the purpose of determining the direction of precession, it makes no difference which end is considered. Rule (1) can be applied indifferently to either end ; the single force is in a different direction at one end from what it is at the other. If the wheel is sufficiently heavy and is spinning rapidly, the operator will be able to feel the effects of the attempt at precession, and he can verify the above rule. The torque should be applied in various planes, vertical, horizontal, and between these as well.

When the force of gravity acts through the centre of the gyroscope, as has been shown there is an equal and opposite force due to the reaction at the point of support of the instrument or to the tension of the string, these forces producing the torque. On occasions, however, we shall refer to a torque as due to the force of gravity, the existence of the reaction or of the tension of the string equal and opposite to the force of gravity being assumed.

The gyrostat

The term "gyrostat" is sometimes used and the reader should know the essential difference between this instrument and the gyroscope. The simple form of gyroscope that has been described can be used as a gyrostat (which means that the ring is stationary, from the Greek *statikos*, stationary) and Fig. I. 3 shows the ordinary gyroscope as a gyrostat. Each end of the frame rests on a light support, not just one end as described in Experiment 3, where precession takes place. Imagine a flywheel mounted in a frame which is capable of turning round a vertical axis, and you have a representation of a gyrostat.

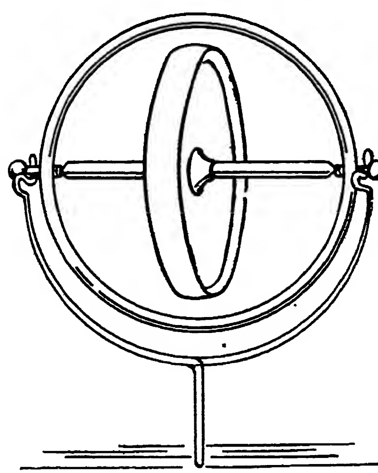


Fig. I.3. A gyroscope which is balanced on its frame so that there is no torque and hence no precession. This form is often known as the gyrostat. The supporting pin holds the gyrostat upright.

Unfortunately, the term "gyrostat" has various applications which are liable to create some confusion. Thus, some writers describe the gyroscope as a potential gyrostat whose plane would remain the same if only the wheel could be spun with an infinite velocity. This is a mathematical fiction because there is no such thing as an infinite velocity, but if the apparatus did possess such a velocity it is quite true that no finite force could change the plane of the wheel. It should be remembered, however, that no gyroscope is a gyrostat, strictly speaking, and an outside couple, however small, will change the plane of spin in time.

Sir William Thomson (afterwards Lord Kelvin) designed a gyrostat which was used to illustrate the dynamics of rotating bodies. An account of the instrument appeared in *Nature*, vol. xv., p. 297. It is unnecessary, so far as the scope of this book is concerned, to deal fully with the gyrostat, but we shall consider the principle of its application to Brennan's monorail in Chapter 3.

CHAPTER 2

TYPES OF GYROSCOPES

Up to the present we have conducted our experiments with the simplest type of gyroscope—the single-framed form. Although experiments performed with this type of gyroscope are very useful and afford an insight into the reasons for a number of performances of the instrument, it would be better if the reader could secure more scientifically constructed gyroscopes. The first of these that will be described is shown in the frontispiece. It can be described as a two-framed gyroscope.

Two-framed gyroscope

The wheel and single frame A are the same as in the type previously described, though they are usually heavier, but in addition, the frame A is mounted in another frame B and can turn about it round an axis YY′. This last frame is mounted in a pedestal and can turn about a vertical axis when the locking screw is not tightened. The reason for supplying this screw will be seen later. The following experiments should be made :

Experiment 1. Loosen the screw and spin the wheel, and then set the axle in any direction. The axle will remain pointing in the same direction unless a slight pressure is exerted on the frame, when precession will take place.

If the screw is tightened so that precession in a horizontal plane is prevented, the slightest touch on the frame will cause it to rotate on its axis and no more resistance is experienced than would be felt if the wheel were not spinning.

Experiment 2. Loosen the screw so that precession can take place, and then spin the wheel and apply a weight W to one end of the frame at X′ where the axis enters it. Precession in a horizontal plane will take place, the weight slowly descending and tilting the axle XX′ out of its original horizontal position, if it was set horizontally. It can be set in any position and the weight will make one end descend, the rate of precession increasing and the axle tilting more from its first position. Try different weights and notice that the heavier the weight the more rapid is the speed of precession. Spin the wheel more slowly and notice that the slower its speed the greater is the speed of precession. If the weight is placed on the frame at X near the other end of the axle, precession will take place in the opposite direction.

These experiments are similar to those described on p. 16-17, experiments 3 and 4 in particular. In the latter the weight of the whole apparatus acted as a torque to turn the gyroscope round a horizontal axis through its point of support. In the experiments with the present type of gyroscope the extra weight attached near the end of the axle serves the same purpose, and precession takes place for the same reason. The rules for precession given on p. 22-23 apply in this case also.

Experiment 3. Tighten the screw and spin the wheel, applying the weight as before. Immediately the frame and wheel collapse with the attached weight. This position is approximately that shown in the frontispiece.

Experiment 4. Loosen the screw and spin the wheel, then attach the weight as before. Now support the frame under the weight by the finger or in any other way. Precession will not take place and it will be seen that there is no tendency for it to take place so long as there is no torque. On removing the finger so that a torque comes into operation, precession starts immediately.

Experiment 5. Repeat experiment 2, and while precession is taking place try to hurry it on or to retard it. This can be done by twining a piece of string round the vertical axle above the locking screw, and pulling it either in the direction of precession or in the opposite direction, while an assistant holds the base. When the precession is hurried on the weight rises and when it is retarded the weight falls. It is possible to make the axis rise almost into a vertical position by hurrying on the precession or to fall into a vertical position by retarding it.

The reader can perform these experiments with the single-framed gyroscope, though not so satisfactorily. By pushing with or against the direction of precession in the experiments described on pp. 16-17 the frame will be made to rise or drop, but the results cannot be observed quite so well as with the type of gyroscope just described. With the single-framed type it is also possible to stop precession by placing an obstruction against the frame, the effect being the same as tightening the screw, and it will be seen that the centre of gravity of the apparatus descends immediately.

An explanation of these experiments is given on p. 46.

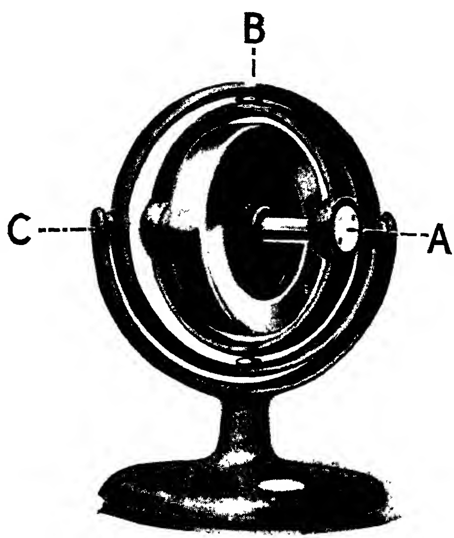


Fig. I. 4. A model gyro which can be utilised to illustrate a number of principles used in navigation instruments. A is the end of the rotor axle, B and C are the pivots of the frames.

The Model Gyro

One of the most important applications of the gyroscope is its use as a compass, and to understand properly the principles involved in this, the Sperry Model Gyro or something similar should be used. This is shown in Fig. I. 4 which explains the main features of the instrument.

A is the end of the spinning axis, the inner frame in which the wheel is enclosed (not lettered in the figure) being free to turn about a vertical axis B in another middle frame. This last frame is also free to turn about a horizontal axis C in a third outer frame which is a semicircle and is part of the base on which the instrument stands.

Experiment 1. Spin the wheel and hold the middle frame firmly so that it has no motion. Apply a slight pressure on the inner frame containing the spinning wheel and notice that this frame can be moved easily, exerting practically no resistance. If the wheel is not spinning, no difference between the forces required to move the inner frame will be detected.

Experiment 2. Spin the wheel but do not hold the middle frame. On attempting to change the direction of the axle of spin by applying pressure on the frame containing the wheel, a very decided resistance is felt, and instead of the axle altering its direction in the direction towards which the force is applied, the middle frame will start to move round its supports in the outer frame, or in other words, precession will take place in the direction P, shown by the arrow, T being the direction of pressure (Fig. I.5).

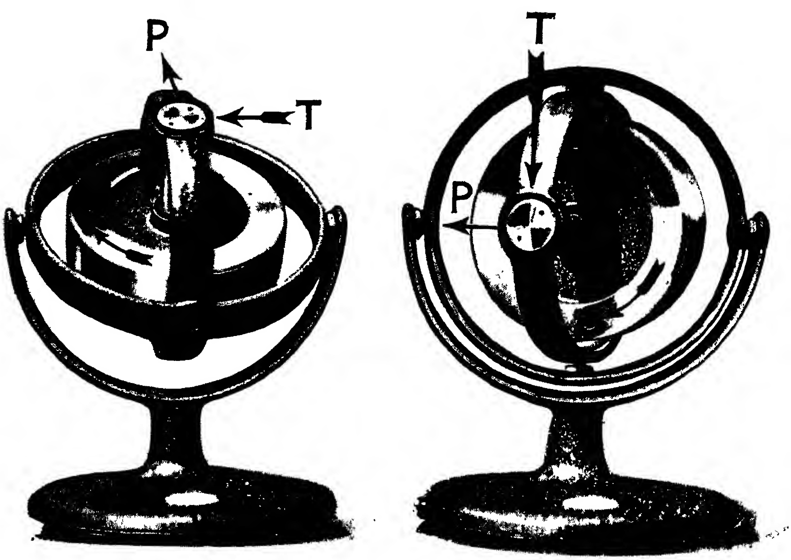


Fig. I. 5. A model gyro showing the direction of precession, indicated by the direction of the arrow P, when a torque shown by the direction of the arrow T is applied.

The same effect was observed in the simpler form of gyroscope when the screw was loosened, precession taking place, whereas when the screw was tightened, thus preventing precession, the slightest pressure on the frame containing the wheel was sufficient to move it in the direction of pressure.

Experiment 3. As this experiment is very important it is suggested that the axle should be orientated as directed, and although this makes no difference to the results, it will simplify the explanation of the use of the gyroscope as a compass.

Point the axle of the wheel east and west and denote the ends pointing in these directions by E and W respectively. Tilt the axle a little so that E is higher than W, and spin the wheel in such a way that, looking at it from E, it is spinning anti-clockwise. The axle will show no tendency to change its direction, but on applying a torque on the middle frame so that it is moved towards the vertical plane through the centre of the gyroscope, the end E will move towards the north. If the instrument is oriented as directed, the outer frame will be in the meridian and so will lie north and south, and by continuing the pressure on the middle frame which tends to make it vertical, the end E can be brought to the meridian north and the end W to the meridian south. When the axle lies in the meridian it will be found that it will show no tendency to depart from it, no torque being exerted. Torques exerted, which are equivalent to up and down forces on the axle, always rotate the gyro axle in azimuth.

It is not necessary to start with the axle tilted. It can be spun in a horizontal position and then, by applying a torque that would tilt the outer frame out of the vertical if the wheel were not spinning (the frame must lie in the vertical if the axis is horizontal) precession will take place as before. Neither is it necessary to start with the axle pointing east and west or at right angles to the plane of the outer frame. It can be started in any position provided it is not in the plane of the outer frame, that is, in the meridian.

This experiment does not show why the gyro compass finds the north and south, or in other words, sets itself in the meridian, but the following explanation will assist the reader in understanding the matter.

Why the gyro compass finds the north

To make the subject as simple as possible imagine that the gyroscope is used at the equator and that the axle is pointed east and west, say at a star when it is rising at 9 p.m. (denoted astronomically by 21h.). Assume that friction has been eliminated, the rotation of the wheel being continuous.

We have seen that if the instrument is left alone the axle will tend to maintain its same position in space so that the axle will continue to point to the star. The speed of a point on the earth is 1,038 miles an hour in equatorial regions but this does not affect the principle that the conservation of angular momentum will tend to make the axle point in the same direction. Now as the earth rotates the star appears to rise higher and higher in the heavens until it attains its greatest elevation at 3 a.m., when it is in the zenith. As the axle continues to point to the star it is obvious that it will be vertical at 3 a.m., the E end being at the top and the W end underneath. An observer might think that the spinning wheel was turning over through 90° in 6 hours or that it was completing a revolution in a day, but actually it is the earth that is turning over and the observer with it, while the axle points in the same direction all the time.

Suppose it is about midnight, when the axle will be tilted at an angle of 45° to the horizon, and the observer tries to tilt the outer frame to bring it back to the vertical. (In all cases when the axle is inclined to the horizon the frame is tilted out of the vertical.) What will take place? From experiment 3 we should expect precession to occur, and if the wheel is spinning anti-clockwise as viewed from E, this precession will move the E end of the axle towards the north and will finally bring it into the meridian. As in experiment 3, it is not necessary to start with the axle pointing east and west, but the effects of precession are more obvious when it is in this position than when it is pointing partly towards the north and south.

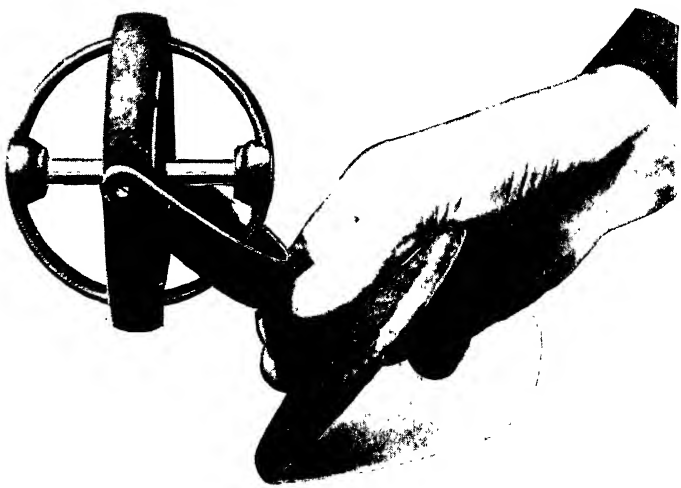


Fig. I.6. Tilting the base of a model gyro illustrates the effect of the earth's rotation. The spinning axis maintains the same direction during the tilting.

Imagine that the base of the gyroscope is the horizon and that it can be tilted over from west to east, just as the earth rotates. If the axle is pointing in the east-west direction and the base is tipped up so that its east side is lower than its west side, we have a fairly good representation of the rotation of the earth (Fig. I.6). If this is done while the wheel is spinning, it will be seen that the axle maintains the same direction and that precession does not take place. The frame remains in the same plane all the time and if we start with the axle horizontal this plane will be vertical. Now imagine that there is some force which prevents the middle frame from remaining in the same plane, and we will suppose that this frame is made to coincide with the outer frame, which implies that, regarding the base of the apparatus as the horizon, we propose compelling the middle frame to maintain a position perpendicular to the changing horizon of the earth all the time. What will take place in such circumstances? The answer can be given from another simple experiment.

Experiment 4. Place a thin piece of elastic around the middle and outer frames so that the latter frame cannot depart far from the former

(Fig. I.7). If one is moved away from the other the elastic draws it back again. While the wheel is spinning with its axis horizontal and in an east-west position, tilt the base from west to east so that the middle frame is forced to remain perpendicular to the base which, as we have seen, can be regarded as the horizon. The E end of the axle will be seen to precess towards the north, assuming that an anti-clockwise spin as seen from that end, has been given, and the axle, after a few oscillations, will finally settle in the meridian, which is supposed to be the plane of the outer frame, providing that the rotation representing that of the earth continues, and friction is assumed to exist.

When this experiment and the principles underlying the precessional movement of the axle are understood, there will be no difficulty in understanding the working of the gyro compass.

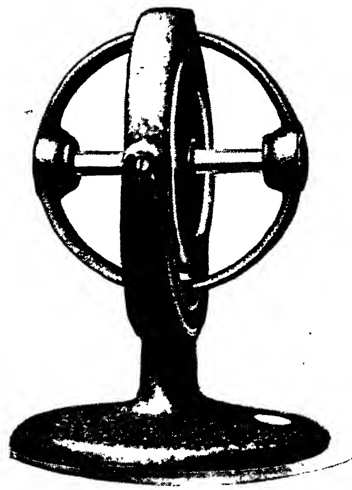


Fig. I.7. Illustration of the fact that a couple applied to the middle frame causes precession and is responsible for the spinning axis setting itself near the meridian.

Unless the gyro axis lies in the meridian the rotation of the earth will produce a tilt in the E end (to be more correct the tilt is in the horizon, but it amounts to the same thing). If a weight were attached to the middle frame at its lowest point, a couple would be applied as soon as the axle deviated from the horizontal position. If the axle were horizontal and therefore the middle frame vertical, whatever the weight on the frame might be it would not produce a couple, but the slightest deviation from the vertical would bring a couple into action and tend to turn the frame into the vertical and the axle into the horizontal positions. Precession would start and the axle would set itself, if damped, in the meridian. As will be seen, a weight would play the same part as the piece of elastic in the model.

Needless to say, an ordinary weight would not be very successful on a rolling ship because acceleration effects would be produced which would render the gyro-compass unreliable. This can be verified by oscillating the stand backwards and forwards fairly rapidly, when the effect on the precession of the frame and wheel will be seen to be somewhat erratic. The method by which such difficulties are avoided will be explained in Section 2 ; detailed explanations are outside the scope of this Section.

Although the equator has been taken as the most suitable place for showing the effects of the earth's rotation, the same argument applies to all latitudes except that of the poles. Certain complications arise except at the equator, and these will be dealt with in Section 2, which shows the practical application of the Gyro Compass.

CHAPTER 3

GYROSCOPE PROBLEMS

Up to the present most of this Section has been devoted to the observation and recording of experiments with different types of gyroscopes, but nothing has been developed on the dynamics of the instrument. If this subject were considered fully it would involve mathematics beyond the scope of the book, and it will suffice to deal with the more elementary formulae which are used in solving certain gyroscopic problems. Readers who have only a small mathematical equipment will have no difficulty in following the methods developed for handling simple problems connected with the gyroscope. Numerous examples are worked out fully and if these are carefully studied they will assist those who feel disposed to pursue the subject more fully in advanced text-books.

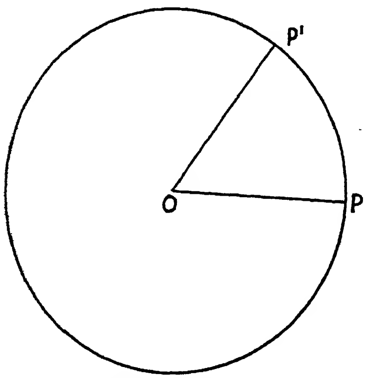


Fig. I.8. Explanation of the radian. The angle POP′ is a radian when the length of the arc PP′ is equal to the length of the radius OP.

Angular velocity

It has been shown that the angular momentum is expressed in the form *mvr* but there is another way of expressing angular momentum, and this is practically always used. To explain this method it will be necessary to digress to deal with a few elementary principles in trigonometry.

Let O be the centre of a circle of radius r and take any point P on the circumference of the circle (Fig. I. 8). Measure an arc PP′ so that its length is equal to r, that is, so that PP′ is the same length as the radius of the circle. The circumference of the circle is $2\pi r$, and the whole circumference subtends an angle 360° at the centre of the circle. Hence, if an arc $2\pi r$ subtends 360°, an arc of length r will subtend $360°/2\pi$, so that the arc PP′ subtends an angle $360°/2\pi = 180°/\pi$, or about 57·296°. This angle is known as the *radian* and has very important applications in many problems. It is used as the unit of angle when we measure angular velocity as the foot is used as the unit of length when we measure linear velocity, though it is a less arbitrary unit than the foot. If we say that the angular velocity of the weight previously referred to is ω, this means that in each second the rope turns through ω radians, and by giving ω different values we can ascribe any angular velocity we please to the weight. Thus, if we say that ω is 6, this means that in each second the rope traces out an angle equal to 6 radians, and as each radian is 57·296°, the rope will turn through nearly 344°, not quite a complete rotation, in a second.

Relation between linear and angular velocities

There is a simple relation between the linear velocity and the angular velocity, which will be established first of all for the particular case under consideration, and then for every case.

Suppose the body of mass 100 lb. is moving in a circle of radius 8 ft. with a velocity of 20 ft./sec. The circumference of the circle is 16π and hence the body will complete a revolution in $16\pi/20$ sec. Since a radian is $1/2\pi$ of a revolution, the body will complete a radian in $16\pi/20$ multiplied by $1/2\pi$ sec., that is in $8/20$ sec., and hence in 1 sec. will move through $20/8$ radians. As it has been agreed to denote by ω the number of radians described by a body moving in a circle each second, $\omega = 20/8$, which is simply the linear velocity divided by the radius. The result can be generalised very easily and the formula connecting linear velocity, radius, and angular velocity is

$$v = \omega r, \text{ or } \omega = v/r$$

It will be seen that the use of the radian instead of degrees introduces simplicity into the method of computation.

The following examples will illustrate the use of the above formula :

A disc is rotating with angular velocity 30. What is the linear velocity of a point on it (a) 3 feet from the centre ; (b) 2 ft. from the centre ? (The rotation takes place round a line through the centre at right angles to the plane of the disc).

$$\text{(a) } v = 30 \times 3 = 90 \text{ ft./sec.}$$
$$\text{(b) } v = 30 \times 2 = 60 \text{ ft./sec}$$

If the disc makes 6,000 revolutions per minute find its angular velocity and the linear velocity of a point 6 in. from its centre.

It makes 100 revolutions per sec. and since each revolution is equivalent to 2π units (the unit being the radian), its angular velocity is 200π or just over 628 rad./sec. (The abbreviation rad./sec. is used for radians per second.)

A point 6 inches from the centre will move with a linear velocity of $628 \times \frac{1}{2} = 314$ ft./sec.

Angular velocity is not restricted to motion in a circle and is applied to any form of curve. If any point P is moving relatively to a point O, but not along the line OP, the point P is said to have angular velocity about O. The rate at which the line OP is describing an angle is the angular velocity of P. If the motion is not in a circle the linear velocity can be measured by taking the ratio of the small arc described in a short interval to the interval, and the angular velocity is then measured by dividing this last value by the distance of P from O at the time. Generally speaking, the problems on the gyroscope are restricted to circular motion, but the angular velocity need not be uniform, just as the linear velocity need not be uniform.

To make this clear, suppose a sphere is capable of rotating round a line drawn vertically through its centre. If we start rotation and then discontinue the force that originated it, the sphere would, if there were no friction, rotate with a uniform angular velocity. As friction is always in evidence, the sphere will not have a uniform angular velocity but will rotate with a continuously decreasing angular velocity until it comes to rest. On the other hand, if we persist with the force that started rotation, the angular velocity of the sphere will increase. At any time in its rotation the linear velocity could be ascertained by finding how long a small portion of its surface, say an inch, required to pass over a point fixed outside the sphere, and then dividing the distance by the time. The angular velocity is easily deduced from this if the perpendicular from the portion under consideration to the axis of rotation is known. It is obtained by dividing the linear velocity by the length of this perpendicular.

It has been shown that the angular momentum is written in the form mvr, and since $v = \omega r$, it can be expressed in the more convenient form ωmr^2. This form will be frequently used because in many cases the angular and not the linear velocity is given, and ω is a constant for every point on a body, whereas v varies from point to point. Of course the angular velocity can always be expressed in terms of linear velocity, when the radius is known, and then the angular momentum can be computed by the first formula, but this is both tedious and unnecessary. In the example following, both methods will be used, and readers are recommended to make themselves familiar with the formulae because this will assist considerably when more difficult problems are dealt with later.

A flywheel consists of an axle, spokes and a heavy rim, so that all its mass may be assumed to be concentrated in its rim. The weight of the flywheel is 3 cwt., its diameter is 6 ft., and it revolves 3,000 times a minute. Find its angular momentum.

In this case $m = 336$ lb., $r = 3$ ft., and the wheel revolves 50 times a second. Its circumference is 6π ft. and as it moves through 50 circumferences in a second its velocity is 300π ft./sec. Hence its angular momentum is $336 \times 300\pi \times 3 = 302{,}400\pi$ or 950,017 lb.ft.sec.

Now use the second formula ωmr^2. Since the wheel revolves 50 times a second, which implies 100 radians a second, expressed as angular velocity, the angular momentum is $100\pi \times 336 \times 9 = 302{,}400\pi$ lb.ft.sec.

The same result is obtained, as might be expected, but the latter method adds simplicity to the calculation.

It should be noticed that nearly all the mass of the wheel is supposed to be concentrated in the rim. In these circumstances the above expressions for the angular momentum are nearly correct, but if the mass is distributed, as happens in a disc, they cannot be used. We shall now deal with this problem.

Moment of inertia and angular momentum for various bodies

It has been shown that the angular momentum of a rotating wheel, all the mass of which is supposed to reside in its rim, is ωmr^2. This expression, however, is valid only for these ideal and hypothetical conditions and the problem becomes a little more difficult when we deal with the bodies that are actually encountered in the practical affairs of life.

Suppose we have a disc which is symmetrical and is rotating about an axis through its centre perpendicular to its plane. If we take a very small angle at the centre of the disc, this angle being subtended by a very small portion of the outside rim which is moving with linear velocity v, its angular momentum, if its mass is m, is mvr, as previously shown. Another thin portion inside the rim will have the same angular velocity as the outer portion, but obviously less linear velocity, the linear velocities decreasing as we approach the centre of the disc where there is no linear velocity. Hence the angular momentum of the next thin portion would be less than mvr, because m is a little smaller, v is *less* and so is r. We may express it in the other form by saying that the angular momentum of the outer rim is ωmr^2, but although ω is constant, m and r decrease.

Before dealing with this problem it will be necessary to define another term which will be frequently used in this book.

Suppose we have a body that is capable of rotating about any axis AB which need not necessarily pass through its centre of gravity. Take any small portion of the body of mass m and distance r from the axis, and consider the expression mr^2. This will vary according to the position of the particle, being greater the farther it is from the axis and vice versa. Now suppose we could take the sum of an infinite number of these products mr^2 so that we included the whole of the body in the summation, the result is known as the moment of inertia of the body. It is independent of the angular velocity and indeed has no connection with it; every body possesses a moment of inertia about any line which may be considered, but it possesses moment of momentum only when it is rotating. The moment of momentum or angular momentum is found by multiplying the moment of inertia, usually denoted by I, by the angular velocity, ω. It will be seen that when the mass of a wheel is concentrated in its rim its moment of inertia is simply the mass of the whole rim multiplied by the square of the radius, assuming that the moment of inertia is reckoned round a line through the centre at right angles to the plane of the wheel. Its angular momentum is the product of the last expression by ω, and this merely gives the result that we obtained previously for this simplest of all cases.

When we have obtained the value of the summation mr^2 for the whole body, if the total mass of the body is M it is possible to find an expression Mk^2 which is equal to this summation. The symbol k denotes a length and is called the radius of gyration of the body.

A simple example of the above will now be given and it will be shown how the moment of inertia can be easily found from elementary integral calculus.

Take a thin rod AB of length l units and mass μ per unit length. Find its moment of inertia about a line drawn from one end A perpendicular to its length (see Fig. I. 9).

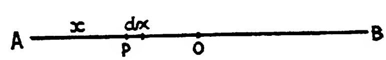


Fig. I.9. Moment of inertia of a rod AB about one end and also about its middle point O.

Take any point P on the rod at a distance x from A. The mass of a small element dx at P is μdx, and multiplying this by the square of its distance from A, the moment of inertia of the small portion is $\mu x^2 dx$. Hence the moment of inertia of the whole rod is

$$\int_0^l \mu x^2 dx = 1/3\mu l^3 = 1/3\mu l \cdot l^2 = 1/3Ml^2 \text{ if } M \text{ is the mass of the rod,}$$

because $M = \mu l$.

From the definition of k previously given it is obvious that $k^2 = l^2/3$, or $k = l/\sqrt{3}$.

If the moment of inertia of the rod is required about a line through O, its middle point (see Fig. I.9), we can deal with each half separately. The moment of inertia of the portion OA about this line is the mass of this portion multiplied by one-third of OA squared, and similarly for the portion OB. Hence the total moment of inertia is twice the above, or the mass of the whole rod multiplied by one-third the square of half its length, that is $Ml^2/12$.

3

In the case of a disc like that shown in Fig. I.10, if the moment of inertia about a line through its centre perpendicular to its plane is required, consider a thin ring at a distance r from the centre. We need not deal at present with a thick disc, and we shall suppose it is very thin, like a piece of cardboard. If the mass of the section under consideration is μ per unit area, the mass of the ring is $2\pi\mu r dr$, so that its moment of inertia is $2\pi\mu r^3 dr$. Integrating this last expression, the result is $\frac{1}{2}\pi\mu r^4$ or $\frac{1}{2}Mr^2$ where M is the mass of the disc. We can extend this to a thick disc which can be supposed to be built up of a large number of thin discs, and as each one of these will have a similar expression for the moment of inertia, the total moment of inertia for the disc is $\frac{1}{2}Mr^2$.

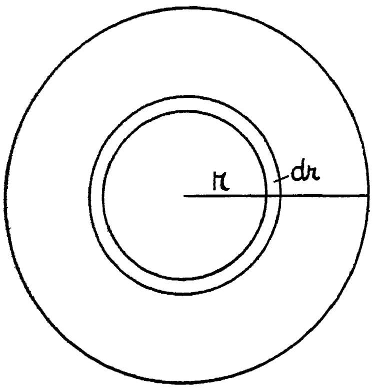


Fig. I.10. Moment of inertia of a circular disc about an axis through its centre perpendicular to its plane.

The moment of inertia of various other bodies can be obtained in the same way, but it is not proposed to deal with each case separately. At the end of the chapter a list of moments of inertia for different bodies will be found, and this can be referred to when problems arise in this or in subsequent chapters.

A few examples follow to illustrate the formulae given in the text.

A homogeneous rod weighing 10 lb. rotates on a pivot at its centre, performing 6 rotations per second. Find its moment of inertia, its radius of gyration, and its moment of momentum, if the length of the rod is 8 ft.

Using the formula $Ml^2/12$, and substituting 10 for M, and 8 for l, the moment of inertia is $53\frac{1}{3}$ lb.-ft.

If k is the radius of gyration, the moment of inertia is Mk^2 or $10k^2$, which is epual to $53\frac{1}{3}$. Hence $k^2 = 5\frac{1}{3}l^2$, or $k = 2.3l$.

The rod turns through 12π radians per sec., so that $\omega = 12\pi = 37.7$ radians. Hence the moment of momentum, which is $I\omega$, is $53\frac{1}{3} \times 37.7 = 2011$ ft. pd. sec.

The kinetic energy of a body of mass M moving with a velocity v is expressed in the form $\frac{1}{2}Mv^2$. If M is expressed in pounds and v in feet per second, the energy is given in foot poundals (written in the form ft. pdls.), a poundal being a force equal to $1/g$ part of the attraction of the earth on a standard pound, and g being the value of gravity at the place. As g does not vary very much over the surface of the earth, its approximate value of 32 can be used in the examples.

Just as the kinetic energy of a moving body is expressed in the form $\frac{1}{2}Mv^2$, so the kinetic energy of a rotating body is expressed in the form $\frac{1}{2}I\omega^2$. Thus, in the above example, suppose we are asked to find the kinetic energy of the rotating rod, we proceed as follows :

$I = 53\frac{1}{3}$, $\omega = 37{\cdot}7$, $\frac{1}{2}I\omega^2 = 37{,}901$ ft. pdls., or 1,184 ft. pds.

The value of π^2 is 9·87 and for approximate purposes it can be taken as 10. Thus, if ω is 12π, ω^2 is $144\pi^2$ approximately, and $\frac{1}{2}I\omega^2$ is 38,400 ft. pdls., which is nearly the same as the value obtained above.

The reader will now see why it was assumed that the mass of a weight on the end of a rope (p. 18) was supposed to be concentrated into a point. If this assumption were not made the angular momentum would not be $m\omega r^2$ because all portions of the weight are not at the same distance r from the operator's hand.

Parallelogram of velocities

It is presumed that readers have some knowledge of the ordinary parallelogram of velocities. Briefly, this principle states that if a particle P possesses two velocities, say u and v, in directions PA and PB, and if lengths PA and PB are set off representing the values of u and v on any convenient unit, the resultant velocity of the particle is represented in magnitude and direction by the diagonal PC of the parallelogram PACB (see Fig. I.11). The principle can be extended to the case of a body possessing a number of velocities, the resultant of any two being compounded with another and the resultant of these compounded with another, and so on.

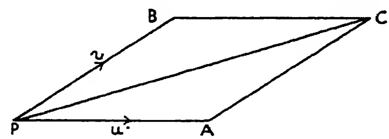


Fig. I.11. Parallelogram of linear velocities.

It is very important to understand clearly what is implied by a body possessing two or more velocities. When we speak of a velocity we mean a velocity relative to something whether in motion or at rest. Thus if a ship is moving with a speed of 25 feet a second it is implied that this is the speed relative to some mark—a rock, a buoy, etc. If a man walks on the deck with a speed of 5 feet a second, we mean that this is his speed relative to a mark on the deck of the ship, not relative to the buoy. His speed relative to the buoy is found, as already explained, by means of the parallelogram of velocities, one side of the parallelogram representing the velocity of the ship, relative to the buoy, in magnitude and direction, and the other side representing the velocity of the man in magnitude and direction, with reference to the mark on the deck. The principle is applied to angular velocities as follows.

Parallelogram of angular velocities

Imagine a body, say a gyroscope, which is held in the hand in a certain direction. It is possible to give the wheel two different rotations in the following way. First of all spin the wheel in the usual manner and while it is spinning, turn the frame so that the plane of the wheel alters. Obviously the wheel will have two different rotations: (a) it will rotate about its axis with an angular velocity say ω, this velocity being relative to the frame; (b) it will rotate with another angular velocity say Ω, which is due to the rotation of the frame with reference to some fixed point or line in space. How can the resultant angular velocity with reference to the line be found?

In Fig. I.12 let OA and OB be two axes in a rigid body and let the angular velocity round OA, relative to an imaginary frame AOB, be ω_1. At the same time imagine that the frame itself is rotating relative to a line outside it, say a line in space, with an angular velocity ω_2. Lay off OA and OB to represent the magnitudes of these rotations on any scale that is convenient and complete the parallelogram OBCA. It is assumed that each rotation is positive as seen from O, that is, an observer at O judges each rotation to be anti-clockwise. Then OC represents the magnitude and direction of the resultant rotation which can be denoted by ω.*

The convention regarding signs presents difficulties in some cases. We have assumed that both rotations are positive, but how is the figure to be drawn if one is positive and the other negative?

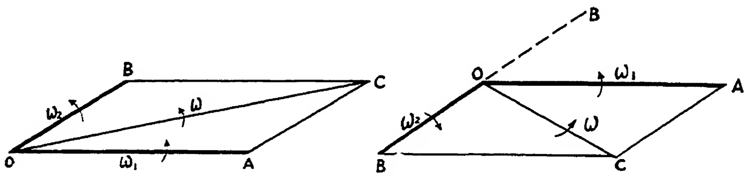


Fig. I.12. Parallelogram of angular velocities.

. A very convenient method is as follows: Draw OA and OB in such directions that ω_1 and ω_2 are in the same direction as seen from O. Thus, if ω_1 is anti-clockwise and ω_2 is clockwise, we can draw OA in the same direction as previously, but if we draw OB towards the top of the page the rotation of ω_2 will not be the same sign as that of ω_1. If, however, we draw OB towards the bottom of the page, then, as seen from O, the rotation ω_2 will have the same sign as ω_1. Completing the parallelogram OABC, the diagonal OC will represent the magnitude of the resultant angular velocity.

The results obtained apply also to angular accelerations and angular momenta. Thus, if I_1 and I_2 are the moments of inertia of the body about the axes OA and OB, the angular momentum in each case will be $I_1\omega_1$ and $I_2\omega_2$, and if these are represented by OA and OB, the resultant angular momentum is about the line OC and is represented by OC.

An example will illustrate the application of these principles.

A homogeneous rod 4 ft. long and weighing 10 lb. is rotating horizontally about a vertical axis through its centre O, with angular velocity 6 rad./sec. The rod is also rotating about a horizontal axis drawn from the centre of one face to that of another, the section of the rod being a circle of diameter 3 in. The angular velocity in this last case is 20 rad./sec. Find the resultant angular velocity and the resultant angular momentum. Assume the first rotation round the vertical axis to be positive as regarded from O looking upward, and the second negative as regarded from O looking to the right.

Set off OA equal to 6 units representing the magnitude and direction of the first rotation ω_1. If OB is taken to the right of O to represent the second rotation ω_2, its sign will differ from that of ω_1, and hence, in accordance with the suggestion regarding signs, it will be better to lay off OB to the left of O to represent ω_2. By doing so both ω_1 and ω_2 are given the same sign of rotation. The diagonal OC of the parallelogram OACB represents in magnitude and direction the resultant angular velocity and is $\sqrt{(6^2 + 20^2)} = 20{\cdot}9$ rad./sec.

*This applies only to the velocities at any particular instant. If velocities over a finite time are considered, the axis of the angular velocity must change its position in the body.

The moment of inertia of the rod about the vertical axis is $10 \times 16/12 = 13\frac{1}{3}$ lb.ft., and hence its angular momentum is $13\frac{1}{3} \times 6 = 80$ ft.lb.sec.

The moment of inertia of the rod about its horizontal axis is $\frac{1}{2} \times 10\frac{(1)^2}{8}$ $= 5/64$ lb.ft. The angular momentum is $20 \times 5/64 = 3.125$, and the resultant angular momentum is $\sqrt{(80^2 + 3.125^2)} = 80{\cdot}06$ ft.lb.sec.

If the axes were inclined at an angle θ the resultant angular velocity would be obtained by the well-known formula employed for linear velocities.

$$V^2 = u^2 + v^2 + 2uv \cos\theta, \text{ or, for angular velocities,}$$

$$\omega^2 = \omega_1{}^2 + \omega_2{}^2 + 2\omega_1\omega_2 \cos\theta.$$

The same formula would apply for the resultant angular momentum.

Couples

The word "couple" is frequently used in connection with engineering problems and occurs in gyroscopic problems as well. A few words of explanation may be advisable.

Two equal and opposite parallel forces acting on a rigid body constitute what is called a couple. The tendency of a couple is to turn a body round in the plane in which the two forces lie. Imagine a rod capable of turning about an axis through its centre, and a force of say 10 poundals acting at right angles to the rod at one end which is 6 feet from the centre. The moment of the force about the axis is $10 \times 6 = 60$ pdls. ft., and if an equal force acted in the opposite direction at the other end of the rod its moment would be the same. The moment of the two forces is 120 pdls. ft., or it is the product of one of the forces into the distance between them, this distance being 12 feet. It makes no difference where the axis is, it may be at any point in the rod or even outside it—the value of the couple will still be the same, as the reader can verify by taking the axis at various parts of the rod. Engineers often use the term "torque" instead of couple and the word will sometimes be employed in the text, the symbol K being used to denote the value of the moment of a couple or a torque. Reference to the term has already been made (see p. 22).

Relation between a couple, moment of inertia and angular velocity

In the ordinary problems dealing with forces and velocities we know that a force is measured by the change of velocity that it produces on a body of certain mass in a fixed time. Thus, a force of a poundal ($1/g$ lb.) acting for a second on a mass of 1 lb. will change its velocity by 1 ft./sec., or produce an acceleration of 1 ft./sec. per sec. In dealing with rotating bodies we can apply the same principle, substituting a couple for a force, moment of inertia for mass, and angular acceleration for acceleration. Thus, instead of the formula $F = mf$ where F is the force and m and f the mass and acceleration, we can use the formula $K = I\alpha$, where K is the torque and I and α the moment of inertia and the angular acceleration respectively. From this formula $\alpha = K/I$.

The following example will illustrate the application of this formula.

A solid sphere of diameter 2 feet and density 5 rotates on an axis through its centre and is acted on by a couple applied at the ends of a diameter which is at right angles to the axis of rotation. The couple is the equivalent of equal and opposite forces each equal in magnitude to the weight of 20 lb. at each end of the diameter. Find the angular velocity of the sphere at the end of a second, assuming it was originally at rest.

The volume of the sphere is $4\pi r^3/3 = 4{\cdot}19$ cubic feet. A cubic foot of water weighs 62·43 lb., and as the density of the sphere is 5, its mass is $4{\cdot}19 \times 62{\cdot}43 \times 5 = 1308$ lb.

The moment of inertia of a solid sphere (see table at end of chapter) is $2Mr^2/5 = 523{\cdot}3$ lb.ft. The value of the couple is $640 \times 2 = 1280$ pdls.ft. because it is 20×2 lb.ft., and this is the same as 1280 pdls.ft.

The results are as follows: $I = 523{\cdot}3$ lb.ft.; $K = 1280$ pdls.ft. Then α, the angular acceleration, is $K/I = 2{\cdot}45$ rad./sec. per sec.

If the couple ceased to act at the end of a second the sphere would continue to rotate with the angular velocity of 2·45 rad./sec., ignoring the effects of friction. If it continues to act then the angular velocity will go on increasing by 2.45 rad./sec. each second because 2.45 is the angular acceleration produced by the couple. It is similar to the case of a body moving under the action of a force; the change of velocity at the end of a second is really the acceleration produced by the force and if this acceleration is denoted by f the velocity of the body at the end of t seconds is ft. The angular acceleration of the sphere in the above example being 2.45, if the couple acted for 10 seconds the angular velocity would be 24·5 rad./sec.

The moment of inertia of the sphere remains constant but its moment of momentum naturally increases continually with the increasing value of ω. The rate at which this moment of momentum $I\omega$ changes measures K, the couple acting about the axis. This applies even for very short intervals of time, not necessarily a second, and the principle is important in dealing with the next point.

Relation between a torque, angular momentum of the rotating wheel and rate of precession

Suppose a gyroscope is held with the axle of the wheel horizontal, the angular velocity of the spin being ω. If the moment of inertia of the wheel is I, then its moment of momentum, $I\omega$, will be represented by the vector aa_1 in Fig. I.13. Now apply a couple to the axle of the wheel in such a direction that it would tend to rotate the axle in a plane at right angles to the plane in which the spin is taking place; as a consequence it will generate angular momentum about an axis at right angles to the axis of spin, and we can represent this additional angular momentum by the vector aa_2. Completing the parallelogram, the diagonal aa_3 represents the resultant angular momentum in magnitude and direction. We can imagine this resultant re-resolved into its component parts aa_1 and aa_2, the former merely representing the original angular momentum and the latter the added angular momentum. In what plane will the components lie?

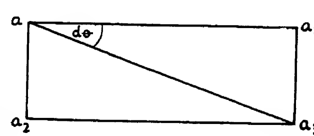


Fig. I, 13. Derivation of the formula $K = I\,\omega\,\Omega$, connecting the angular momentum of rotation of the wheel with the rate of precession.

Suppose that the couple or torque is applied vertically, say to the frame by the force of gravity, then the additional angular momentum produced by the applied torque will be a horizontal vector, parallel to the axis of the couple which produces it. Hence aa_1, and also aa_2 are in the same horizontal plane and so also is aa_3, the vector representing the resultant angular momentum. For this reason the whole apparatus now possesses an angular momentum about an axis parallel to aa_3 and in the same horizontal plane as the original axis of spin which has, therefore, been turned through the angle a_1aa_3. The effect of applying the torque vertically has therefore been to turn the gyroscope round in a horizontal plane.

Suppose the angle a_1aa_3 is very small, say $d\theta$, and that the gyroscope turns through this small angle in a short interval dt. Then $aa_2 = a_1a_3 = aa_3\ d\theta$. But $aa_2 = K\,dt$, the added angular momentum, and $aa_3 = I\omega$, hence

$$K\,dt = I\omega d\theta, \text{ or}$$

$$K = I\omega\frac{d\theta}{dt} = I\omega\Omega$$

where Ω is the angular velocity of precession, which is the same as $d\theta/dt$, the rate of change of the angle θ with regard to time.

The above equation is very important and must be thoroughly understood before proceeding with other problems in the gyroscope. Its application will be exemplified by a few problems which will be worked out fully.

Problems illustrating the formula $K = I\omega\Omega$

The details regarding a small gyroscope are as follows :

Radius of wheel 0·1 ft.

Radius of frame 0·13 ft.

Distance of end of set screw to centre of gravity of frame 0·17 ft.

Mass of wheel 0·22 lb.

From these data calculate the angular momentum of the wheel, if the angular velocity is ω, and also the angular momentum of the gyroscope when it is precessing with angular velocity Ω, supposing that the frame is precessing when it is horizontal, and the mass of the frame is ignored.

Assuming the flywheel homogeneous its moment of inertia I may be taken as $\frac{1}{2}Mr^2 = \frac{1}{2} \times 0{\cdot}22 \times 0{\cdot}01 = 0{\cdot}0011$ lb.ft.². Hence the angular momentum, $I\omega$, is $0{\cdot}0011\omega$ ft.pdls.-sec.

The angular momentum of the gyroscope round a vertical line through its point of support is $0{\cdot}22 \times 0{\cdot}17^2\Omega = 0{\cdot}064\Omega$ ft.pds.-sec.

Apply the formula $K = I\omega\Omega$ to find the angular velocity of the wheel if Ω is 2·27, that is, if precession takes place at the rate of 2·27 radians per sec. (It should be noticed that a complete revolution is equivalent to 2π radians, so that 2·27 radians $= 2{\cdot}27/2\pi$ of a revolution, and hence this fraction of a revolution, 1/3·61, takes place in a second, or one precession takes place in 3·61 seconds.)

We may consider the torque as due to the wheel of mass 0·22 lb., ignoring the mass of the frame, and the length of the arm of the couple as 0·17 ft. Hence $K = 0{\cdot}22 \times 0{\cdot}17 \times 32$ pdls.ft. $= 1{\cdot}1968$ pdls.ft. It has been shown that $I = 0.0011$ lb.ft²., and Ω is assumed to be 2.27 rad./sec., hence

$$0{\cdot}0011 \times 2{\cdot}27\,\omega = 1{\cdot}1968, \text{ from which}$$
$$\omega = 480 \text{ rad./sec.}$$

The flywheel, therefore, spins through 480 radians, or completes $480/2\pi = 51$ turns, per second.

A heavy wheel in the form of a disc and weighing 50 lb. is rotating about its axle with angular velocity, 32 rad./sec. A couple of 200 lb.ft. is applied. Find the rate of precession if the radius of the wheel is 2 ft.

Referring to the table at the end of the chapter, $I = \frac{1}{2} \times 50 \times 2^2 = 100$ lb.ft.². $K = 200 \times 32 = 6400$ pdls.ft. $\omega = 32$ rad./sec. Hence,

$$100 \times 32\,\Omega = 6400, \text{ from which}$$
$$\Omega = 2 \text{ rad./sec.}$$

This is equivalent to $2/2\pi = 0.3$ revolution per second, or one revolution in about 3 seconds.

A motor cycle has a heavy flywheel in the form of a disc of 4 in. radius and weighs 35 lb. It is making 1800 revolutions a minute while the cyclist is rounding a curve of 30 ft. radius and travelling at 20 miles per hour. The axis of the flywheel is parallel to the axes of the wheels. If the total weight of the machine and rider is 300 lb. how far must he move the centre of gravity of himself and the machine while he is rounding the curve, owing to the rotation of the flywheel ?

The data are as follows :

$$r = 1/3,\ M = 35,\ I = \tfrac{1}{2}Mr^2 = 35/18 \text{ lb.ft.},\ \omega = 30 \times 2\pi = 60\pi$$
$$= 188{\cdot}5 \text{ rad./sec.}$$

Since 20 miles per hour is 88/3 ft./sec., and the radius of the curve is 30 ft., $\Omega = v/r = 88/90$. (Notice that rounding the curve is equivalent to precession.)

If d is the horizontal displacement of the centre of gravity, the couple introduced is $300 \times d \times 32$ pdls.ft. $= 9600d$. Hence

$$9600\,d = \frac{35}{18} \times 188{\cdot}5 \times \frac{88}{90}, \text{ from which}$$

$$d = 0{\cdot}0424 \text{ ft.} = 0{\cdot}51 \text{ in.}$$

The propeller shaft of a torpedo-boat destroyer is a cylinder of radius 4 in., mass 12 tons, and revolves with an angular speed of 750 revolutions per minute. If the speed of the ship is 35 knots when it is turning in a circle of radius 605 yards, find the torque in lb.ft. exerted by the bearings of the shaft.

Here $r = 1/3$, $M = 26{,}800$, $I = 1493$, $\omega = 12{\cdot}5 \times 2\pi = 78{\cdot}54$ rad./sec. A speed of 35 knots is 35×6080 ft. per hour or $59{\cdot}1$ ft./sec. The angular velocity Ω in describing the circle is $v/R = 59{\cdot}1/1815 = 0{\cdot}0326$ rad./sec. Hence

$$K = 1493 \times 78{\cdot}54 \times 0{\cdot}0326 \text{ pdls.ft.} = 119{\cdot}5 \text{ lb.ft.}$$

The rotating parts of an aeroplane engine are in front of the pilot, and weigh 100 lb., their radius of gyration being 10 in. The engine runs at 1600 revolutions per minute, and the direction of rotation is clockwise, as seen from the pilot's seat. When running at 40 miles an hour, the aeroplane begins to turn to the right along a curve of 300 ft. radius. Find the magnitude of the gyroscopic couple in lb.ft., and show that it tends to make the machine dive.

(Trinity College, Cambridge, March 1910).

$I = Mk^2 = 100 \times 25/36 = 69{\cdot}44$ lb.ft., $\omega = 1600 \times 2\pi/60$
$= 167{\cdot}5$ rad./sec.

Velocity of aeroplane is 176/3 ft.sec. and Ω = velocity divided by 300 = 176/900 = 0·196 rad./sec. Hence

$K = 69{\cdot}44 \times 167{\cdot}5 \times 0{\cdot}196 = 2279{\cdot}7$ pdls.ft. $= 71{\cdot}2$ lb.ft.

Spin the wheel of a simple gyroscope and suspend it in a neutral position, as described on p. 16, so that the direction of spin, as seen from the back, is clockwise. Try turning the frame to the right and it will tilt downwards in front. The reason for this is obvious from the rules for the direction of precession previously given on p. 23.

Illustrations of precession

If you look at a child making a hoop roll along the ground, you will notice that the hoop frequently moves out of the vertical and then its path becomes a curve instead of a straight line. How can this phenomenon be explained on the gyroscopic principles just considered?

Suppose the hoop tilts over a little to the right. The weight of the hoop and the reaction of the ground form a torque which tends to turn the plane of the hoop horizontally.

Apply the rule given on p. 23 and consider that the hoop has an imaginary axle. The weight of the hoop and the reaction of the ground produce a couple, and if the line representing the force of gravity is drawn downwards and then rotated 90° in the direction of the spin, it will arrive at the rear of the hoop. The right-hand end of the imaginary axle is thus made to move to the rear so that precession takes place in the direction in which the hoop is leaning.

In the case of an ordinary bicycle in which the wheels are light in comparison with the weight of the rest of the machine and the rider, they cannot exercise a very great effect on the motion of the machine. Centrifugal considerations are of primary importance in the stabilisation of the bicycle, but we are not dealing with these and gyroscopic action only will be considered. This effect is of some importance if the bicycle is moving fast, and the effort of the rider to right himself looks, on first appearance, as if he were doing the wrong thing and endangering his stability.

Suppose a rider finds that he is falling over to the left. One would think that he should turn his handlebars quickly to the right to save the situation, but he does just the opposite—he turns them to the left. To understand the effect of this, imagine that a bicycle wheel is suspended by its axle and spun in the same way as it revolves when a rider is cycling forward. Then imagine that the top of the wheel is tilted towards the left, what will happen? This can be easily demonstrated by using a gyroscope. Hold it so that the left side of the axle is lower than the right side and imagine that a force is applied at the front of the wheel towards the left, corresponding to the twist given by the rider to the handlebars. Rotate the line representing this force through 90° in the direction of the revolution of the wheel and it will be applied at the lowest point of the wheel acting towards the left (see rule 2, p. 23). The effect can be seen better if we look at the back portion of the wheel acted on by a force to the right, as it obviously would be if the front of the wheel is acted on by a force towards the left. In fact, we may regard the wheel as turning under the influence of a torque, the back portion of the wheel moving to the right as looked at from behind. Now rotate the line representing this force through 90° in the direction of the motion of the wheel, and it will be seen that all the top part of the wheel will tend to move towards the right—or in other words, the effect is to restore it to the perpendicular.

Precession plays a prominent part in the heavy wheels of a railway engine. Suppose the engine is rounding a curve and is turning to the right. Precession to the right, when the wheels are revolving in the forward direction, can take place only in consequence of a couple tending to lift the left-hand end of the axle and to depress the other end. Suppose the left-hand or outer rail were not raised, what would happen? The precession of the right-hand end of the axle gives this end a direction of motion to the rear, and by the precession rule, by rotating the direction of this force through 90° in the direction of the spin of the wheel, it is seen that there is a torque giving an upward thrust to the inner wheel. Hence, to counteract this, a torque must be introduced giving a downward tendency to this wheel, and this is provided for by raising the outer rail. The precessional effect is in addition to the ordinary centrifugal force which is in evidence as the engine describes the curve.

The effects of precession are seen in the case of the earth's poles which describe circles round the ecliptic poles in a period of about 26,000 years. A spinning top which is tilted a little from the vertical is a good illustration of the conical motion of the earth. The axis of the top moves in the same direction as the top rotates, and this axis describes a cone whose vertex is the point of the top. If we could imagine the axis prolonged below the point of support this portion would also describe a cone whose vertex is the point of the top. The earth's axis behaves in nearly a similar way, the apex of the two cones being the centre of the earth, but, for reasons given later, the precession of the earth's axis is in a direction opposite to that of a top spinning on its point.

The gravitational pull of the moon and to a less extent of the sun on the protuberant portions of the equatorial regions tends to make the axis of the earth more perpendicular to the plane of the ecliptic than it is at present (the inclination is about 66½°). If the earth had no rotation there would be little opposition to this force but, owing to the axial rotation of the earth, it resists the pull of the sun and moon.

Try the following experiment with a gyroscope.

Spin the wheel and hold the gyroscope in such a manner that this spin is from west to east—the same direction as the earth's rotation. Tilt the instrument a little out of the vertical and place its south end on a table. Notice that the gyroscope also precesses from west to east and the rule for precession shows that this occurs because the pull of the earth tends to make the axle of the wheel deviate still more trom the vertical. If we applied a force tending to make the axle vertical then precession would take place in the opposite direction—east to west. This can be verified by suspending the gyroscope and noticing the precession.

The attraction of the moon and sun tends to make the earth's axis perpendicular to the ecliptic, and hence precession takes place opposite to the earth's direction of rotation, that is, it takes place from east to west. Fig. I.1 b, showing a spinning top suspended by a string, illustrates this point.

An alternative method for explaining precession and deriving the formula $K = I\omega\Omega$

An explanation of the precession of a wheel has already been given (p. 38-39), but there is another method of dealing with this problem, based on the principle of the conservation of angular momentum, and this will now be dealt with.

Let us start with the case of a juggler on a spinning disc, and we shall suppose that he is changing his angular velocity by moving heavy weights in and out towards and from the centre of the disc. When the weights approach the centre the angular velocity is increased and when they recede from the centre it is retarded. We shall generalise this phenomenon and express it in the following law :

If a particle is approaching the axis of a spinning body there is an apparent force which accelerates the rate of spin, or which acts in the same direction as that of the rotation. If the particle is receding from the axis of the spinning body there is an apparent force which acts in a direction opposite to that of the rotation.

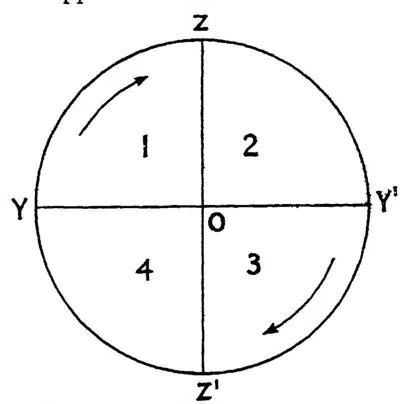


Fig. I.14. An alternative method for explaining precession. See text for explanation.

Let us take the case of a disc which is rotating in the plane of the paper about an axis perpendicular to this plane, the direction of rotation being as shown by the arrows, Fig. I. 14. Divide the surface of the disc into four sectors marked 1, 2, 3, 4 by two lines YY′ and ZZ′ intersecting at the centre O of the disc. Imagine that there is a couple which tends to turn 1 and 2 out of the plane of the paper and 3 and 4 into this plane, that is, 1 and 2 are turned towards the observer and 3 and 4 away from him, about an axis YY′.

We shall simplify the problem by imagining that the disc is without weight but that the weight of the system is made up of four bodies 1, 2, 3, and 4, of equal mass, connected rigidly to the disc and all at the same distance from the centre O. Rotation is taking place clockwise but we are not concerned with the rotation as such in the plane of the paper. Our chief interest is that 1 is receding from the axis YY′, 2 is approaching it, 3 is receding from it, and 4 is approaching it.

It has been assumed that the couple tends to move 1 and 2 towards the observer, that is, away from the plane of the paper, and that this rotation takes place round the axis YY′. Because 1 is receding from this axis, then in accordance with the law just enunciated, there will be a force opposing that causing rotation, and hence there will be a force opposing the movement of the sector 1 towards the observer. This implies that there is a force pushing the sector 1 into the plane of the paper.

Now consider 2. This is approaching YY′ and hence, in accordance with the law, there will be a force acting in the same direction as the force pulling 2 out of the plane of the paper, so that this force will tend to move 2 towards the observer.

In the case of 3 which is receding from YY′ the force in this sector will oppose the force which tends to move 3 into the plane of the paper, and hence this force will tend to move 3 towards the observer.

In sector 4 the mass is approaching YY′ and the force is therefore assisting that which tends to move 4 into the plane of the paper. Hence there will be a force moving 4 into the plane of the paper.

Summarising the results, we have the following :—

1 is pushed into the plane of the paper
2 is pulled out from the plane of the paper
3 is pulled out from the plane of the paper
4 is pushed into the plane of the paper.

Since 1 and 4 push the disc into the plane of the paper and 2 and 3 pull it out from the same plane, the disc will rotate about the axis OZ, the left-hand side moving into the paper and the right-hand side moving out from it.

This result is interesting, showing, as it does, that when the body is rotating about an axis perpendicular to the plane of the paper, the application of a couple about YY′ makes the body turn about the third axis OZ. Referring to p. 22, it was shown that one rule for precession was as follows : "If a free gyroscope is acted on by a torque in a plane through the gyro axis, then that axis will precess in another plane which is perpendicular both to the plane of the spin and to the plane of the torque." How does this rule fit in with the results obtained above ?

The torque was turning the disc round an axis YY′ and it was shown that precession would take place round the axis ZZ′ in a plane at right angles to the plane of the paper. This latter plane is perpendicular to the plane of the spin, which is in the plane of the paper, and it is also at right angles to the plane of the torque, which is perpendicular to the plane of the paper.

Now apply the rule for the direction of precession given on p. 22-23. The original torque acts from Z towards the observer and from Z′ away from him. Turn the point of application of Z through 90° in the direction of the spin of the disc, and it will be seen that it arrives at some point on the line YY′ on the right of the figure, so that the portion on the right of ZZ′ will be pulled out of the plane of the paper by the torque created. We could have dealt with the force at Z′ instead of that at Z. This force is moving into the plane of the paper and by rotating Z′ through 90° in the direction of the spin it will be somewhere on the line YY′ to the left of the figure, so that the portion to the left of ZZ′ is pushed into the paper. This is the same as we obtained in the summary previously given and confirms the results obtained by a slightly different method.

It was shown on p. 38-39 how the formula $K = I\omega\Omega$ was derived, and it will now be shown how this formula can be obtained from the method that has just been considered. The problem will be stated as follows :

A wheel with all its mass concentrated in its rim is rotating in the plane of the paper with uniform angular velocity ω. It is turned about OZ with uniform angular velocity Ω. Find an expression for the couple K which produces the motion about OZ.

It has been assumed for the sake of simplifying the problem that the mass is concentrated in the rim. If the mass is distributed as in the case of a disc, certain complications arise which render the problem more difficult, but the principle is the same and it may be assumed that what holds for the ideal case under consideration will hold for all cases.

Take a small length of the rim at a point P and let the mass of the material be μ per unit length. If the length assumed is ds, its mass is μds, and if the angle POZ is φ, the mass is $\mu R d\varphi$, R being the length of the radius OP (Fig. I.15).

From P draw PQ perpendicular to OZ and let PQ$=r$,

so that $r=R \sin \varphi$.

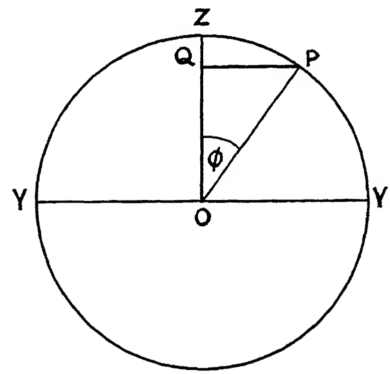


Fig. I.15. Alternative method for deriving the formula $K = I\omega\Omega$. See text for explanation.

The wheel is turning about OZ so that P is moving out of the plane of the paper towards the reader and is describing a circle with radius r. It is shown in elementary text books on dynamics that the acceleration of P perpendicular to the plane of the paper is given by the expression

$$\frac{1}{r}\frac{d}{dt}\left(r^2\frac{d\theta}{dt}\right)$$

where θ is the angle through which the plane of the wheel has rotated at the time from some fixed plane.

Now $\frac{d\theta}{dt}$ simply measures the rate of precession, which will be denoted by Ω, and since this rate is uniform $\frac{d\Omega}{dt}$ or $\frac{d^2\theta}{dt^2} = 0$. Hence the above expression for the acceleration of P becomes

$$\frac{1}{r}\frac{d}{dt}(r^2\Omega) = 2\Omega\frac{dr}{dt}$$

$$\text{Since } r = R\sin\varphi, \frac{dr}{dt} = R\cos\varphi\frac{d\varphi}{dt}$$

Just as $\frac{d\theta}{dt}$ measures the rate of precession Ω, so $\frac{d\varphi}{dt}$ measures the rate of spin, which is ω. Hence the acceleration of P is

$$2\omega\Omega R\cos\varphi$$

The mass of the small portion of the wheel at P is $\mu R d\varphi$, and hence the force producing the above acceleration, (the product of the mass by the acceleration), is

$$2\omega\Omega\mu R^2\cos\varphi d\varphi$$

The moment of this force about the axis YY′ is the product of the force by the distance of P from this axis, and as this distance is $R\cos\varphi$, the moment of the force about the axis YY′ is

$$2\omega\Omega\mu R^3 \cos^2\varphi d\varphi$$

Hence the fourth part of the rim of the wheel from the top to the right-hand side is responsible for a moment about YY′ equal to

$$\int_0^{\frac{\pi}{2}} 2\omega\Omega\mu R^3 \cos^2\varphi d\varphi = \tfrac{1}{2}\pi\omega\Omega R^3$$

Each of the other sectors can be dealt with in the same manner and as the forces all act to turn the two sectors above YY′ towards the observer and the two sectors below YY′ away from him, the total couple will be four times the above, that is $2\pi\omega\Omega\mu R^3$.

Since $2\pi R$ is the circumference of the wheel its total mass M is $2\mu\pi R$, and hence the couple is $\omega\Omega MR^2$, which is $I\omega\Omega$ because in the case under consideration where the mass of the wheel is concentrated in the rim, $I = MR^2$, I being reckoned about the axis of the wheel perpendicular to its plane. Hence $K = I\omega\Omega$.*

A brief explanation of the behaviour of the two-framed gyroscope will follow, and this will afford a general explanation for all types. (See pp. 24-25 for the experiments under consideration.)

Explanation of the experiments with the two framed gyroscope

In Experiment 1 the gyroscope is neutral and as no torque exists no precession takes place. As pointed out before, if $K = 0$, then $I\omega\Omega = 0$, and because neither I nor ω is 0 it follows that Ω is 0, so that precession does not take place. A very small torque will start precession, as the reader can verify by pressing gently on the frame.

When the locking screw is tightened precession is prevented so that $\Omega = 0$, and hence $K = I\omega\Omega = 0$. When the wheel is spinning in this way, precession not being allowed, there is no more difficulty in tipping the axle into a different plane than there is if there is no spin.

Experiment 2 has already been explained in connection with the single-framed gyroscope.

Experiment 3. In Experiment 3 the moment of the weight tends to set up precession but as the locking screw is tightened the screws at Y and Y′ offer resistance to the movement of the frame A. As a consequence a couple is set up which counterbalances the gyroscopic effects of the wheel, and the gravity couple is allowed to have its normal effect about its own axis, so that the weight drops.

Experiment 4 shows that precession requires a torque for its maintenance. When this torque is neutralised precession ceases.

Experiment 5 is easily explained by the principle of energy. When we hurry the precession we are doing work on the apparatus and the potential energy of the system increases. As a consequence, the centre of gravity rises. For the same reason, retardation of the precession implies that work is done by the gyroscope and its potential energy decreases, so that its centre of gravity descends.

---

* This subject has been dealt with by H. Crabtree in *Spinning Tops and Gyroscopic Motion.* The above method of treatment is similar to that adopted by Crabtree, but certain simplifications have been introduced.

The Brennan Monorail

Reference has already been made to the gyrostat and it was stated that some account of its application to Brennan's monorail would be given (p. 23). A detailed description of this is not suggested and it will suffice if the main principles of the monorail are outlined.

Before proceeding with this it will be profitable if the reader will make use of the two-framed gyroscope again for another experiment which has an important bearing on the monorail. Some of these gyroscopes are provided with a quadrant which can be screwed on to the semi-circular vertical frame B, thus preventing the frame containing the wheel from turning over from a horizontal position (see frontispiece). This quadrant prevents the frame from turning over in one direction only, but it is possible to secure the two together by a piece of fine string so that the frame containing the wheel always remains in a horizontal position so long as the base of the gyroscope remains on a horizontal plane. We have now a wheel in a vertical plane whose frame A can rotate round a vertical axis in a horizintal plane, and the arrangement makes a very good gyrostat for demonstration purposes. If we could imagine the front wheel of a bicycle capable of turning completely round a vertical axis—the fork of the handlebars—while the direction of the horizontal bar remains fixed, we have a rough illustration of a gyrostat.

If the wheel of the gyrostat is spun it remains in the same plane unless it is disturbed, but the slightest touch will make it move round its vertical axis. A torque has been denied the apparatus and hence there can be no precession. If K is 0 so also is $I\omega\Omega$, but as I and ω are not zero, the solution of the equation shows us that Ω is zero, or precession will not take place.

Now imagine that such an apparatus is placed on a miniature car which has only two wheels and that the car is travelling in a straight line. There is nothing to prevent a two-wheeled car from doing this for a short distance, provided a sufficient velocity is attained, just as in the case of a bicycle, but a difficulty might arise if the wind caused the car to tilt to one side. We have already shown how a cyclist is able to right himself when his bicycle tilts over to either side, but the monorail would not be quite so easy to control. To see what would happen to the gyrostat, the spin of which will be assumed to be in the same direction as that of the car wheels, try tipping the gyrostat over when it is spinning, that is, imagine that the car is travelling from east to west, and that we attempt to tip the gyrostat slightly from north to south. Remember that the plane of the wheel is parallel to the direction of the car which is travelling from east to west. Precession will immediately start, the gyrostat moving in an anti-clockwise direction as regarded from above. This can be easily seen by applying the rule for precession or it may be verified by spinning the toy gyrostat and experimenting with tipping up the north end of the base.

Previous experiments have shown that hurrying on the precession causes the gyroscope to rise, and our gyrostat may now be regarded as acting like a gyroscope when the tipping over occurs. Hence, if the base of the instrument is secured to the miniature car and we hurry on the precession developed, there will be a tendency for the tilted wheel to attain the perpendicular position and to pull the car with it. The method for hurrying on the precession may be effected by an automatic arrangement or it may be effected by someone in control merely exerting muscular power at the right moment.

Fig. I.16 shows a rough outline of the system, the rotor or gyrostat rotating on an axle perpendicular to the plane of the paper, which implies that the plane of the wheel is parallel to the length of the car. The axle is mounted in a frame AB pivoted at A and B, and the frame can turn about a vertical axis coinciding with AB and perpendicular to the axis of the flywheel. A handle permits an operator to turn the gyrostat if an automatic control is not provided.

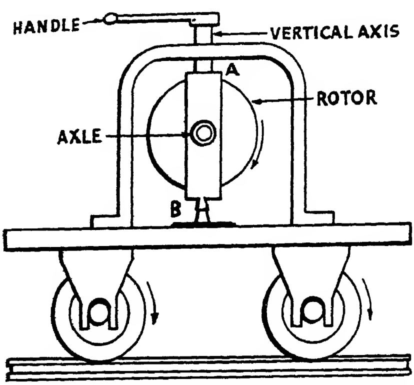


Fig. I.16. Principle of the Brennan Monorail Car.

When the car turns a corner or moves in a curve further complications arise which present serious difficulties, but these need not be dealt with in this brief outline. Brennan's first monorail car, which provided accommodation for forty people, was first displayed in 1909 and afterwards in 1913 at the Anglo-Japanese Exhibition. Unfortunately it did not achieve great practical success. The performance of the car was erratic and sometimes the automatic arrangements for straightening it into the vertical did not operate very well. Brennan was forced to abandon his project owing to lack of funds.

Considerable improvements were effected by P. P. Schilovsky, a celebrated Russian inventor, and one of the greatest authorities on the subject. The description of his inventions and appliances to secure stability for the system is quite beyond our scope, but readers who are interested in the subject should consult his work : *The Gyroscope : Its Practical Construction and Application*, published by E. & F. N. Spon Ltd. Although his improvements accomplished a considerable amount of stability and safety, it is doubtful whether the monorail will ever be utilised to any great extent, in spite of the fact that much time and material would be economised in the construction of the rail, and much less fuel would be required for propulsion.

One serious objection to the system may have occurred to the reader—the large weight of the flywheel in comparison with that of the car if it is to act effectively in restoring the car to the vertical. This is not such a serious objection as it seems, and to show how effective the flywheel is, a hypothetical case will be taken, though the figures can be accepted as approximately correct for some cases.

Weight of car, 1,400 lb.

Height of its centre of gravity above the rail, 3 ft.

Maximum angle of inclination of car from equilibrium position, 10°.

Angular velocity of spin of flywheel, 40 revolutions per sec., or $\omega = 80\pi = 251$ rad./sec.

Angular velocity of precession, one revolution in 25 seconds, or $\Omega = 0{\cdot}25$ rad./sec. approximately ($2\pi/25 = 0{\cdot}25$ approximately).

Moment of inertia of flywheel I, to be obtained in the solution.

The torque tending to overturn the car is $1400 \times 3g \sin 10° = 23{,}332$ ft.pdls., taking g as 32 ft./sec. per sec.

Using the formula previously established,

$K = I\omega\Omega$, we find that

$23{,}332 = I \times 251 \times 0{\cdot}25 = 62{\cdot}75\, I$, from which

$I = 372$ lb.ft.^{2}

The radius of the flywheel varies but 2·75 ft. can be taken as reasonable, and since $I = \frac{1}{2}Mr^2$, M being the mass of the wheel,

$372 = \frac{1}{2}M \times 2{\cdot}75^2 = 3.78\, M$

Hence $M = 98{\cdot}4$ lb.

The ratio of the mass of the flywheel to that of the car is just under 1/14 or about 7%, so that the gyrostat is not so cumbersome as it appears on first consideration.

These results have been obtained on the assumption that the car is travelling along a straight, horizontal track, and that only lateral stability has to be considered. In addition, it is assumed that the gyrostat has been neutrally suspended. Considerable modifications and complications are introduced under the actual conditions encountered, but the above figures can be taken as a rough guide to the relative masses of the gyrostat and the car.

Table of moments of inertia for some ordinary solids

In all cases the axes are taken through the centre of gravity of the body, unless otherwise stated. Axes not passing through the centre of gravity are denoted by an asterisk.

1. Thin straight rod about an axis perpendicular to its length :
   *(a) Through one end, $Ml^2/3$.
   (b) Through the centre of gravity, $Ml^2/12$. l is the length in each case.
2. Thin rectangular lamina, sides $2a$, $2b$:
   (a) About an axis perpendicular to the plane of the lamina, $M(a^2 + b^2)/3$.
   (b) Parallel to side $2a$, $Mb^2/3$.
3. Rectangular parallelopiped sides $2a$, $2b$, $2c$:
   Perpendicular to $2b$, $2c$, $M(b^2 + c^2)/3$. If perpendicular to the other sides the results can be written down immediately from symmetry.
4. Circular wire, radius r :
   (a) Perpendicular to plane, Mr^2.
   (b) Perpendicular to diameter, $Mr^2/2$.
5. Circular disc, radius r :
   (a) Perpendicular to plane, $Mr^2/2$.
   (b) Perpendicular to diameter, $Mr^2/4$.
6. Circular cylinder, radius r, about central axis :
   (a) Solid, $Mr^2/2$.
   (b) Hollow, radii a and b, $M(a^2 + b^2)/2$.
7. Spherical shell, radius r :
   Diameter, $2Mr^2/3$.
8. Sphere, diameter ; radius r ·
   $2Mr^2/5$.

Moments of inertia can be determined experimentally by different methods, such as (a) oscillation on the tri-filar suspension table ; (b) rolling down inclined rails ; (c) if a gyro, by precession produced by a known torque. These methods can be used for bodies of any shape and mass distribution where the formulae given above would not be applicable.

General Survey.

As a linkage between the theory described in the preceding pages and the practical applications of the gyroscope which follow it may be helpful to give a very general survey. From the descriptions of the practical applications in the following pages it will be seen that gyroscopes vary very much in size, in speed of rotation and in methods of mounting and driving, depending on their functions.

These functions may be described as indicating or controlling or a combination of both. The first provides a means or datum by which a human operator may visualise and regulate the course of his vehicle in the air or on the sea. Examples are the artificial horizon in aircraft and the gyroscopic compass in ships. The second provides what may be regarded as the brains of an apparatus which does the controlling (and may itself be gyroscopic) ; examples are the auto-pilot of aircraft (universally known in the R.A.F. as "George") and a corresponding apparatus known as the gyro-pilot of ships, the ship stabiliser and the directional control of the torpedo.

The actual functioning of the gyroscope in these appliances is described in the appropriate following chapters, from which it will be seen that it is hardly fanciful to describe the gyroscope itself as the brain controlling a complicated mechanical organism.

The mass and size of the rotors of these gyros varies from about a pound in weight and 2 inches in diameter up to over 100 tons in weight and as much as 15 feet in diameter, and the speed of rotation from 800 r.p.m. for the large ship's stabilisers up to as much as 27,000 r.p.m. for the small aircraft and torpedo instruments.

For such widely-varying instruments methods of driving and mounting must obviously also vary. Electricity is the most commonly employed driving force in which the rotor is in effect the armature of an electric motor, but an air jet in which the rotor offers cups on its periphery to a stream of high-speed air is used in aircraft and in the torpedo. In this air-driven system the rotor may be compared to the corresponding part of a jet reaction steam turbine, though steam is not applied to gyroscopic driving. Incidentally it may be noted that the rotor of a high-speed turbine may itself exercise a gyroscopic effect.

These variations in size and speed of rotation involve very tricky problems of bearing design and construction, problems that in many applications are a long way from final solution. Elimination of friction is perhaps a more important item in the gyro than in any other instrument, and though ball bearings are used more extensively than any other kind, the design of the ball bearing to meet gyroscope requirements is no easy matter. Whether some of the smaller instruments will ever adopt jewel bearings or some of the particularly hard minerals such as agate, is a possibility to be borne in mind. At the other end of the scale some of the new plastics materials have been tried with promising results.

It is to be regretted that detailed reference to some interesting applications of the gyroscope, e.g., in naval gunfire control and in the stabilisation of gun platforms is not possible.

APPENDICES

1. SPEED AND COURSE ERROR

The explanation of this error and the formula for making the necessary corrections are given in Section II. The method for deriving the formula is given below, first for all cases, including those in which the speed of the ship cannot be neglected in comparison with the speed of rotation of the earth, and then for the special circumstances where the speed is small in comparison with the earth's speed.

The earth's equatorial radius is 3963·35 English miles, from which the equatorial circumference is easily found to be 24,902·46 English miles. An English mile is 0·868421 nautical miles, and hence the equatorial circumference of the earth is 21,625·82 nautical miles. The speed of the earth in equatorial regions, due to its daily rotation, is, therefore, 21,625·82/24 = 901·08 nautical miles her hour or 901·08 knots. Strictly speaking, we should deal with the sidereal hour, not the mean solar hour, because the earth makes a complete rotation in a sidereal day and this should be used in dealing with gyroscopic problems. Since the sidereal day is 0·99727 mean solar day, approximately, the actual speed of the earth is 901·08/0·99727 = 903·55 knots at the equator. At a latitude λ it is 903·55 cos λ.

For all practical purposes in navigation it is sufficiently accurate to take 900 instead of 903·55, and this figure is generally used.

In Fig. I. 17 let OE represent in magnitude and direction the linear velocity of the earth at any latitude, with reference to a star, and let OS represent on the same scale the speed of the ship in magnitude and direction, with reference to the earth. Let the line OS make an angle φ with the meridian OM. Complete the parallelogram OERS and draw the diagonal OR. This diagonal will represent in magnitude and direction the resultant speed of the earth and the ship. The line OM′ drawn perpendicular to OR is the virtual meridian.

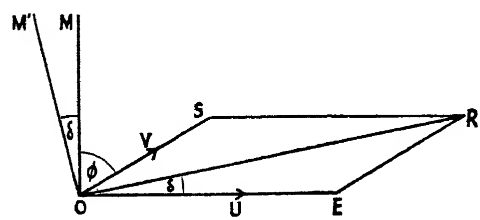


Fig. I. 17. Derivation of formulæ for speed and course error.

Let U and V denote the velocities of the earth and ship respectively, and let δ be the angle EOR. Because each of the angles EOM and ROM′ is a right angle, by taking away the common angle ROM the angle EOR is equal to M′ OM. The angle SOR is, therefore, $90°-(\varphi+\delta)$.

In the triangle ROE, we have the simple relation

$$OE/ER = \sin ORE/\sin ROE = \sin [90 - (\varphi + \delta)]/\sin \delta$$

Substituting U for OE and V for ER (because ER = OS = V), it follows that

$$U/V = \cos (\varphi + \delta)/\sin \delta = \cos \varphi \cot \delta - \sin \varphi$$

Hence,

$$\cot \delta = U \sec \varphi/V + \tan \varphi \qquad (1)$$

Substituting $903{\cdot}55 \cos \lambda$ for U in (1), the value of δ is obtained rigorously, but such extreme accuracy is seldom or never necessary, and simpler though less accurate formulae, but good enough for all practical purposes, will be derived.

(1) can be expressed in the form

$$\tan \delta = V \cos \varphi/(U + V \sin \varphi) \tag{2}$$

If U is taken as $900 \cos \lambda$, the last equation becomes

$$\tan \delta = V \cos \varphi/(900 \cos \lambda + V \sin \varphi) \tag{3}$$

In dealing with nautical applications of the gyroscope the angle δ is small, generally less than 5°, and hence with sufficient accuracy the tangent of δ can be taken equal to its circular measure. Since the circular measure of an angle is obtained by dividing the angle in degrees by 57·3, we can write $\delta/57{\cdot}3$ for $\tan \delta$ in (3) and then obtain

$$\delta = 57{\cdot}3^\circ V \cos \varphi/(900 \cos \lambda + V \sin \varphi) \tag{4}$$

Error in ignoring the east or west component of the ship's speed

In Section II only the northern or southern component of the ship's speed is taken into consideration. This is compounded with the earth's speed of rotation and the resultant OR is obtained, the virtual meridian OM′ being at right angles to OR. The question now arises: "Is it permissible to ignore the east or west component of the ship's speed?"

It appears from (4) that the error consists in neglecting the term $V \sin \varphi$ in the denominator, and hence the error introduced by using the approximate formula

$$\delta = 57{\cdot}3^\circ V \cos \varphi/900 \cos \lambda \tag{5}$$

is $V \sin \varphi$ in $900 \cos \lambda$ or 1 in $900 \cos \lambda/V \sin \varphi$. To obtain accurate results by using (5) it will be necessary to decrease the figures obtained by this formula by $\Delta\delta$, where

$$\Delta\delta = V \sin \varphi . \delta/900 \cos \lambda \tag{6}$$

It is possible to express (5) in another form, which is more convenient for computation, as follows:

$$\delta = 0{\cdot}0637^\circ V \cos \varphi \sec \lambda \tag{7}$$

The following example will illustrate the application of this principle.

Suppose a ship is sailing at 30 knots on a course of 45° in latitude 60°. Find the speed and course error (1) accurately, (2) with sufficient accuracy for all practical purposes.

(1) From (4) $\delta = 57{\cdot}3^\circ \times 30 \times 0{\cdot}7071/(900 \times 0{\cdot}5 + 30 \times 0{\cdot}7071)$
$= 2{\cdot}58^\circ$

(2) From (5) $\delta = 57{\cdot}3^\circ \times 30 \times 0{\cdot}7071/900 \times 0{\cdot}5 = 2{\cdot}70^\circ$

(3) From (7) $\delta = 0{\cdot}0637^\circ \times 30 \times 0{\cdot}701 \times 2 = 2{\cdot}70^\circ$

If the figures obtained in (2) or (3) are decreased by $3 \times 0{\cdot}7071 \times 2{\cdot}70^\circ/900 \times 0{\cdot}5$, by using (6), the result is $2^\circ{\cdot}70 - 0{\cdot}12^\circ = 2{\cdot}58^\circ$, or 2°35′, the value found from the less accurate formula being 2° 42′. The difference of 7′ is of no importance in navigation and in practically all cases (5) or (7) can be used for nautical work.

It appears from (5) that the speed and course error increases with the latitude of the place and also with the speed of the ship. In a few exceptional cases the neglect of the east or west component could be appreciable. Thus, if we take a rather extreme case where the latitude is 70°, and assume the speed 25 knots and the course 60°, the error will be 1 in $900 \times 0{\cdot}2588 \times 25 \times 0{\cdot}866$, or 1 in 11 approximately. In this case (5) gives $\delta = 3° \, 4'$, and a more accurate result is obtained by decreasing this by 17′. In such exceptional cases it would be advisable to use (4) or, if (5) or (7) is used, to apply the correction by means of (6).

The gyro compass cannot be usefully employed on aircraft owing to their high speed.

Speed and course error is not the only one that must be considered. As will be shown in Appendix 3, there is also a "Damping Error," or, as it is sometimes called, the "Latitude Error."

2. PERIOD OF UNDAMPED OSCILLATION OF THE GYRO-COMPASS AXLE IN AZIMUTH

Before deriving an equation for this period something will be said about simple harmonic motion.

If a body is constrained to move so that its acceleration along its path is always proportional to its distance, measured along the path, from some fixed point in the path, the body has simple harmonic motion. To find the period of the body we proceed as follows:

Let O be the fixed point and P the position of the body at any time t, and let the distance OP be denoted by x. Then the velocity of P along its path from O is dx/dt. The acceleration of P along its path towards O is $-d^2x/dt^2$, and as this is proportional, by hypothesis, to OP, we obtain the equation

$$d^2x/dt^2 = -kx \qquad (8)$$

where k is a constant.

Multiplying (8) by $2dx$ and integrating, we get

$$(dx/dt)^2 + kx^2 = \text{a constant.}$$

This constant can be determined from the initial conditions. Let $x = a$ when the body is just starting its motion, that is, when $dx/dt = 0$, then

$$0 + ka^2 = \text{constant.}$$

Hence the constant is $-ka^2$, so we have the equation

$$(dx/dt)^2 = k(a^2 - x^2)$$

From this we derive

$$dx/\sqrt{(a^2 - x^2)} = \sqrt{k}\, dt$$

Integrating we get

$$\sin^{-1}\frac{x}{a} = t\sqrt{k} + b$$

where b denotes a constant.

Hence

$$x = a\sin(t\sqrt{k} + b) \qquad (9)$$

If we expand the right-hand side of (9) we have

$$a \sin t\sqrt{k} \cos b + a \cos t\sqrt{k} \sin b,$$

and this can obviously be written in the form

$$C \cos t\sqrt{k} + C' \sin t\sqrt{k},$$

because $a \cos b$ and $a \sin b$ are constants.

Hence the complete solution of (8) is

$$x = C \cos t\sqrt{k} + C' \sin t\sqrt{k} \qquad (10)$$

The constants C and C' can be determined from the conditions of the motion. For instance, if the body starts from rest at O, then $x = 0$ when $t = 0$, and we have

$$0 = C \cos 0 + C' \sin 0 = C + 0, \text{ so that } C = 0.$$

In this case equation (10) becomes

$$x = C' \sin t\sqrt{k}.$$

Differentiating (10) with regard to t,

$$dx/dt = -C\sqrt{k} \sin t\sqrt{k} + C' \sqrt{k} \cos t\sqrt{k}$$

from which the value of $v = dx/dt$ can be found.

If we increase t by 2π the above value of v will repeat itself and the same applies to x. Hence (10) can be written in the more general form

$$x = C \cos \sqrt{k}\left(t + \frac{2\pi}{\sqrt{k}}\right) + C' \sin \sqrt{k}\left(t + \frac{2\pi}{\sqrt{k}}\right) \qquad (11)$$

From (11) it is obvious that the period is $2\pi/\sqrt{k}$.

A simple application of the above results is found in the case of the pendulum, the motion of which is a simple harmonic when the angle of swing is small.

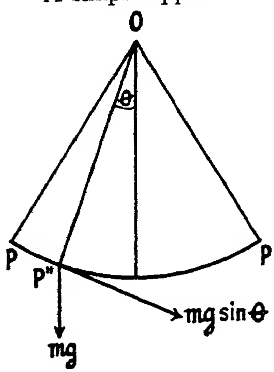


Fig. I.18. Simple harmonic motion of a pendulum.

In Fig. I, 18 a weight of mass m is attached to a thread OP and allowed to swing in the small arc PP′. At any point P″ of its swing the component of mg along the tangent at P″ is $mg \sin \theta$, where θ is the angle which OP″ makes with the vertical. The pull of the thread has no effect along the tangent to the arc at P″ and hence the acceleration of the mass m towards the lowest point O is proportional to $\sin \theta$ and is $g{\cdot}\text{chord}/l$, where l being the length of the thread OP. Instead of k in (8) we now write g/l, and hence the period of a swing, to and fro, is

$$t = 2\pi\sqrt{(l/g)} \qquad (12)$$

The same method is applicable to determine the time of the swing of a magnet which is suspended and influenced by the earth's magnetic field, and to other similar problems. In the case of the gyro-compass, for the length of the pendulum we substitute the angular momentum, and for the value of gravity at the place we substitute the restoring couple applied by the pendulous casing which is inclined and hence is responsible for a precession towards the meridian as already explained (see p. 18-29). This assumes that the motion of the gyro-compass is harmonic, and before dealing with this problem something will be said about the position of the axle of the gyro-compass.

The directive force of the gyro-compass is proportional to the *horizontal* component of the angular momentum of the gyro, and if the axle were vertical this directive force would vanish. It is proportional to the cosine of the angle that the axle makes with the horizon, and hence the nearer the axle approaches the horizontal position the greater is the directive force or *righting moment* as it is sometimes called. Another reason for maintaining the axle as closely as possible to the horizontal position is because large errors in the card reading would occur if a considerable deviation from the horizontal position took place. If the axle were inclined at an angle β to the horizon, then for each n degrees of departure of the vertical ring of the compass from the upright position towards the east or west, there would be an error in the card reading of $n \tan \beta$. If β were a large angle, small errors would be greatly magnified in such circumstances. As will be seen in the remainder of this Appendix, the axle of the gyro-compass does not deviate far from the horizontal position. These points are briefly referred to in Section II.

From Fig. I. 19 it is seen that if λ is the latitude of a place P the angular velocity ω of the earth can be resolved into two components, $\omega \cos \lambda$ about the horizontal meridian PK, PK being the tangent at the point P, meeting the axis CN in K, and $\omega \sin \lambda$ about the line OP, which is the vertical at P. If the axle of the gyroscope is inclined at an angle α to the meridian the horizontal plane is tilting at a rate $\omega \cos \lambda \sin \alpha$ which is greatest in equatorial regions and vanishes at either pole. The other component, $\omega \sin \lambda$, is the rate at which the meridian is turning westward underneath the axle which is supposed to maintain its direction in space, and this is a maximum at either pole and vanishes at the equator.

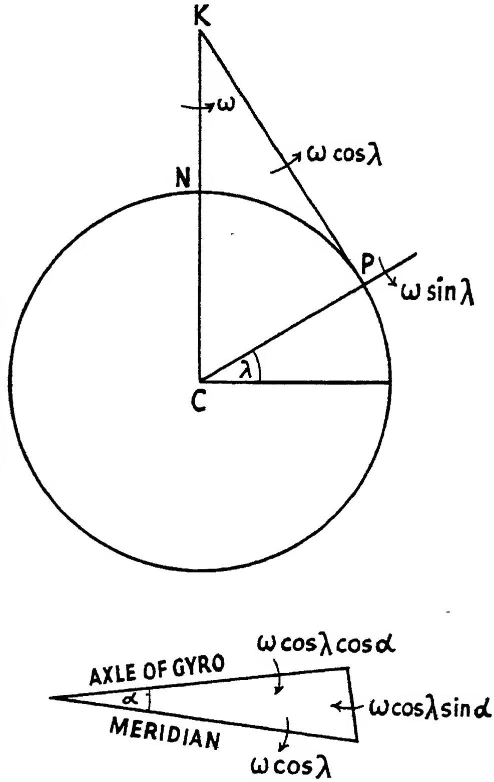


Fig. I.19. Resolution of the earth's angular velocity into horizontal and vertical components.

If α is the easterly deviation of the gyro axle and β is the inclination of the axle to the horizon, then the velocity of precession in *space*, not relative to the earth, is

$$d\alpha/dt - \omega \sin \lambda \text{ in azimuth} \qquad (13)$$

$$d\beta/dt - \omega \cos \lambda \sin \alpha \text{ in altitude} \qquad (14)$$

It will be noticed that the values of the precession in azimuth and altitude, obtained above, with reference to the earth, have been included in (13) and (14). In the pendulous gyro-compass the wheel spins in the same direction as the earth rotates, that is, clockwise as seen from the south, which is reckoned negative.

If H is the angular momentum of the gyro and B is the pendulous moment of the weight, or the product of the weight by its distance from the trunnion axis, the restoring couple is $B \sin \beta$ or $B\beta$ for small angles, as is practically always the case, β being expressed in radians.

The angular momentum rotated in azimuth is

$H \cos \beta$ or H, because $\cos \beta$ is practically 1.

The rotating couple is $B \sin \beta$ or $B\beta$ and hence we derive the equation

$$-H\,(d\alpha/dt - \omega \sin \lambda) = B\beta \qquad (15)$$

We may also consider precession to take place about a horizontal line, though in this case there is no rotating couple, and hence we have

$$H\,(d\beta/dt - \omega \cos \lambda \sin \alpha) = 0 \qquad (16)$$

If α is assumed to be small, (16) can be written in the form

$$H\,(d\beta/dt - \omega \cos \lambda . \alpha) = 0 \qquad (17)$$

Differentiating (15)

$$d^2\alpha/dt^2 = -\frac{B}{H}\,d\beta/dt = -\frac{B}{H}\,\omega \cos \lambda \,.\, \alpha, \text{ by (17)} \qquad (18)$$

From (18) we have

$$d^2\alpha/dt^2 + \frac{B}{H}\omega \cos \lambda \,.\, \alpha = 0 \qquad (19)$$

It will be seen that (19) is of the same form as (8) and that we are therefore dealing with simple harmonic motion. The period T of oscillation in azimuth is, therefore,

$$T = 2\pi\sqrt{(H/B\,\omega \cos \lambda)}\ * \qquad (20)$$

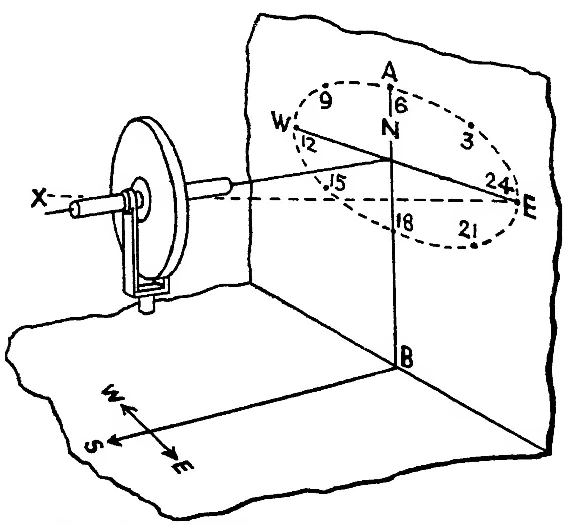


Fig. I, 20. Ellipse traced out on a vertical plane by the axle of an undamped gyro-compass.

The restoring moment is $B\beta$ which was previously denoted by K (see p. 39) or by $I\omega\Omega$, and hence Ω, the rate of azimuthal precession, is $B\beta/I\omega$ or $B\beta/H$. Hence $\Omega = d\alpha/dt = -B\beta/H$, the negative sign being used because $d\alpha/dt$ decreases as the axis of the gyro approaches the meridian.

*No account has been taken of the moments of inertia of the non-spinning parts of the sensitive element because they are relatively so very small that no errors of practical importance result from ignoring them.

From (17) $d^2\beta/dt^2 = \omega \cos\lambda\, d\alpha/dt = -\frac{B}{H}\omega\cos\lambda\,.\,\beta$

and hence $d^2\beta/dt^2 + \frac{B}{H}\omega\cos\lambda\,.\,\beta = 0$ (19a)

Since (19a) is of the same form as (19) the axle performs simple harmonic motion in its tilting movement.

By combining two simple harmonic motions which are at right angles to each other, and differing in phase by 90°, we have an elliptic harmonic motion, and hence the end of the axle will describe an ellipse, as shown in Fig. I. 20 and explained in the caption. The combined movements of the end of the axle are projected on a vertical plane, and with the usual type of gyro-compass, the major axis of the ellipse is about twenty-five times the minor axis.

3. BALLISTIC DEFLECTION

If a ship changes speed the effects of acceleration or retardation act at the point of suspension of the moving system, but the forces of inertia act at the centre of gravity of the moving system. If the acceleration or retardation of the ship is not exactly in an E-W direction the inertia of the moving system produces a precession because there will be a slight tilting couple on the gyro axis.

Let f be the acceleration of the ship and $d\alpha$ the rate of change in azimuth in the gyro in consequence. Applying the law of precession,

$$d\alpha/dt = Bf/Hg \qquad (21)$$

If μ is the change in α in a time T, then

$$\mu = \frac{B}{Hg}\int_0^T f dt \qquad (22)$$

The integral in (22) measures the velocity generated by the impulse, which will be denoted by ΔV. Hence from (22)

$$\mu = \frac{B}{Hg}\Delta V \qquad (23)$$

It has been shown in (7) that the speed and course error can be expressed in the form $\delta = 0{\cdot}0637^\circ \cos\varphi \sec\lambda$. If we imagine that the course is north and use radians instead of degrees, (7) can be written in the form

$$\delta = 0{\cdot}00111 V \sec\lambda \qquad (24)$$

Differentiating (24), regarding δ and V as variables,

$$\Delta\delta = 0{\cdot}00111 \sec\lambda\,.\,\Delta V \qquad (25)$$

If we arrange that the total change of deflection μ of the ship and gyro shall be equal to the change in the speed error, by equating (23) and (25) and eliminating ΔV, we obtain

$$B/Hg = 0{\cdot}00111 \sec\lambda \qquad (26)$$

As (7) is based on a speed expressed in knots (nautical miles per hour) it will be necessary to express g in the same units, and this is easily found to be 19.134. Hence (26) becomes

$$B/H = 0{\cdot}0211 \sec\lambda \qquad (27)$$

By choosing the ratio B/H of the compass to satisfy (27) there will be a horizontal precession in azimuth equal and opposite to the change in the virtual meridian. In such circumstances the gyro will be carried "dead beat" to the new resting position required by the speed error. Most gyro-compasses are adjusted so that (27) is satisfied for a latitude 45°, the adjustment being made by altering B.

It may be noticed that if (5) is used instead of (7) and δ is expressed in radians, then if the ship is moving on a northerly course,

$$\delta = V \sec \lambda / 900$$

Since $R\omega = 900$, approximately, R being the earth's radius, instead of (25) we can use $\Delta\delta = \sec \lambda \, \Delta V / R\omega$

and (26) becomes $B/H = g \sec \lambda / R\omega$, or

$$H/B\omega \cos \lambda = R/g \qquad (26a)$$

Substituting the value of $H/B\omega \cos \lambda$ found by (26a) in (20), the periodic time of a gyro compass with the ratio B/H satisfying the conditions in (27) is

$$T = 2\pi\sqrt{(R/g)} \qquad (28)$$

Gyro compasses are now constructed so that they have a period derived from (28), which is about 84 minutes. This is easily obtained by substituting 20.9×10^6 for R and 32·2 for g.

It has been stated by some that at any latitude in which the ballistic deflections are dead beat, the period of the undamped precessional oscillations is equal to the period of oscillation of a simple pendulum, the length of which is equal to the earth's radius. Others state that this is incorrect and that the length of the pendulum is infinite. As will be shown in the following investigation, the latter is correct.

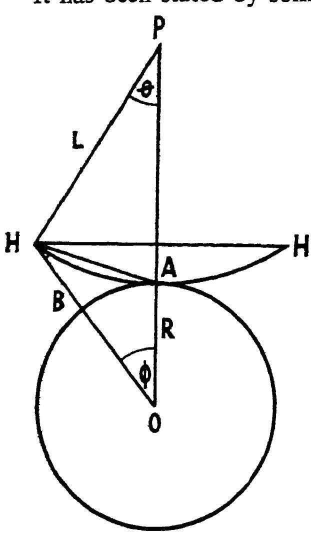


Fig. I.21. Derivation of a formula for the period of swing of a pendulum when its length is very great.

In Fig. I.21 the pendulum is oscillating in a small arc HH′, the plane of oscillating intersecting the sphere in the plane HOH′. O is the centre of the earth, so that OH, OH′ are greater than R, the radius of the earth. The length L of the pendulum is supposed to be comparable with the earth's radius, and as the semi-angle θ through which the pendulum swings is small, its sine can be taken equal to its circular measure. The same applies to the angle HOP, which will be denoted by φ, and hence

$$\mathrm{HO}/\mathrm{HP} = \sin\theta/\sin\varphi = \theta/\varphi \qquad (28)$$

HO is equal to R plus the small portion HB, and since HA is practically a tangent to the sphere at the point A, then from the elementary properties of the circle,

$(2R + \mathrm{HB})\,\mathrm{HB} = \mathrm{HA}^2$, or with sufficient accuracy, since HB is very small in comparison with the earth's radius

$$\mathrm{HB} = \mathrm{HA}^2/2R$$

The force of gravity at H is not g but is gR^2/OH^2, or $gR^2/(R + \mathrm{HB})^2$, because the force of gravity varies inversely as the square of the distance from the earth's centre. Hence the force of gravity at H is $g/\left(1 + \frac{HB}{R}\right)^2$ or $g\left(1 - 2\frac{HB}{R}\right)$, neglecting the squares and higher powers of HB/R.

Substituting $HA^2/2R$ for HB, we obtain for the force of gravity at H, $g(1 - HA^2/R^2)$. Hence, if x is the distance of the pendulum weight from the lowest point A of swing, then g, the force of gravity at H, is found from

$$g' = g(1 - x^2/R^2) \tag{29}$$

When x is small in comparison with R so that second order terms can be ignored, it is seen from (29) that the force of gravity at H can be taken as the force of gravity at the earth's surface. If θ were not a small angle this would not be true, but as both θ and φ are small we can assume the value of g constant throughout the arc in which the pendulum is swinging.

The force of gravity acts along the line HO, and resolving it along the line PH its value is $g \cos(\theta + \varphi)$, which is counteracted by the tension of the string PH. Resolved at right angles to PH, the force is $g \sin(\theta + \varphi)$, and this is nearly in the direction HA. The equation of motion of the pendulum is, therefore,

$$d^2x/dt^2 = -g \sin(\theta + \varphi) = -g(\theta + \varphi) \tag{30}$$

Since $\sin\theta = \theta = x/L$, and $\varphi = L\theta/R$, by (28), it follows from (30) that

$$d^2x/dt^2 = -g\left(\frac{1}{L} + \frac{1}{R}\right)x \tag{31}$$

By (12) the time of an oscillation is

$$T = 2\pi\sqrt{\left(\frac{1}{g(\frac{1}{L} + \frac{1}{R})}\right)}$$

This becomes $2\pi\sqrt{(R/g)}$ only when $1/L$ is zero, or when L is infinite.

It is interesting to notice that this period of oscillation corresponds to the period of revolution of a small body round the earth, just skimming its surface, provided its orbit is circular. This is obvious from the following elementary considerations.

Let v be the velocity of the body when its distance from the centre of the earth is R, the earth's radius. The centrifugal force is proportional to v^2/R and the centripetal force to g. Hence

$v^2/R = g$, or $v = \sqrt{(gR)}$. The period is $2\pi R/v = 2\pi\sqrt{(R/g)}$.

4. DAMPING OF THE OSCILLATIONS OF THE GYRO-COMPASS

Up to the present the Appendix has dealt with undamped oscillations, frictional effects being completely ignored. The reasons for damping the oscillations will be explained in Section II, and the present investigation will be confined to the method for deriving certain equations when we are dealing with damped oscillations.

If the component of the couple about the vertical axis, referred to in Section II, is proportional to β (where β has the same meaning as in (15)), and this is always the case because β is a small angle and $\sin\beta = \beta$, we can represent the couple by $rB\beta$. Hence (17) becomes

$$H(d\beta/dt - \omega\cos\lambda\,.\,\alpha) + rB\beta = 0 \tag{32}$$

Since the couple acts about a vertical axis, equation (15) is not affected by it. Hence

$$-H(d\alpha/dt - \omega\sin\lambda) = B\beta \tag{33}$$

Differentiating (33)

$$-Hd^2\alpha/dt^2 = Bd\beta/dt = \frac{B}{H}\quad(H\omega\cos\lambda\,.\,\alpha - rB^2\beta) \tag{34}$$

Substituting the value of β found from (32) in (34), we have

$$\frac{d^2\alpha}{dt^2} + \frac{B}{H}\,\omega\cos\lambda\,.\,\alpha + \frac{rB}{H}\left(\frac{d\alpha}{dt} - \omega\sin\lambda\right) = 0 \tag{35}$$

The first two terms in (35) are the same as the first two terms in (19) and the last two terms inside the bracket are the same as the terms within the bracket in (15).

Multiplying (35) by H^2/B, we get

$$\frac{H^2}{B}\frac{d^2\alpha}{dt^2} + H\,\omega\cos\lambda\,.\,\alpha + Hr\left(\frac{d\alpha}{dt} - \omega\sin\lambda\right) = 0 \tag{36}$$

Since H is the angular momentum and B is a moment, it follows that the dimensions of H^2/B are those of moment of inertia, and $H\omega\cos\lambda\,.\,\alpha$ is a couple representing the gyroscopic resistance offered to turning the axle away from the meridian ; the name *righting moment* is given to this couple. The turning moment of the couple on the gyro-compass, represented by the last two terms, is composed of two parts. The first, $d\alpha/dt$, is proportional to the rate of deflection relative to the meridian, and the second, $\omega\sin\lambda$, is proportional to the angular velocity of the meridian with reference to a "fixed star."* The turning moment $Hr\,\omega\sin\lambda$, in responsible for the resting position of the gyro-compass being displaced to a position inclined at an angle α to the meridian. There must be some position of lagging behind the meridian for which the damping is just sufficient to maintain the axle at such a tilt that the gravity couple can cause the necessary precession, $\omega\sin\lambda$, about the vertical. The condition for this is

$$H\,\omega\cos\lambda\,.\,\alpha_0 = rH\omega\sin\lambda\text{, or}$$

$$\sin\lambda = \alpha_0\cos\lambda/r \tag{37}$$

Hence

$$\alpha_0 = r\tan\lambda \tag{37a}$$

If β_0 is the value of β when $d\alpha/dt = 0$, it follows from (33) that

$$\beta_0 = \frac{H}{B}\,\omega\sin\lambda \tag{38}$$

The deviation given by (37a) varies with the latitude of the place and hence it has sometimes been called the *Latitude Error*, but is also known as the *Damping Error*.

Since $d\alpha/dt = 0$ when the gyro-compass is at the extremity of a swing east or west through the meridian, (38) gives the value of the inclination of the axle to the horizon in these circumstances. From (37a) and (38) it is obvious that at the equator the resting position of the axle is in the horizontal plane, and in addition, the axle is pointing true north, since $\tan\lambda$ and $\sin\lambda = 0$ at the equator. In other latitudes

*Sometimes the expression "with reference to space" is used, but actually this has no meaning, as those conversant with the elements of relativity know. When it is used, as it often is in the text, readers will understand that it implies "with reference to a fixed star." Although no stars are fixed, every star having a motion, they are so far away from us that they can be regarded as fixed in dealing with gyroscopic problems.

a correction can be made by adding a small weight to one side of the casing containing the gyro wheel. This turning couple will maintain the gyro-compass pointing true north and with its axle horizontal, so it is possible to make α_0 zero for any particular latitude by altering the position or the amount of the weight. If the ship is on an easterly course her speed must be added on to that of the earth and if on a westerly course it must be deducted from the earth's speed, and hence in such circumstances the damping error will be under and over-corrected, respectively. The errors which are introduced are, however, very small and can be ignored in ships, unless the latitude is very high, which will occur in few cases.

Differential equation of a dampled harmonic oscillation.

Substituting the value of $\sin\lambda$ given by (37) in (35), we obtain

$$\frac{d^2\alpha}{dt^2} + \frac{Br}{H}\frac{d\alpha}{dt} + \frac{B}{H}\omega\cos\lambda\,.\,(\alpha - \alpha_0) = 0 \qquad (39)$$

Let

$$\alpha_1 = \alpha - \alpha_0, \quad N = B\omega\cos\lambda/H, \quad M = -Br/2H,$$

Since $d\alpha/dt = d\alpha_1/dt_1$ (39) becomes

$$d^2\alpha_1/dt^2 - 2M\,d\alpha_1/dt + N\alpha_1 = 0 \qquad (40)$$

The solution of this differential equation can be effected as follows :

Let $\alpha_1 = Ce^{mt}$, where e is the Naperian base of logarithms. Then

$$d\alpha_1/dt = Cme^{mt}, \quad d^2\alpha_1/dt^2 = Cm^2e^{mt}$$

Substituting these values in (40) and dividing by Ce^{mt} which is not zero, we obtain the quadratic

$$m^2 - 2Mm + N = 0 \qquad (41)$$

From (41) $m = M \pm \sqrt{(M^2 - N)} = a \pm ib$, where

$$a = M, -b^2 = M^2 - N, i = \sqrt{-1}$$

The general solution of (40) is, therefore,

$$\alpha_1 = C_1e^{(a+ib)t} + C_2e^{(a-ib)t} \qquad (42)$$

From elementary trigonometry we have

$$e^{ibt} = \cos bt + i\sin bt, \; e^{-ibt} = \cos bt - i\sin bt$$

Writing (42) in the form $\alpha_1 = C_1e^{at}\,e^{ibt} + C_2e^{at}\,e^{-ibt}$, and substituting the above values for e^{ibt} and e^{-ibt}, (42) becomes

$$\alpha_1 = (C_1 + C_2)e^{at}\cos bt + (C_1 - C_2)e^{at}\sin bt \qquad (43)$$

Replacing the constants $C_1 + C_2$ and $C_1 - C_2$ by P and Q respectively, we have from (43),

$$\alpha_1 = \alpha - \alpha_0 = Pe^{at}\cos bt + Qe^{at}\sin bt \qquad (44)$$

If the time be reckoned from the instant the axle passes through the resting position, that is, if $t = 0$ when $\alpha - \alpha_0 = 0$, then (44) becomes

$$0 = P + 0, \text{ since } \cos bt = 1, \sin bt = 0, \text{ and } e^{at} = 1$$

Hence $P = 0$, and the final form for the differential equation of a damped harmonic motion is

$$\alpha_1 = \alpha - \alpha_0 = Ae^{at}\sin bt, \qquad (45)$$

where A is a constant of amplitude.

Substituting the constants introduced, we have

$$a = M = -Br/2H,\ b = \sqrt{(N - M^2)} = \sqrt{(B\omega \cos\lambda/H - B^2r^2/4H^2)},$$

and hence $\alpha_1 = \alpha - \alpha_0 = Ae^{-\frac{Brt}{2H}} \sin \frac{\sqrt{(4BH\omega\cos\lambda - B^2r^2)}}{2H}\, t.$ (46)

If T_d denote the period of a damped oscillation, by writing the second term on the right-hand side of (46) in the form

$$\sin\left(\frac{t\,.\sqrt{(4BH\,\omega\cos\lambda - B^2r^2)}}{2H} + 2\pi\right),$$

it follows that

$$T_d = \frac{4\pi H}{\sqrt{(4BH\,\omega\cos\lambda - B^2r^2)}} \tag{47}$$

It was shown in (20) that if T_u is the period of an undamped oscillation,

$$T_u = 2\pi\sqrt{(H/B\,\omega\cos\lambda)}$$

Hence $1/T_u^2 = B\,\omega\cos\lambda/4\pi^2H$

$$1/T_d^2 = (4BH\,\omega\cos\lambda - B^2r^2)/16\pi^2H^2$$

From which $1/T_u^2 - 1/T_d^2 = \left(\frac{Br}{4\pi H}\right)^2$ (48)

If $B^2r^2 > 4BH\,\omega\cos\lambda$, there is no real time of oscillation, but a non-periodic stopping. In these circumstances the adjustment is "dead-beat."

If $B^2r^2 < 4BH\,\omega\cos\lambda$, real oscillations occur. In theory, these never cease, but actually in a short period they become so small that they can be neglected.

Writing (46) in the form

$$\alpha = Ae^{-\frac{Brt}{2H}} \sin\frac{2\pi t}{T_d} + \alpha_0,$$

and taking logarithms of both sides and differentiating,

$$\frac{1}{\alpha}\frac{d\alpha}{dt} = -\frac{Br}{2H} + \frac{2\pi}{T_d}\cot\frac{2\pi t}{T_d} \tag{49}$$

At the extremity of a swing $d\alpha/dt = 0$; hence from (49)

$$\tan\frac{2\pi t}{T_d} = \frac{4\pi H}{BrT_d} \tag{50}$$

If the angle at the extremity of a swing is denoted by η the series of corresponding values of t is given by

$$\frac{2\pi t}{T_d} = \eta + n\pi \tag{51}$$

Let t_1 and t_2 be the times at which two consecutive amplitudes α_1 and α_2 occur. Since these deflections are in opposite directions, it follows from (51) that

$$\frac{2\pi t_2}{T_d} - \frac{2\pi t_1}{T_d} = \pi$$

Hence, $t_2 - t_1 = \frac{1}{2}T_d$, and

$$\alpha_1 = Ae^{-\frac{Brt_1}{2H}} \sin\frac{2\pi t_1}{T_d}, \quad \alpha_2 = Ae^{-\frac{Brt_2}{2H}} \sin\frac{2\pi t_2}{T_d} \tag{52}$$

The value of the ratio α_2/α_1 is

$$\frac{\alpha_2}{\alpha_1} = e - \frac{Br}{2H}(t_2 - t_1) = e - \frac{Br}{4H} T_d = \text{a constant},$$

because $\sin \frac{2\pi t_2}{T_d} / \sin \frac{2\pi t_1}{T_d} = 1$

The expression $e - \frac{Br}{4H} T_d$, which is the ratio of each half swing to the previous half swing, is called the *Damping Factor.*

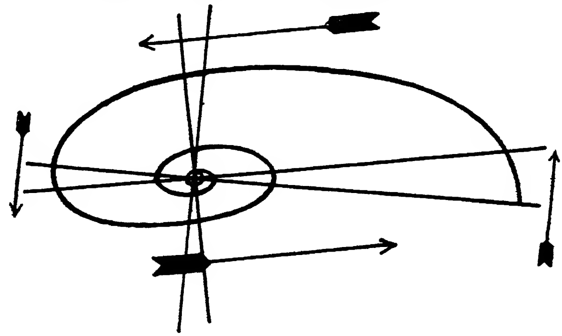


Fig. I, 22. The logarithmic spiral described by the axle of a gyro-compass when damped.

Fig. I.22 shows the elliptical spiral described by the free end. This curve is the well-known logarithmic spiral.

5. AZIMUTHAL ANGULAR VELOCITY AND ACCELERATION OF A BODY MOVING ON THE EARTH'S SURFACE

If a body is moving east or west at the equator with a speed of v knots, its angular velocity ω is v/R relative to the earth, R being expressed in nautical miles. It has been shown in Appendix 1 that the equatorial circumference of the earth is 21,625·82 nautical miles, and hence R is $21{,}625{\cdot}82/2\pi$ nautical miles. Instead of expressing ω in radians it will be more convenient to express it in degrees by multiplying it by $180/\pi$. Hence, if ω° is the angular velocity of the body per hour,

$$\omega^\circ = \frac{180}{\pi} \times v \div 21{,}625{\cdot}82/2\pi = 360v/21{,}625{\cdot}82 = v/60{\cdot}072.$$

It will be sufficiently accurate to use 60 for the denominator, and hence we obtain for the angular velocity in degrees per hour, in the case of a body moving east or west with a speed v knots at the equator,

$$\omega^\circ = v/60 \tag{53}$$

If the body is moving in a latitude λ, the radius of the small circle at the place where it is moving is $R \cos \lambda$, so the factor $\cos \lambda$ appears in the denominator of (53). Hence

$$\omega^\circ = v/60 \cos \lambda \tag{54}$$

If the body is not moving east or west but on a course θ, the component of the velocity east or west is $\omega \sin \theta$, so that for all cases,

$$\omega^\circ = v \sin \theta / 60 \cos \lambda \tag{55}$$

It was shown in Appendix 2 that the angular velocity of the earth at any latitude could be resolved into two components, one of which was $\omega \sin \lambda$ about the vertical at the place. The same applies to a body moving round the earth, and hence the instantaneous angular velocity in azimuth is

$$\omega^{\circ} = v \sin\theta \sin \lambda/60 \cos \lambda = v \sin\theta \tan \lambda/60 \qquad (56)$$

If θ is constant, that is, if the body—ship or aeroplane—is not changing its course, we obtain by differentiating (56)

$$\frac{d\omega}{dt} = \frac{v \sin \theta \sec^2 \lambda}{60} \frac{d\lambda}{dt} \qquad (57)$$

$d\lambda/dt$ is the rate of change in latitude and is $v/60 \times 57{\cdot}2958 = 0{\cdot}000291v$ at the equator if the object is moving north or south. In latitude λ its value is $0{\cdot}000291V/\cos \lambda$, but if the course is θ it will be necessary to resolve the velocity v in the direction of the meridian, and this gives $v \cos \theta$. Hence for $d\lambda/dt$ we can substitute $0{\cdot}000291V \cos \theta \sec \lambda$, and (57) becomes

$$d\omega/dt = 0{\cdot}00000485v^2 \sin \theta \cos \theta \sec^3 \lambda \text{, or}$$

$$d\omega/dt = 0{\cdot}00000242v^2 \sin 2\theta \sec^2 \lambda \qquad (58)$$

If v is eliminated between (57) and (58), another form for (58) is easily obtained, and after simplifying it becomes

$$\frac{d\omega}{dt} = 0{\cdot}0349v^2 \cot \theta \operatorname{cosec} \lambda \operatorname{cosec} 2\lambda \qquad (59)$$

As an example of the application of these formulae take the case of an aeroplane with a speed of 180 knots on a course 30° in latitude 50°. Find its instantaneous azimuthal angular velocity and also its instantaneous azimuthal angular acceleration.

$$\text{By (56) } \omega = 3 \times \tfrac{1}{2} \times 1.192 = 1.79^{\circ}/\text{hour}$$

$$\text{By (58) } \frac{d\omega}{dt} = 0{\cdot}0000242 \times 32400 \times 0{\cdot}866 \times 3{\cdot}767 = 0{\cdot}256^{\circ}/\text{hour per hour}$$

$$\text{By (59) } \frac{d\omega}{dt} = 0{\cdot}0349 \times 3{\cdot}201 \times 1{\cdot}732 \times 1{\cdot}305 \times 1{\cdot}015 = 0{\cdot}256^{\circ}/\text{hour per hour}$$

At the equator ω is always zero since $\tan \lambda$ in (56) is then 0, and (59) is not convenient for computing $d\omega/dt$ in this case because $\operatorname{cosec} \lambda$ is ∞; (58) should be used in these circumstances and generally speaking, it will be found more convenient to use (58) in all cases.

At the pole $\omega = \infty$ and also $d\omega/dt$. For any given latitude and speed ω is a maximum when $\theta = 90^{\circ}$, and $d\omega/dt$ is a maximum when $2\theta = 90^{\circ}$, or $\theta = 45^{\circ}$.

6. EFFECT OF THE EARTH'S ROTATION AND OF LINEAR MOTION ALONG A GREAT CIRCLE ON A SPACE BALANCED FREE GYROSCOPE

The angular motion of a space gyro when carried in a moving body such as a ship or aeroplane, may at first seem a trifle complex. So we shall begin first with a discussion of the actual movement and include a few simple equations dealing with the motion at a later stage.

Suppose we start the gyro at the earth's equator and with its axis of spin vertical as shown at A_1 in Fig. I.23. We shall assume first that the gyro is perfectly balanced so that when rotating it remains stationary relative to a "fixed" star. The earth rotates once per day, i.e., at a rate of 15° per hour, from west to east. Thus if the supporting frame of the gyro is stationary the spin axis will deviate from the vertical at a rate of 15° per hour. After two hours it will be as shown at A_2 and after 6 hours it will be spinning with its axis horizontal as shown at A_3 with the end of the spin axis pointing due east. If the gyro is started up at the geographic N or S pole the spin axis would of course remain in the vertical, since the gyro does not show any relative angular movement which occurs about its spin axis.

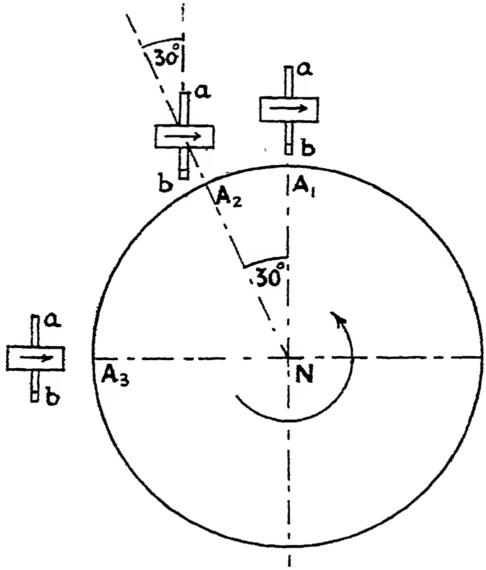


Fig. I, 23. The spin axis of a perfectly balanced gyro, when rotating, points in the same direction. Owing to the rotation of the earth the spin axis deviates from the vertical. This deviation amounts to 15′ per hour at the equator, for which the diagram is specially drawn.

Suppose now that the earth does not rotate and that the gyroscope is carried by an aeroplane flying east along the equator at 300 knots. It was shown in Appendix 5 equation (54) that the gyro axis would then appear to tilt from the vertical at a rate of $300/60^\circ = 5^\circ$/hour. However, since the earth is always rotating, this rate of tilt must be added to or subtracted from (depending on the direction of flight) the velocity due to the earth's rotation. In the present case where the direction of flight is east the velocity must be added, so that there will be an apparent tilt of $15^\circ + 5^\circ = 20^\circ$/hour. If the motion of the aeroplane were due west the gyro would appear to tilt at $15^\circ - 5^\circ = 10^\circ$/hour from east to west in the vertical plane.

Consider now the apparent motion of the gyroscope when it is initially spinning in the vertical at latitude λ° as at P_1 in Fig. I.24. When the earth has turned through 90° the gyro will be in the position shown

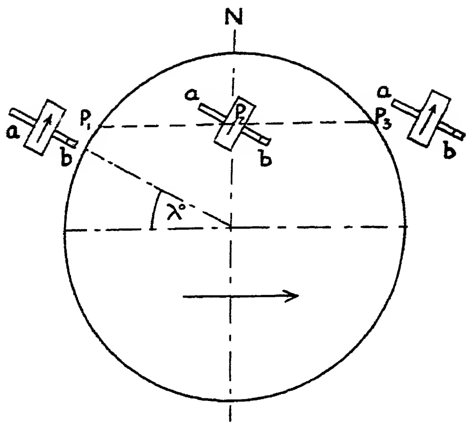


Fig. I, 24. The behaviour of the spin axis is shown for a latitude other than that of the equator.

at P_2, that is, the ends of the gyro axle will have apparently moved through an angle of 90° about an axis parallel to the geographical axis of the earth. Similarly for a further 90° of earth rotation the gyro axle will have moved to the position shown at P_3. Or more correctly, a point P on the earth has moved from 0° through 90° to 180°, and since the angular position of the gyro-axle has remained fixed, it will appear to have tilted.

For a complete rotation of the earth the gyro will make a conical movement as shown in Fig. I.25. The two ends of the gyro axle will appear to move in circles, in the opposite sense to the rotation of the earth, at a rate of 15°/hour. The apex angle of this cone of rotation is equal to $180° - 2\lambda°$ where λ is the latitude at which the gyro was originally spinning vertically.

If the gyroscope is carried on a moving aircraft the same solid of rotation (Fig. I.25) will be traced, but the angular velocity of the conical movement will be decreased or increased depending on whether the E-W component of the aeroplanes' speed is towards the E or the W. The N-S component of the speed will increase the maximum divergence of the gyro axle from the vertical, depending on whether the aeroplane's speed has a N. or S. component and also on whether the gyro is situated in the northern or the southern hemisphere.

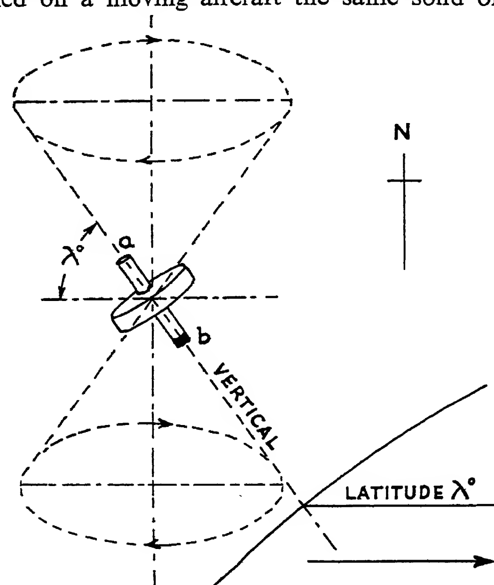


Fig. I, 25. The conical motion of the gyro axis during a complete rotation of the earth.

The rotation of the earth can be resolved into vertical and horizontal components as shown in Fig. I.26. At a point P at latitude $\lambda°$ the earth's rotation may be represented by the rotary vector ω, and hence the component about a vertical axis is equal to $\omega \sin \lambda$ and the component about a horizontal axis in the plane of the meridian is equal to $\omega \cos \lambda$. The gyroscope will of course appear to move in the opposite sense to that represented by the vectors in Fig. I.26 (a), and the horizontal and vertical rotations combine to form the conical movement about an axis parallel to the earth's axis as previously shown in Fig. I.25.

If an aeroplane is flying on a great circle track of $\theta°$ with a speed v_a there will be a N-S component $v_a \cos \theta$ and an E-W component $v_a \sin \theta$. This is shown in Fig. I.26 (b). The reader should regard this illustration as a

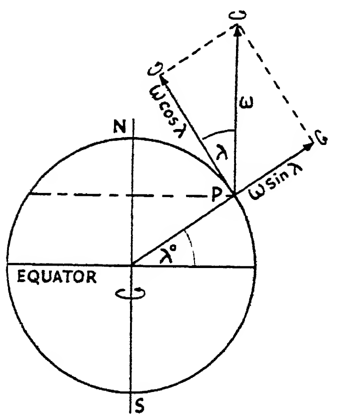


Fig. I, 26(a). Horizontal and vertical components of the earth's angular velocity.

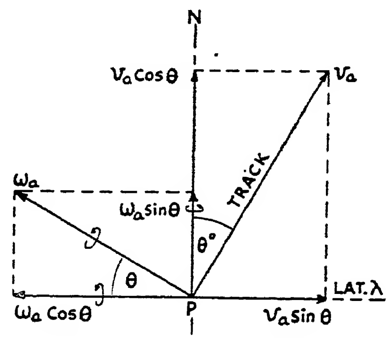


Fig. I, 26(b). The motion of an aeroplane may be regarded as a pure rotation about the earth's centre. Vectors representing the motions of the earth and aeroplane are reversed and the components added to give the apparent motion of the gyroscope relative to the earth in magnitude and direction.

plan of the point P in Fig. I.26 (a) that is looking back along the vector $\omega \sin \lambda$ in the same plane as the page. The aeroplane's motion may also be regarded as a pure rotation about the earth's centre. The rotary vectors are of course perpendicular to the linear vectors, and if we call the rotary motion due to the aeroplane ω_a it is represented in magnitude and direction by the vector ω_a in Fig. I.26 (b). This yields components $\omega_a \sin \theta$ about a N-S horizontal axis and $\omega_a \cos \theta$ about an E-W horizontal axis. Again, the apparent motion of the gyro is in the opposite sense to that shown by the vectors.

The relative motion of the gyroscope, due to earth's rotation and motion of the aeroplane, is given by the vector diagram shown in Fig. I.26 (b). Here the vectors representing the earth's and the aeroplane's motion are reversed and the components are added to give the apparent motion of the gyroscope relative to the earth in magnitude and direction.

Thus we have the following angular velocities :

$\omega \sin \lambda$ about a vertical axis .. .. (60)
$\omega \cos \lambda + \omega_a \sin \theta$ about a N-S horizontal axis .. .. (61)
$\omega_a \cos \theta$ about an E-W horizontal axis .. .. .. (62)

where ω = angular velocity of earth
ω_a = angular velocity of aeroplane about a diameter of the earth
λ = latitude in degrees
θ = track angle of aeroplane in degrees.

Hence, from equation (60), if the aeroplane's track is along the arc of a great circle, the instantaneous value of the gyroscope's apparent angular velocity about a vertical axis is unaffected by the aeroplane's linear motion. It should be particularly noted, however, that for flight along a great circle, the track angle θ will be constantly changing. If, on the other hand, flight is such that the track angle θ does not vary, it has been shown in Appendix 5, equation (56), that the apparent angular velocity about the vertical, caused by the aeroplane's speed alone, is

$$v \sin \theta \tan \lambda/60 \text{ deg. per hour.}$$

Expressing this in the same form as equations (60), (61) and (62), it becomes

$$\omega_a \sin \theta \tan \lambda$$

the sense of the velocity being determined by the value of θ, that is, positive for angles from 0° to 180° and negative for angles from 180° to 360°. This must be added algebraicly to the velocity $\omega \sin \lambda$ caused by the rotation of the earth. Thus, the total apparent angular velocity about a vertical axis is

$$\omega \sin \lambda + \omega_a \sin \theta \tan \lambda, \quad \text{or} \qquad (63)$$

$$15 \sin \lambda + v \sin \theta \tan \lambda/60 \text{ deg. per hour} \qquad (64)$$

where v is the aeroplane's linear speed in knots.

SECTION II—MARINE APPLICATIONS

CHAPTER 1

THE GYRO COMPASS

A generation ago the gyroscope was comparatively unknown to seamen; to-day it is playing an increasingly important part in the navigation and equipment of ships of both naval and merchant type. Of the many applications of the gyroscope for marine use. the gyro compass is, without doubt, the principal and the most widely used. Every man-of-war carries at least one master gyro compass operating numerous repeater compasses for a large variety of purposes. Additionally, merchant ships of all types, from mammoth transatlantic liners to small "tramp" freighters, are nowadays equipped with gyro compasses operating repeaters for such purposes as steering, observation of terrestrial, celestial and radio bearings, and for the automatic recording of courses steered. Frequently also the steering of merchant ships is automatically effected through the medium of a gyro pilot operating in conjunction with the gyro compass system.

It is a remarkable fact that while the magnetic compass is known to have been in navigational use for more than 4,500 years, yet within the last thirty years the gyro compass, deriving its directive force from the earth's rotation, the force of gravity and gyroscopic phenomena, has found its way into every class of ship afloat.

Evolution of the magnetic compass

For a proper appreciation and understanding of modern scientific apparatus, it is frequently found useful to study the historical aspect, and it is certainly of interest to know something of the evolution of the magnetic compass, and the necessity which has arisen for a non-magnetic direction indicator in the modern ship, before passing to a technical description of the gyro compass.

The earliest known reference to a magnetic compass in crude form is found in ancient Chinese writings of the year 2634 B.C. in the 64th year of the reign of Emperor Ho-ang-ti. It is there recorded that this potentate, pursuing his enemy Tchi Yeou in the plains of Tchou-lou, encountered an artificially created dust storm and was only enabled to continue the pursuit, and to capture his enemy, by means of Tchinan or "Chariot of the South" which successfully led his army. This compass-carrier consisted of a chariot in which a piece of magnetite, or magnetic ore, was freely suspended by a silken thread, when it was found to point persistently to the south, due, so it was believed, to the efforts of a devil imprisoned within, whose home lay in the South of China.

Early workers in metal must have known of the strange property of magnetite, so called from the province of Magnesia in Asia Minor, in which it was found in large quantities. The fact, however, that it could communicate its mysterious nature to wrought iron was, in all probability, discovered accidentally. That a piece of such metal, so induced, possessed direction indicating properties when freely suspended is mentioned briefly in a Chinese dictionary of 121 A.D. The Greeks and Romans were certainly acquainted with the magnetic properties of various substances, but no record of the use of the magnetic needle in European waters is found until the eleventh century when reference to this is made in the works of Ara Fröde, the Norwegian historian. During the next century its use spread all over Europe.

An early magnetic compass, described by Bailak in 1242, consisted of a bowl of wood, or china, marked inside with lines representing the four cardinal points, and partially filled with water on the surface of which was floated the magnetised needle supported by a cornstalk or piece of wood. At about the same time variation, or the divergence between the magnetic and true meridians, became known, though it was not fully understood until 1492, when Columbus made his celebrated voyage across the Atlantic. The inclination, or "dip" of the magnetic needle was established factually in 1576 by Robert Norman, "a skilled navigator and ingenious artificer." A treatise published by Dr. Gilbert in 1600, entitled *De Magnete*, laid the foundations of the study of terrestrial magnetism.

The position of the north magnetic pole of the earth in lat. 70° 5′ N long. 96° 43′ W was established by Sir James Ross in 1831, and ten years later the same navigator deduced from his observations that the south magnetic pole was located in lat. 73° 30′ S and long. 147° 30′ E. The fact that these magnetic poles are located approximately a thousand miles from the true geographical poles of the earth, and the introduction of iron and steel as materials for shipbuilding, resulting in local deviation of the magnetic compass needle from the magnetic meridian, were largely responsible for the beginning of research into the problem of finding a non-magnetic compass for marine use. The introduction into ships of electricity for lighting, and power for electro-magnetic machinery, further emphasised the need for an instrument which would provide indications of direction relative to true north and which would be free from errors due to terrestrial or local magnetism.

Early history of the gyro compass

The possibility that the gyroscope, suitably controlled, could meet this need had been known and understood for some time following Foucault's gyroscopic demonstration of the earth's rotation in 1852, but the difficulties of maintaining a high uniform rate of speed of the spinning rotor, and of reducing the friction in the bearings and mountings of the gyroscope to a minimum which could be disregarded, could not be overcome until the advent of the highspeed electric motor and also of virtually frictionless ball bearings.

At the beginning of the twentieth century scientists of several nations were working upon the solution of the problem of constructing a practical gyroscopic compass which would function successfully at sea. Dr. Hermann Anschütz Kaempfe in Germany, who patented his gyro compass in 1908, must be accredited the pioneer who produced the instrument in its earliest practical form, but he was quickly followed by Dr. Elmer

A. Sperry of the U.S.A., who patented his gyro compass in 1911. In England Mr. S. G. Brown, with Professor John Perry, was working on similar lines and patented the Brown gyro compass in 1916. Before dealing with these three compasses individually there are certain common principles which may usefully be described.

All gyro compasses embody a spinning rotor or flywheel driven at high speed by either D.C. or A.C. electric motors. The rotor is contained in bearings in a casing which has freedom to turn about a horizontal axis in the vertical plane, and also about the vertical axis in the horizontal plane, so that the rotor conforms within limits to the requirements of a 'free' gyroscope having freedom about the spinning, horizontal and vertical axes respectively.

Apparent movement of free gyroscope relative to earth's surface

Such a gyroscope, if set spinning on the equator with its axle in the true meridian and horizontal to the plane of the earth's surface (and therefore parallel with the earth's axis), will exhibit gyroscopic inertia which will maintain the axle of the gyro in the true meridian irrespective of the earth's rotation. It will, in fact, be pointing its axle to the celestial pole, and unless caused to precess from that direction by the application of a disturbing torque or the effects of friction, will maintain the true north indication which is required. If set spinning on the equator with its rotating axis in the east-west direction (see Fig. II. 1) it would appear to turn a complete revolution about its horizontal axis once in every twenty-four hours, maintaining the direction of its axis of rotation relative to a fixed point in space while the horizontal or plane of the earth's surface turns through 360 degrees.

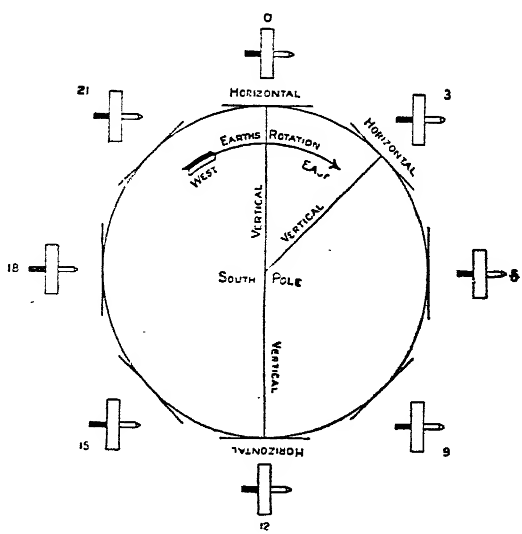


Fig.II.1. At the equator a gyroscope set spinning with its axle East and West will appear to make a complete revolution about its horizontal axis relative to the earth's surface as the earth rotates through 360° in the twenty-four hours.

If, however, the gyroscope be moved to the N (or S) pole of the earth, and set spinning with its axle horizontal to the plane of the earth's surface, it will only demonstrate the rotation of the earth through its diurnal revolution, and can be of no use as a direction indicator. At any other point on the earth's surface between the poles and equator, the gyroscope, if set spinning in the true meridian, with its axle parallel to the axis of the earth, will maintain the indication of true north irrespective of the earth's rotation, under the same conditions as at the equator, but the gyro axle will be tilted relative to the plane of the earth's surface by an amount equal to the latitude. On the other hand, in any latitude other than at the pole or equator (see Fig. II. 2), if the gyroscope be set spinning with the axle in the true meridian, and horizontal to the plane of the earth's surface, two movements will apparently take place. As the earth rotates from west to east, and the gyro axle maintains gyroscopic inertia relative to a fixed point in space, the north end of the axle will deviate to the east of the true meridian in the northern hemisphere, and will tilt up relative to the plane of the earth's surface. In the southern hemisphere the south end of the gyro axle will deviate to the east of the true meridian and tilt up relative to the plane of the earth's surface.

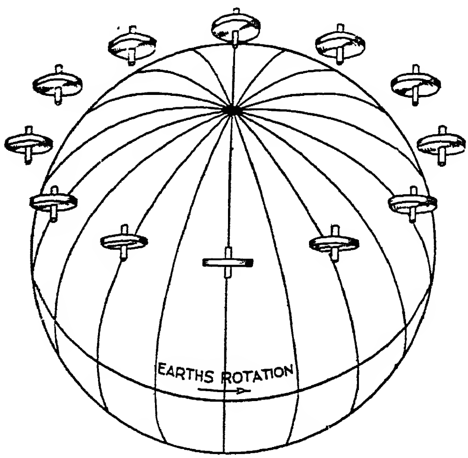


Fig. II.2. In any other latitude but that of the equator a gyroscope set spinning with its axle in the plane of the true meridian, and horizontal to the earth's surface will apparently move about its horizontal axis relative to the earth's surface, and also about its vertical axis relative to the true meridian as the earth rotates from West to East.

Essential requirements for a meridian seeking gyroscope

In considering how best to make an efficient north-seeking compass, three facts have to be taken into consideration :

(i) That the perfect gyroscope exhibiting complete gyroscopic inertia is virtually impossible to produce mainly due to the difficulty of eliminating friction in bearings.

(ii) That it is desirable to have the gyro axle horizontal, or almost horizontal, to facilitate the reading of its indications which would otherwise have to be projected vertically down from the uptilted axle on to the horizontal plane.

(iii) That the meridian-seeking torque of the gyro compass is at its maximum when the gyro axle is horizontal, i.e., the directive force of the compass is proportional to the horizontal component of the angular momentum of its gyroscope, so that in lat. 60° only half the available directive force would be effective if the axle were parallel to the earth's axis.

The gyroscope had, therefore, to be constructed with its axle horizontal, or nearly so, and to be made to *seek* the meridian so persistently that not only the easterly deviation from the meridian would be overcome, but also any precessional effects due to friction in bearings.

Early gyro compasses

In early gyro compasses this north-seeking function was produced by making the gyro casing pendulous or bottom heavy, so that, as the axle of the gyro acquired tilt as the result of the earth's rotation, the effect of gravity was introduced through the medium of the weight or 'bail.' This produced a couple about the horizontal axis which resulted in precession about the vertical axis and the direction of spin of the gyro rotor, in the same direction as the rotation of the earth (i.e., clockwise when viewed from the south end of the axle) was arranged so that this precession took place in the desired direction to return the axle to the true meridian.

Gyro compasses having gyros made pendulous by the use of bottom weight were not found to be very satisfactory under actual sea conditions as, when subjected to heavy rolling and other rapid movement or acceleration forces resulting from location of the compass at points above or

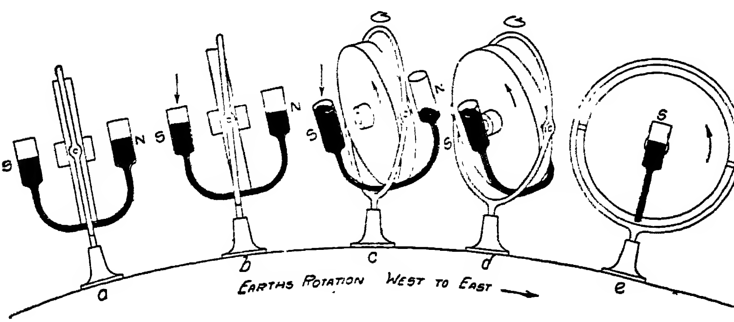


Fig. II.3. A gravity-controlled gyroscope set spinning with its axle in the East / West plane on the Equator will tilt as the earth rotates from West to East. The liquid in the ballistic will flow from the higher to the lower reservoir and cause precession about the vertical axis until the spinning axle aligns itself at right angles to the plane of rotation of the earth.

below the rolling centre, undesirable effects were introduced which detracted from its efficiency. The devices that are used by the respective patentees and manufacturers to overcome these difficulties will be described individually under their various headings. A simple form of such device is shown in Fig. II. 3. It comprises two reservoirs, located north and south of the gyro axle respectively, partially filled with mercury and connected by a small bore tube. As the gyro axle tilts relative to the plane of the earth's surface, mercury flows from the reservoir at the higher end to that at the lower end, introducing a torque about the horizontal axis thus causing precession about the vertical axis to take place until the gyro axle is aligned at right angles to the earth's rotation.

Effect of ship's course and speed

As already explained, the motive force for the precessional north-seeking movement of the sensitive element of the gyro compass is provided by a combination of the angular rotation of the earth and the effect of gravity. The angular rotation of the earth is slow, and as the ship is travelling over the earth's surface the movement of the ship is compounded with that of the earth as shown in Fig. II/4. The resultant movement to which the gyro compass is subjected, and at right angles to which it aligns itself, is not therefore in the true west/east direction but in a direction relative to a fixed point in space indicated by OR in Fig. II. 4. The virtual meridian ON′ at right angles to the resultant movement which is indicated by the gyro compass differs from the true meridian ON by the angular amount of the angle EOR or NON′ which is generally referred to as the speed error. It will be appreciated, however, that while this error is primarily due to the speed of the ship over the earth's surface, it is also affected by the course which the ship is

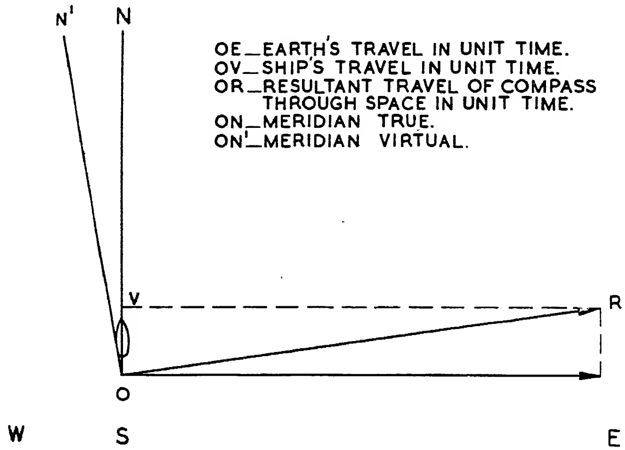


Fig. II.4. The angular motion of the earth OE is from true West to East and the true meridian ON is at right angles to this motion. If a northerly or southerly component OV or ER is introduced by the ship's travel the resultant of the movements of the earth and the ship is shown along OR. The virtual meridian indicated by the gyro compass will be ON′ and the speed and course error will be the angle NON′ corresponding to the angle ROE.

steering and the latitude in which it is situated. When the ship is travelling due east or west its movement over the earth's surface only adds to or subtracts from the speed of rotation of the earth in that particular latitude, and the error is negligible. When, however, the ship is travelling due north or due south, the effect of its speed over the earth's surface is at the maximum and the error is greatest. On any other course between west or east, and north or south, the error will vary as the cosine of the course, or as the northerly or southerly component of the course. The ratio of ship's speed to that of the earth varies, however, according to the latitude, the effect being least on the equator where the earth's speed is greatest and increasing in the ratio of secant latitude as the speed of the earth decreases in higher latitudes. In a ship steaming due north at 30 knots in the latitude of London, this error will amount to 3°, or approximately one degree for every ten knots of speed. This error is westerly on northerly courses, and easterly on southerly courses.

In the Sperry gyro compass means are provided for the automatic correction of the latitude, course and speed error, so that the resultant reading at the 'lubber line,' or mark indicating the ship's heading, is correct. In other gyro compasses a mechanical device for setting in the correction manually from appropriate tables is provided.

Ballistic deflection

By reference to the example quoted above of a ship steaming due north at 30 knots, in the latitude of London, it will be noted that the Lat/Course/Speed error amounts to 3° westerly. If now the ship be turned through 180°, which can be done quite quickly, the Lat/Course/Speed error will change to one of 3° easterly, making a total change of six degrees in the virtual meridian. On first thoughts it might appear almost impossible for the gyro axle to follow this rapid deflection of the virtual meridian, but it will actually do this provided that the periodic time of the gyro compass be appropriately arranged. With such a complete undamped period of approximately 85 minutes the stabilizing effect of the gyro will hold the casing in the true vertical position during the turn and the resulting couple applied will cause a horizontal precession in azimuth equal and opposite to the change in the virtual meridian. For this reason gyro compasses are constructed so as to have this undamped period as nearly as possible.

Damping of oscillation about the meridian

As already described, the north-seeking property of the gyro compass is derived from the precessional effect of a torque produced by the effect of gravity when the gyro axle tilts relative to the plane of the surface of the earth during rotation. This precessional movement of the gyro axle back towards the meridian continues until such time as the axle has passed the plane of the meridian. In north latitude the end of the gyro-axle which was formerly pointing east of north, will now be pointing west of north, and the tilt of the gyro axle relative to the plane of the earth's surface will be decreased by the earth's rotation until such time as the rate of precession is less than the deviation from the meridian, caused by the earth's rotation. The gyro axle will then steady and begin to move back eastward to the meridian again. The gyro axle will, therefore, oscillate about the meridian, but will not settle on the meridian unless some means of damping out the oscillation can be introduced.

In the Sperry gyro compass this damping effect is achieved by linking the pendulous mercury ballistic to the gyro rotor casing eccentrically (see Fig. II. 5) so as to introduce a small torque about the vertical axis, in addition to the major torque about the horizontal axis, thus causing the gyro axle to precess back towards the horizontal as well as to precess in azimuth. This reduction of the angle of tilt, resulting in progressive reduction of oscillation about the meridian, and final settling on or very near the meridian, is termed 'damping,' and the ratio of the progressive reduction of oscillation is termed the 'damping factor.' In the Sperry compass the damping factor produced by offsetting the point of attachment of the ballistic link to the gyro casing slightly to the eastward of the true vertical, is 67%, i.e., two-thirds of the oscillation (varying with latitude) is damped out at each swing. If the compass is started 30° east of the meridian. the first swing will carry the gyro axle to 10° west, the second to 3·1 3° east then 1·1 9° west, etc. This damping factor, however, varies with latitude.

In the original Anschütz compass with single gyro the reaction of a jet of air, issuing from the gyro casing and controlled by a pendulous shutter, was used to produce the damping effect. The reaction of the jet, acting either clockwise or counter-clockwise about the vertical axis, was controlled by the direction of tilt of the gyro casing relative to the pendulous shutter, the magnitude of the reaction being in accordance with the angle of tilt. In later models having two or three gyros, the damping of the Anschütz compass is effected by the use of a viscous fluid contained in chambers interconnected by restricted passages. The couple produced by the flow of the fluid between the chambers as the gyro system tilts, is opposite in effect but smaller in magnitude, and slower in operation than the couple produced by the pendulous nature of the gyro, and the appropriate damping effect on the oscillations of the gyro axle about the meridian is thereby introduced. In the Brown gyro compass damping is effected by a somewhat similar method using damping bottles, although the gyro is not pendulous in the accepted sense. The couples produced by the 'working' bottles of the Brown gyro compass are similar in effect to those produced by a pendulous gyro. The opposing couple produced by the damping bottles is less than that of the working bottles and is controlled by a needle valve which makes the flow of oil to the low side sluggish and the effect to lag behind that of the working bottles, thus producing the necessary damping effect at the maximum oscillation at each swing.

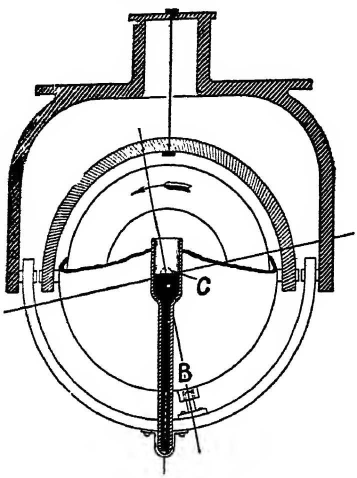


Fig. II.5. In the Sperry gyro compass damping of the oscillation of the gyro axle about the meridian is effected by linking the mercury ballistic eccentrically to the gyro casing, as at B, thus introducing a small torque about the vertical axis in addition to the major torque about the horizontal axis.

A C is the centre line of the compass.
B point of connection of ballistic eccentrically to gyro casing.
C gyro axle.

As regards damping arrangements, it may be stated that the Sperry compass is damped by a couple around the vertical axis which successively reduces the tilt of the axle at each swing, and thereby reduces the couple about the horizontal axis while the later Anschütz compass, and also the Brown compass, accomplish the same effect by a couple around the horizontal axis which opposes the couple produced by the pendulum effect while less in magnitude and slower in accumulative result.

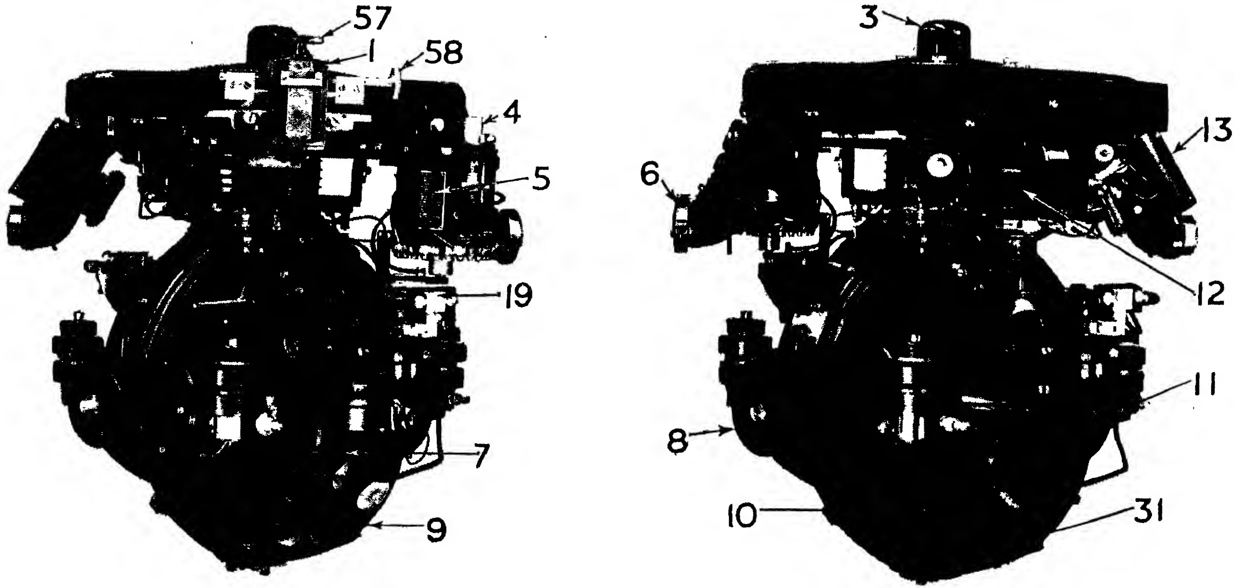


Fig. II.6. The Sperry Mark XIV gyro compass removed from its binnacle and shown as viewed from the North and South ends respectively.

1. Speed and Latitude corrector
3. Suspension cap
4. Transmitter lost motion Adjusting Knob
5. Transmitter
6. Trunnion bearings
7. Vertical ring
8. Compensator weight
9. Phantom ring
10. Rotor case
11. Mercury ballistic
12. Azimuth motor
13. Spider terminal Block
19. Trolley adjusting Screw
31. Vertical ring and Rotor case lock
57. Speed and latitude corrector setting knob
58. Auxiliary latitude corrector setting

CHAPTER 2

THE SPERRY MARK XIV GYRO COMPASS

Sensitive element

The gyro wheel, or rotor, of the Sperry gyro compass (see Fig. II. 6), weighing approximately 52 lb., which is spun by an alternating current induction motor at 6,000 r.p.m., is mounted in a rotor case on ball

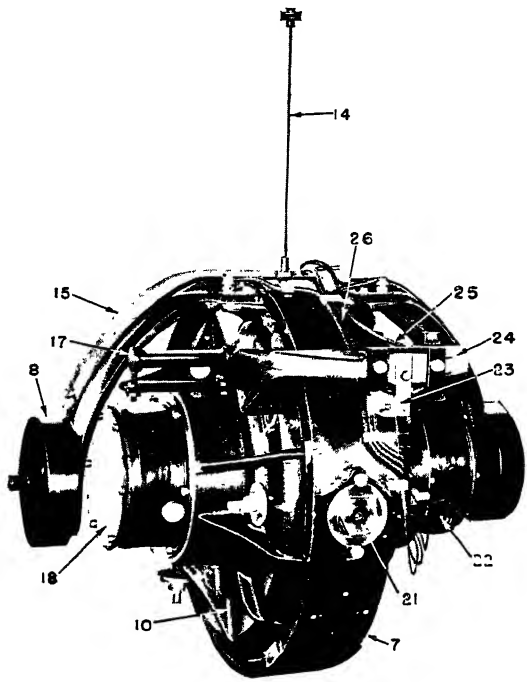


Fig.II.7. The Sperry Mark XIV gyro compass sensitive element.

7. Vertical ring
8. Compensator weight
10. Rotor case
14. Suspension
15. Compensator weight frame
17. Case level
18. Rotor bearing housing plate
21. Horizontal case bearing
22. Oil well window
23. Trolley
24. Trolley bracket
25. D.C. return from trolley
26. A.C. 3 phase Supply to gyro

bearings, giving freedom about the spin axis. This case is provided with studs in horizontal alignment on the east and west sides which rest in bearings in an encircling ring termed a 'vertical ring.' providing freedom about the horizontal axis. This vertical ring is provided with ball bearings in alignment with the vertical axis of the compass which are termed the upper and lower guide bearings. The actual weight of the sensitive element (i.e., rotor, rotor case and vertical ring) is taken by suspension from a point at the top of the stem of the 'phantom' or shadowing element. The gyro has, therefore, the necessary freedom about the spin, horizontal and vertical axes respectively. The mass of the sensitive element in the E W plane is balanced by the addition of compensator weights positioned at the north and south ends of the sensitive element on frames attached to the vertical ring, equalising the inertia effects about the vertical axis. Pendulum effects, which would

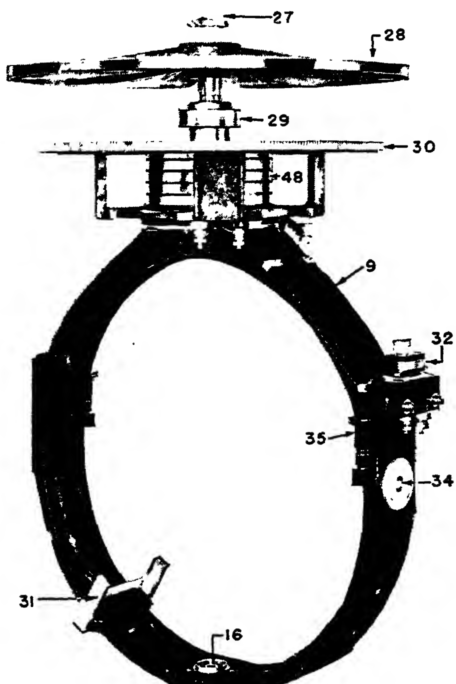


Fig. II.8. The Sperry Mark XIV gyro compass, phantom element.

9. Phantom ring
16. Lower guide bearing
27. Suspension adj. fork
28. Compass card
29. Upper stem bearing
30. Azimuth gear
31. Vertical ring and rotor case lock
32. Contactor
34. Mercury ballistic bearing
35. Mercury ballistic bearing oil cup
48. Stem slip rings

tend to turn the gyro into a direction with its axle at right angles to the plane of the swing, to which it might be subjected, are thus eliminated. The gyro wheel and induction motor in its casing, mounted in bearings in the vertical ring complete with compensator weights, is termed the 'sensitive element.'"

Phantom element

The sensitive element (Fig. II. 7) is the north-seeking element of the compass, and must be mounted with ability to turn about the vertical axis in order to provide the third axis of freedom. This matter of providing virtually frictionless freedom to turn in azimuth is one of considerable difficulty, but is ingeniously overcome in the Sperry compass by suspending the sensitive element from a point in upper vertical alignment on the vertical ring by a group of wires which is secured to the top of the stem of what is termed the 'phantom' element (Fig. II. 8). As this phantom element is made to follow every movement in azimuth, however small, of the ship about the sensitive element, the suspension remains torsionless and friction about the vertical axis is to all practical purposes eliminated. As the phantom element is kept in constant alignment with the sensitive element, the compass 'card' is conveniently mounted on the top of the stem of the phantom element with its graduations commencing at 0° in alignment with the north end of the gyro axle and continuing round clockwise through 360°.

Spider element

The phantom element stem is supported by the spider element (Fig. II. 9), the two elements being kept in alignment by means of stem ball bearings which permit free rotation of the phantom within the spider, the weight of the phantom and its contained sensitive element being supported on a roller thrust bearing from the hub of the spider element.

The spider element is mounted on athwartship trunnions on the gimbal system of the binnacle, and consists of a main frame designed to bear the weight of the phantom and sensitive elements. It carries on its upper rim a detachable ring engraved with a lubber line against which the compass card is read. This lubber ring is capable of rotation on the spider rim, and the corrections for latitude, speed and course errors are actually made by a movement of the lubber ring by the automatic mechanical correctors resulting in a movement of the lubber line against which the ship's heading is read. The spider element also carries the azimuth motor which drives the phantom element around to follow the sensitive element (see Follow-up System), the Transmitter, which controls the operation of the repeater compasses (see Transmission System), and the Speed and Latitude corrector and Auxiliary Latitude Corrector.

Gimbal system

The whole compass, of which the centre of gravity is below the point of suspension, is mounted in a binnacle on a gimbal system which allows freedom to the compass to remain practically undisturbed by motion of the ship, whether of rolling or pitching, within limits of 45° roll and 20° pitch.

Gyro drive system

The gyro-drive system forms the link between the ship's electrical supply and the gyro rotor. Most merchant ships have an electrical supply of either 110 or 220-volts D.C. and this supply is used to drive a generator which provides the three-phase alternating current at 50-volts 210-cycles for the gyro drive induction motor, and additionally an output of 70-volts D.C. which is used for the azimuth motor follow-up system, and also for the step-by-step motors in the transmission system to the repeaters. The gyro drive induction motor is composed of a squirrel-cage rotor which forms part of the gyro wheel itself, while the stator is secured to the inside of the gyro casing. It will be appreciated that the gyro forms part of the sensitive element, which remains stationary relative to the true meridian while the ship, and with it the gyro compass binnacle, gimbal system and spider element, turns in azimuth around it,

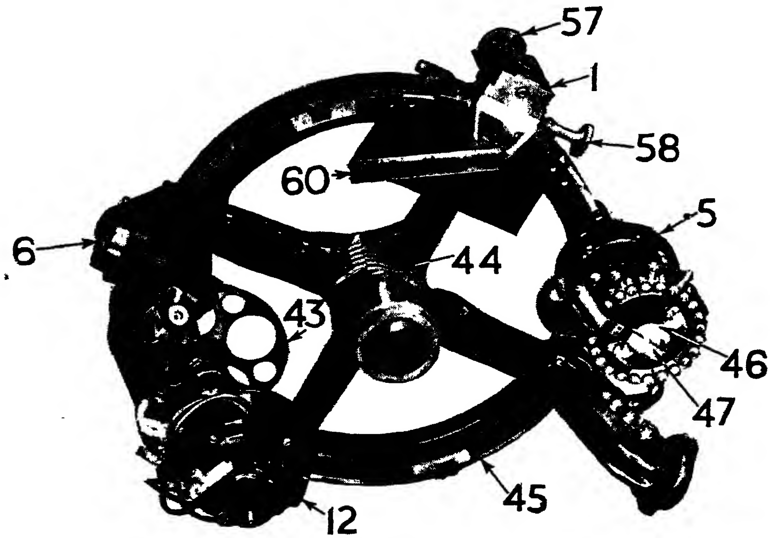


Fig. II.9. The Sperry Mark XIV gyro compass. Spider Element

1. Speed and Latitude corrector
5. Transmitter
6. Trunnion bearings
12. Azimuth motor
43. Azimuth motor large gear
44. Stem collector ring brushes
45. Lubber ring
46. Trans. roller carriage
47. Trans. centre contact Arm
57. Speed and Lat. corrector setting knob
58. Aux. lat. Corrector setting knob
60. Cosine cam Arm

when alterations of course are made. The supply of A.C. must, therefore, be fed to the gyro drive induction motor irrespective of the ship's movements. This is accomplished by leading the supply to terminal blocks on the binnacle and spider element, and thence through slip rings mounted on the stem of the phantom element to terminals on the phantom ring. From here connection is made to terminals on the vertical ring by means of coiled helix wires, thence down the side of the vertical ring to the horizontal axis of the gyro case where connection is made by flexible leads to terminals on the case itself leading to the stator of the gyro drive motor inside. By these means current is fed from the generator (through a control panel) to the fixed binnacle, and from there to the sensitive element about which it rotates without the introduction of any disturbing effect. Care, however, must be taken to avoid disturbing the coiled helix wires conveying current from the terminals on the phantom ring to the terminals on the vertical ring, and those between the vertical ring and gyro casing, otherwise small torques about the vertical and horizontal axes may be introduced leading to a slight error in the settling point of the compass.

Follow-up system

The follow-up system is the term given to the arrangement by which the phantom element is kept in constant alignment with the vertical ring of the sensitive element. It consists of an electric motor, termed the azimuth motor, attached to the fixed spider member and geared to the azimuth gear wheel on the phantom stem. This azimuth motor, or 'Azimotor,' as it is usually named, is a split field series motor specially designed for quick reversal of direction of rotation, and is controlled by trolley and contactor switching. A trolley is carried on arms attached to the vertical ring, the wheel of which rides across the face of a contactor, consisting of two contact blocks, which is attached to the phantom element. These two contactor blocks are connected respectively to the opposing fields of the azimotor, and are so arranged that the trolley wheel bridges the central air gap between the contact blocks when phantom and vertical ring are in exact alignment. Any displacement of the phantom ring relative to the vertical ring results in movement of the trolley on to one or the other of the contact blocks. The consequent operation of the azimotor, in the direction necessary to restore alignment, results in a movement of phantom element and compass card to the new ship's heading. The azimotor must therefore be capable of quick reversal of direction. A mercury damping weight, secured to the lower end of the armature shaft reduces the shock of reversal and assists smooth operation. As there is no neutral position between the two contact blocks, the trolley and azimotor are constantly hunting over the central position of alignment of phantom and vertical rings so long as the ship remains on her course. Any movement of the ship's head to port or starboard of the course is followed so quickly by re-alignment of the phantom ring with the vertical ring, that there is virtually no lag even with the quickest turns.

The trolley and contactor circuit which controls the operation of the azimotor in this follow-up system, is duplicated on each side of the phantom and vertical rings, so that the possibility of a complete failure is exceedingly remote. The trolley wheels are made with gold rims and the contactor blocks are faced with tungsten metal so that sparking at the faces is reduced considerably and is still further reduced by suitable discharge resistances across the motor field coils. The daily attention to trolleys and contactors which is recommended by the manufacturers, however, is to pass a strip of clean paper slantwise between each trolley and contactor in turn so as to remove any deposit caused by such sparking as may be occurring. This also has the effect of turning the trolley wheel so that a new section of the rim is presented to the contactor block. As the circuit is duplicated the temporary interruption of the circuit at one side will not affect the operation of the follow-up system which will meanwhile be carried on by the set of trolleys and contactors on the other side.

The latest modification of the Sperry gyro compass eliminates even this minor daily attention by replacing the trolley and contactor control of the azimotor by an electro-magnetic pick-up device in which there is no physical contact between the phantom and vertical rings. A soft iron armature secured by brackets to the vertical ring moves over the poles of an electro-magnet attached to the phantom ring. A small uniform air gap separates the armature and the poles of the electro-magnet and so long as the armature is centrally located relative to the poles of the electro-magnet no current is induced in the secondary windings, but displacement of the armature to one side or the other causes the induction of minute currents in the secondary winding of one pole or the other of the electro-magnet. These minute currents are amplified by a valve amplifier similar to that used to amplify radio signals received by a wireless set, and the resulting output is used to control the direction of rotation of the azimotor. This modification of the Sperry gyro compass embodying the electro-magnetic control may be of 'hunting' or 'non-hunting' type, but the general opinion appears to be that the hunting type is more satisfactory as the constant slight motion thereby imparted to the mercury ballistic control is beneficial to its operation.

Transmission system

The transmission system is the link between the master compass and the various repeaters, course recorders (and gyro pilot if fitted) operated from the master as illustrated in Fig. II. 10. It consists of a transmitter which is attached to the lubber ring of the master gyro compass, and which is connected electrically, through the control panel switches, to the step-by-step motors, mounted in each repeater compass casing and connected to the repeater compass cards. The transmitter consists of a series of electrical contacts, arranged about the circumference of a circle,

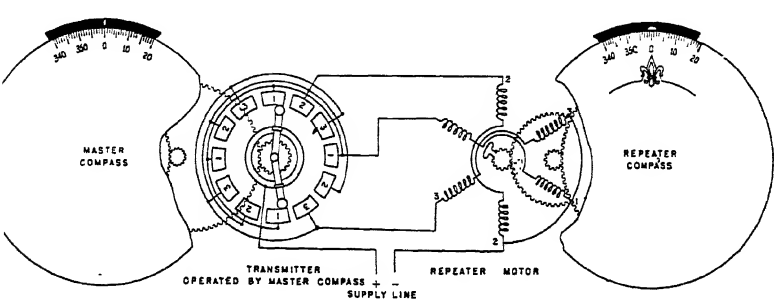


Fig. II.10. The Sperry Mark XIV gyro compass—schematic diagram showing the electrical step-by-step transmission system from master compass to repeater compasses.

with which contact is consecutively made by the transmitter roller carriage, or rotating arm, driven by gearing from the azimuth gear attached to the stem of the phantom element of the master compass below the compass card. In certain models of the Sperry gyro compass a feature of the follow-up system, keeping the phantom ring in alignment with the vertical ring, is a hunting movement of the master compass over an amplitude of about half a degree. As it is undesirable to transmit this hunting movement away to the repeaters, a lost motion device is introduced between the gearing and the transmitter roller carriage, which effectively eliminates hunting of the repeaters while the ship is steady on her course, and yet permits instantaneous transmission of any movement of the ship's head. It should be noted that by the attachment of the transmitter to the lubber ring, instead of to the spider element itself, the corrections which are automatically made for latitude, course and speed errors by movement of the lubber ring, are thereby also transmitted away to the entire repeater system.

The transmission system is operated by direct current at 70-volts, obtained from the generator for the gyro compass installation in the case of the ship's electrical supply being of 220-volt D.C. In the case of a ship having a supply of 110-volt D.C., the 70-volt D.C. supply for the transmission system is obtained by reduction of the mains voltage by means of a series resistance.

Control element

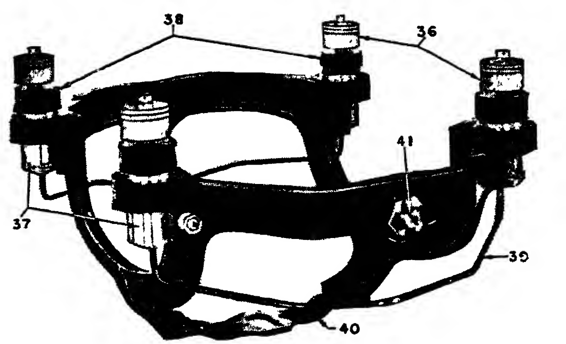


Fig.II.11. The Sperry Mark XIV gyro compass—control element or mercury ballistic.

36. Balancing weights
37. Mercury reservoirs
38. Mercury reservoir covers
39. Mercury tube
40. Link arm
41. Ballistic bearing stud

The mercury ballistic or control element (Fig. II. 11) is suspended on horizontal studs, termed ballistic bearing studs, fitted into ball bearings on each side of the phantom ring. A linking arm passes beneath the gyro rotor casing to which it is connected by a link bearing at the bottom of the rotor case which is offset approximately $\frac{1}{8}$ in. to the east of the vertical axis. This mercury ballistic is made non-pendulous as regards the horizontal axis, and the reservoirs are interconnected in pairs on east and west sides by small-bore tubes. Approximately eight ounces of mercury are contained in each pair of reservoirs and connecting tube. It will be appreciated that as the weight of the mercury ballistic is borne by the phantom element, the only effect of the ballistic upon the sensitive element is that transmitted through the link bearing at the bottom of the gyro rotor case. As this is offset slightly to the east of the vertical axis, the damping effect produced by a small couple about the vertical axis is introduced additional to the couple about the horizontal axis of the gyro when tilting of the axle occurs, relative to the plane of the earth's surface, as a result of the earth's rotation.

Speed and latitude corrector

The speed and latitude corrector mechanism (Fig. II. 12) is attached to he spider element at the rear, or after end, of the compass, and is connected to the lubber ring which is rotatably mounted on the rim of the spider frame. The corrections solved by the corrector mechanism, which are necessary to the indications of the compass as controlled by the sensitive element, are introduced by a slight rotation of the lubber ring in azimuth, so that the position of the lubber line, against which the ship's heading is read, is actually altered by the amount of the correction necessary. This correction could be set in to the compass

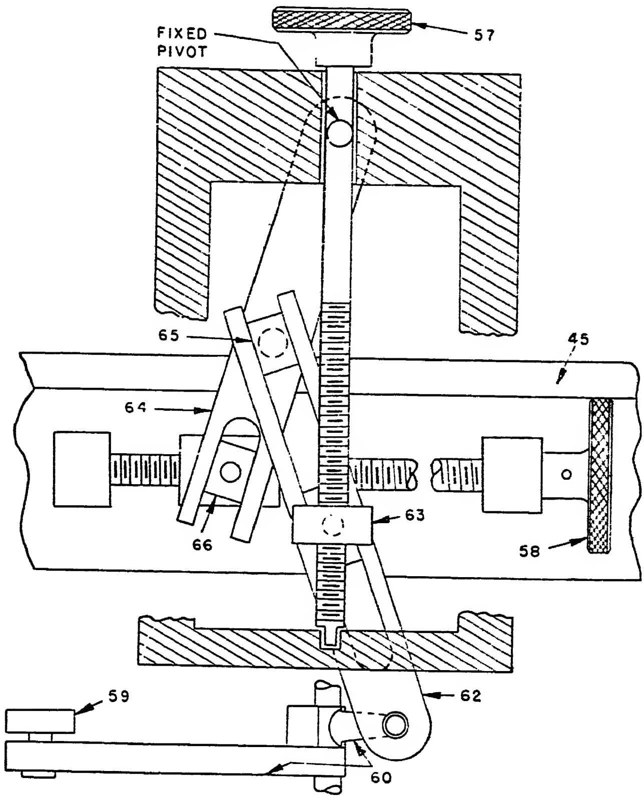


Fig. II.12. The Sperry gyro compass speed and latitude corrector mechanism.

45. Lubber ring
57. Speed & Latitude setting knob
58. Aux. latitude setting knob
59. Cosine cam roller
60. Cosine cam arm (bell crank)
62. Arm
63. Adjustable pivot
64. Arm
65. Fixed pivot
66. Adjustment block and pivot

indications periodically were it not for the fact that the correction varies, not only with latitude and speed, but also with the course which the ship is steering. It will be recalled that upon due east or due west courses there is no error and that upon due north or due south courses the error is at a maximum. The error varies as the cosine of the course and accordingly a groove termed a cosine groove is cut eccentrically into the underside of the azimuth gear of the phantom element. A crank arm fitted on a pivot extending from the corrector mechanism, follows the course of this ccsine groove as the ship's head moves in azimuth, and so a lateral movement of the arm is effected which is transmitted by means of the crank arm to another arm which is pivoted about an adjustable fulcrum. The position of this fulcrum is determined by the setting of latitude and speed, on the scale provided, by means of the setting knob. This motion is imparted to another arm having a fixed pivot at the upper end and, at the lower end, a fork working on an adjustment block and pivot which is attached to the lubber ring by means of the auxiliary or tangent latitude corrector fitting. Thus, through the train of levers, a proportion of the maximum error for latitude and speed of the ship, according to the course which the ship is steering, is applied to move the lubber ring so that the reading of the ship's head against the lubber line is correct, taking into account the error, due to latitude and speed, for the actual course which is being steered.

Auxiliary latitude corrector

The auxiliary or tangent latitude corrector, to which the motion originally imparted by the crank arm is finally passed through the system of adjustable levers, is necessary in the Sperry gyro compass because of the method of damping used, which is peculiar to this compass (and to the earlier model of the Anschütz compass which also used a couple around the vertical axis to produce damping of the oscillation about the meridian). With such a method of damping the compass settling point is slightly to the east of the true meridian in northern latitudes, and slightly to the west in southern latitudes. The error in the settling point is small and changes slowly with changes in latitude, so that attention to the setting of the auxiliary corrector is only required at intervals involving a change of latitude of approximately five degrees.

It should be noted that while this corrector is termed the auxiliary or tangent latitude corrector, it could more accurately be named damping error corrector, as the error for which it corrects is quite distinct from the error for which corrections are made by the latitude and speed corrector. Speed error is the result of the compounding of the movement of the ship with the movement of the earth's surface, creating a virtual meridian at right angles to the resultant movement of the compass in space, while damping error is due entirely to the method of damping the oscillations about the meridian. In the first case speed error is affected by latitude because the speed of the earth decreases with an increase of latitude, and thus the effect of the northerly or southerly component of the ship's course is greater in higher latitudes. In the second case auxiliary latitude error, or more correctly damping error, increases in higher latitudes by reason of the greater tilt of the gyro axle, relative to the plane of the earth's surface, which has to be reduced by the damping torque about the vertical axis.

Sperry gyro compasses in use on board ship to-day may be divided into two main classes, naval and commercial. While the commercial type has evolved through many modifications to what is now known as Mark XIV type, utilising a phosphor-bronze rotor spinning in a non-vacuum casing, the naval type, while embodying all later commercial modifications and many others peculiar to naval needs, is essentially based on an earlier model utilising a steel rotor spinning in a vacuum case.

Simplifications have been possible and necessary for commercial gyro compasses, used purely for navigational purposes in merchant ships, which are not desirable or necessary in men-of-war where constant skilled attention is more easily provided and the greatest possible accuracy is needed for gunnery control and other strictly naval purposes.

CHAPTER 3

THE BROWN GYRO COMPASS

The gyro compass manufactured by S. G. Brown & Company, of North Acton, London, is made in two types termed 'A' and 'B' respectively. Essentially, the master compasses are the same for both types, the difference being that type 'A' compass is provided with a repeater system, while type 'B' is a self-contained compass with no provision for repeaters. It is, however, fitted with a projector tube through which an enlarged image of the compass card in the region of the lubber line is thrown upon a mirror so that the helmsman can steer from the master gyro compass itself.

While the absence of a repeater system makes it impossible to use the type 'B' compass for purposes other than those of steering and checking magnetic compass readings, it has the great advantage of ease of installation and simplicity, and is particularly suitable for wheelhouse installation.

Comparison of Sperry and Brown gyro compasses

In the previous chapter the Sperry gyro compass was fully described, and before starting the description of the Brown gyro compass it will be interesting to note the essential points of difference between the two types of gyro compass.

Rotor. In the Brown compass a much smaller rotor is used than in the Sperry compass. To obtain accuracy the rotor speed has, therefore, of necessity, to be far greater. The rotor of the Brown compass weighs 4½ lb., and spins at approximately 14,000 r.p.m. as compared with the rotor of the Sperry compass which weighs 52 lbs., and spins at approximately 6,000 r.p.m. The controlling system of the Brown compass produces the effect of bottom heaviness of the gyro, so that the direction of rotation of the rotor is clockwise as viewed from the south end, while the Sperry gyro rotor is top heavy in effect and rotates in an anti-clockwise direction as viewed from the south end.

Suspension. While the critical matter of friction at the lower bearing is overcome in the Sperry compass by the suspension of the sensitive element within a shadowing or phantom element, the sensitive element of the Brown compass is supported on a pulsing column of oil produced by a pump driven by an electric motor at about 180 beats a minute.

As the result of the constant motion of the sensitive element stem, friction at the lower bearing of the Brown compass is reduced to a minimum and no phantom element is therefore necessary.

Control Element. Whereas the Sperry control element contains mercury which flows by gravity to the low side as the gyro axle tilts, the Brown control element utilises oil which is forced up to the control or 'working' bottle on the high side by pressure of air generated within the gyro casing by centrifugal action of the spinning rotor.

Damping. The oscillation of the Sperry compass about the meridian is damped by the offsetting of the ballistic link to produce a small torque about the vertical axis. The Brown compass is damped by the use of a torque about the horizontal axis opposing the controlling torque. This is effected by means of a second and smaller pair of interconnected oil bottles working in opposition to the oil bottles of the main control, but in which the movement of oil is made sluggish by the restriction of flow by a needle valve. No settling error results from the use of this system of damping.

Follow-up System. In the Brown compass the method of suspension is independent of the follow-up system. The follow-up system can, therefore, function without connection with the sensitive element and a failure of the system does not affect the operation of the master compass as is the case with the Sperry system.

General description

Sensitive Element. The rotor of the Brown compass is 72 ounces in weight, with a diameter of 4 in. and is mounted on a flexible shaft in ball bearings. The use of a flexible shaft obviates the need for accurate dynamic balancing of the rotor which must, however, be accurately balanced statically. Any slight out of balance effect when running above the critical speed is allowed for by the flexibility of the shaft. The rotor is spun at approximately 14,000 r.p.m. by an induction motor operating from 70-volts A.C. The direction of rotation is the same as the direction of rotation of the earth, i.e., clockwise as viewed from the south end.

The rotor is mounted in ball bearings in an aluminium casing with aluminium cover plates, one of which carries the stator winding. The squirrel-cage rotor of the induction motor forms part of the gyro wheel. A sighting window is provided on the south side of the rotor casing, for observing the direction of rotation of the rotor, and also the speed of rotation by means of a stroboscope. At the east and west sides of the rotor casing are knife edge horizontal pivots which rest in V blocks, or on flat hardened steel plates, providing tilting freedom in the vertical plane about the horizontal axis, within a vertical ring. Under each knife edge pivot are holes allowing the egress of air which is admitted through holes around the rotor bearing housings, and which passes through cooling vanes around these bearings. Under the east knife edge pivot a pick-up scoop is fitted inside the rotor casing to increase the pressure of air for purposes connected with the control system. The considerable centrifugal action on the air within the gyro casing, caused by the high rate of spin of the rotor, results in a pressure corresponding to a 3 in. head of water at the outlet. This air blast passes into a chamber

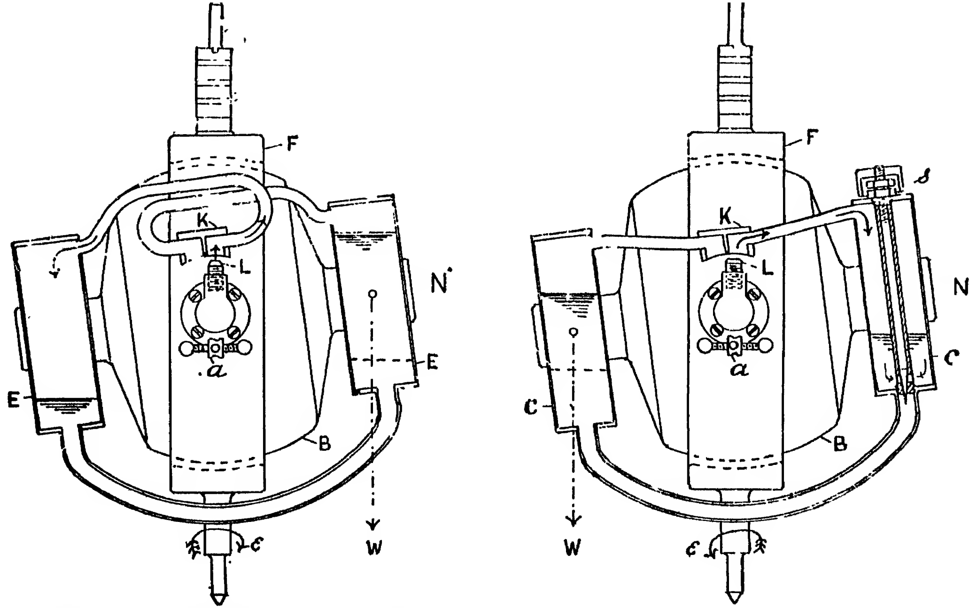


Fig. II.13. The Brown gyro compass—control and damping systems. The gyro casing is shown tilted. Air emerging under pressure from the air jet is passing through the air chest to blow on the surface of the oil in the lower bottle of the control system, and in the higher bottle of the damping system. The flow of oil in the damping system is restricted by a needle valve and the effect is in delayed opposition to that of the control system.

B Gyro casing
C Damping bottles
E Working bottles
F Vertical ring
K Air chest
L Air jet
a screw adjustment for Air jet
s Needle valve adjustment

fitted to the vertical ring, and passes out vertically upwards through a jet also located on the vertical ring.

Control System. This system is illustrated in Fig. II. 13. Two interconnected pairs of bottles half filled with oil are attached to the rotor casing, of which the larger pair, situated on the east side, are termed "working" bottles, and the smaller pair, on the west side, are termed "damping" bottles. Pipes connect the tops of all four of these bottles to an air chest which is attached to the rotor casing, and is positioned at the east side of the rotor casing immediately over the air jet, located on the vertical ring, which is normally vertical. A V-shaped block divides the entry of the air chest into two equal parts.

With the gyro axle horizontal the air pressure is divided by the V-shaped block in the air chest into equal parts, so that the pressure on the oil surface in all four bottles is the same. Any tilting of the gyro axle and air chest relative to the jet results in a greater pressure of air being directed to one side of the other of the V-shaped block, with corresponding increase of pressure on the oil surfaces in two bottles of the interconnected pairs, and a reduction of pressure in the other two bottles. The pipes connecting the working bottles to the air chest are crossed so that when the north end of the gyro axle tilts up, air blows on the surface of the oil in the south working bottle, and at the same time on to the surface of the oil in the north damping bottle. Similarly when the south end of the gyro axle tilts up, air blows on the surface of the oil in the north working bottle, and also in the south damping bottle. The result of the excess air pressure blowing into one bottle of either pair, is to raise the level of oil in the opposite bottles, thereby making the gyro heavier at the end having the excess of oil which introduces a torque about the horizontal axis resulting in precession in azimuth.

It has already been stated that the working bottles are larger than the damping bottles, and by cross connection of the air pipes leading from the air chest to the working bottles, the damping effect is in opposition to the main control though smaller in amount and slower in operation by reason of the needle valve restriction of the flow of oil between the damping bottles.

Undamped Oscillation about the Meridian. Let us assume that the needle valve in the north bottle of the damping system (Fig. II.14) is altogether closed, and that the gyro axle is horizontal and pointing east of north in north latitude. The gyro being in a state of balance will exhibit inertia and tend to remain with its axle pointing to a fixed point in space. As the earth rotates from west to east, the axle will acquire upward tilt of the north end at a rate which will be proportional to the amount of deflection east of the meridian, and also to the cosine of the latitude. The acquired tilt relative to the plane of the earth's surface will cause pressure to be applied by the air jet to the south working bottle, resulting in an immediate flow of oil which will make the gyro axle north heavy, i.e., heavy at the north end. Precession towards the meridian will begin, the rate of precession increasing as the tilt increases, but the rate of tilt decreasing as the gyro axle precesses towards the meridian. The gyro will arrive at the meridian with sufficient tilt to maintain precession to the westward until such time as it reaches a westerly deflection equal to the original easterly deflection when the axle will again be horizontal. The gyro axle now being west of the meridian continues to tilt downwards below the horizontal, and the direction of precession will be reversed by the flow of oil to the south working bottle under air pressure in the north bottle. This will cause the gyro axle to precess eastward, returning to its original deflection east of the meridian having maintained an undamped oscillation about the meridian both in azimuth and tilt.

Damping Arrangements. Let us now imagine that the needle valve in the damping bottle has been opened up slightly. As the gyro tilts relative to the plane of the earth's surface, air pressure on the surface of the oil in the north damping bottle will cause a slow flow of oil to the south damping bottle in opposition to the almost immediate flow of oil from the south working bottle to the north. The effect of this flow of damping oil, while negligible at first, is felt in a slowing-up in the rate of precession as the gyro axle crosses the meridian and travels west. The effect increases as the gyro approaches its maximum westerly deviation, which is reduced in extent. The super-elevation retained by the damping oil as the gyro reverses the direction of precession will now assist the action of the working bottles in bringing the axle back to the meridian more quickly. As a direct result the gyro axle will have less tilt on reaching the meridian, travelling eastward, so that the rate of precession is slowed down and the extent of easterly deviation diminished. Progressive damping out of the oscillation about the meridian is thus accomplished and the axle will finally settle on the meridian without error.

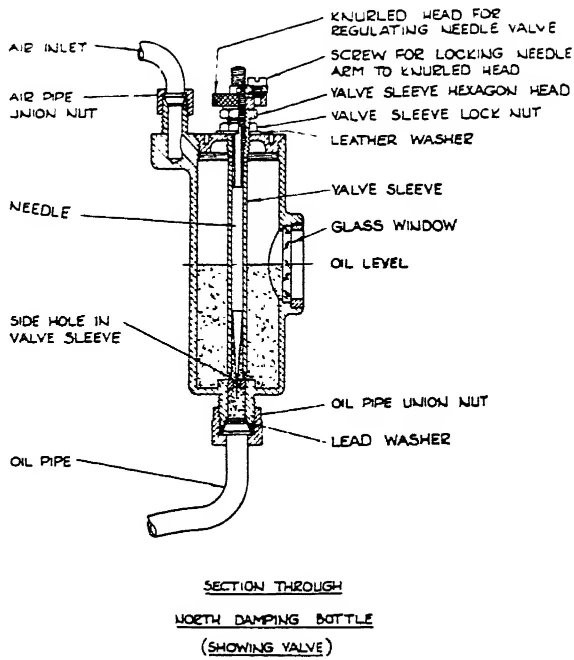


Fig. II.14. The Brown gyro compass—North damping bottle shown in section to illustrate component parts of needle valve for restricting flow of oil in damping system.

We have considered the damping of the oscillation as affected by opening the damping bottle needle valve slightly. If the needle valve be opened up fully, the restriction on the flow of damping oil is removed and the working of the damping system will, in the main, merely oppose the operation of the main control by the working bottles, thereby lengthening the period of the compass and producing little or no damping effect. The valve should, therefore, be opened only as much as is necessary to give the desired damping of approximately 67% at which the period of the compass is lengthened by only about 10 minutes over that of the undamped compass.

Turning Error. This method of damping out the oscillation of the gyro axle about the meridian, by the introduction of opposing but delayed precession in azimuth, does not involve any error in the settling point, and at the same time allows ballistic deflection when altering course. The Brown compass is, however, subject to a slight error and small wander after a turn which is referred to as turning error. The fact that the whole of the master compass swings outward when a large alteration of course is made, results in a false tilt of the air jet relative to the V-shaped block in the air chest. Excess pressure of air will, therefore, be blown on to the surface of oil in the working bottle on the inside of the turn. The direction of rotation of the gyro rotor in the Brown compass being the reverse of that of the Sperry compass, this will have a similar effect to the piling up of mercury in the outside pots of the Sperry ballistic, and will result in a torque precessing the compass towards the new settling point. Exact precession to the new settling point, however, occurs only in one latitude, so that in other latitudes a slight error will exist temporarily after every appreciable alteration of course, but this error will be damped out in the usual manner. At the same time when the compass swings out towards the outside of a turn, the damping bottles will also be affected. When the turn is completed, and the compass resumes the normal vertical position, while the oil in the working bottles will level out immediately, the oil in the damping bottle which was on the outside of the turn, will be higher than that in the bottle on the inside of the turn, and will not immediately level out because of the restriction of flow by the needle valve. A slight wander in the settling point will therefore be apparent until such time as the damping oil finally levels out.

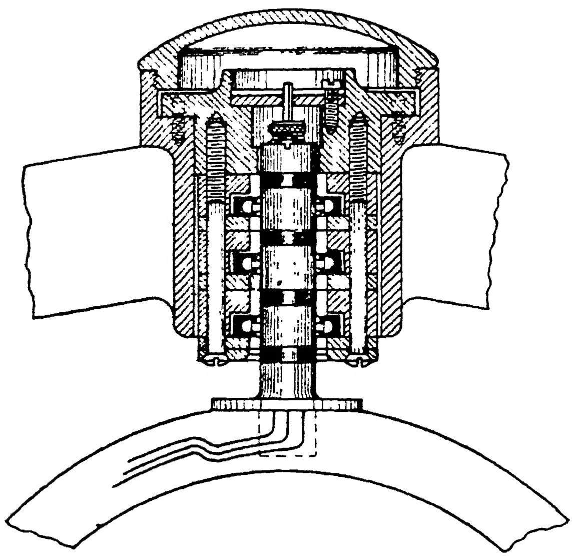


Fig. II.15. The Brown gyro compass—upper bearing of vertical ring. Section through top housing of vertical axis showing spindle, bearing and arrangement of mercury rings conveying current from fixed frame to moving sensitive element.

Gimballing, binnacle and anti-shock arrangements

The whole master compass, weighing about 27 lb., is carried in gimbals in a binnacle ring which is generally also in an anti-shock mounting, and is fitted with a bowl and cover. This arrangement permits freedom to the compass to remain vertically upright during the rolling and pitching motion of the ship, and also to move horizontally or vertically to take up shock transmitted from the hull. Oil dashpots are fitted about the gimballing axes to restrain the motion of the master compass in heavy weather.

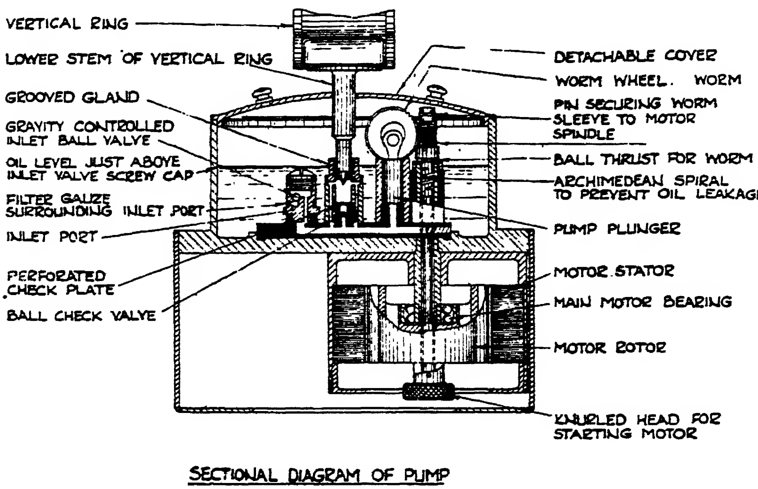


Fig. II.16. The Brown gyro compass—lower bearing of vertical ring. Section through pump chamber showing general arrangement.

Vertical Ring. The vertical ring in which the rotor case is supported on knife edges, and which carries the compass card, is made of aluminium. It is fitted at the east and west sides with phosphor-bronze bushes, which carry the supports for the knife edges. At the top of the vertical ring (Fig. II.15) is a spindle, of which the upper section, of small diameter, works in a plain bearing in the upper part of the top housing of the frame. The lower section of this spindle, of larger diameter, carries three insulated steel rings, against which mercury, carried in hollow rings in the lower part of the top housing, makes contact to convey current from the fixed frame to the moving sensitive element. At the bottom of the vertical ring (Fig. II.16) is the lower stem which fits into the pump chamber located at the base of the frame. This pump chamber contains a small pump driven by worm gearing from a 3-phase induction motor which maintains a pulsing column of oil, raising and lowering the sensitive element within its lower guide bearing approximately 180 times per minute. An ingenious arrangement of ball valve and ports in the pump cylinder allows for the efficient oil cushioning of the sensitive element at each suction stroke of the pump.

Follow-up System. The lubber ring is attached to the frame and is provided with means of adjustment of the lubber line position for correction of permanent error. Underneath the lubber ring is the follow-up ring, a large gearwheel having freedom to rotate, driven through gearing by the follow-up motor, of step-by-step type, fitted in a recess on the starboard side of the frame. The follow-up ring carries an "air vane" plugged into its lower side to which current is carried by three pairs of silver contact brushes pressing against three superimposed and insulated silver contact rings on the upper side of the follow-up ring. The air

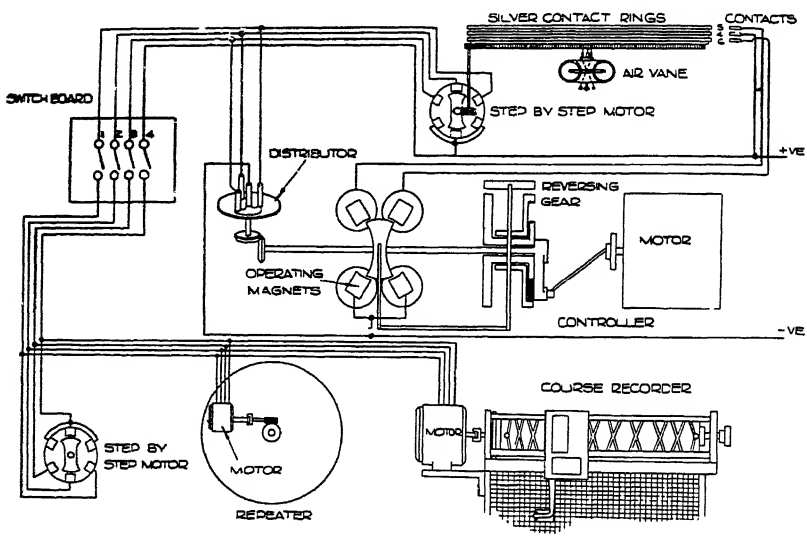


Fig. II.17. The Brown gyro compass. Type A—transmission system from master compass to repeater compasses and course recorder—showing electrical connections.

vane is fitted with a central contact, which makes contact with one or other of two adjustable contact screws between which it is located, and it is operated by air pressure issuing from the jet at the east side of the vertical ring. In the normal position with the ship steady on her course, the air vane "hunts" between the two contact screws, and the follow-up motor (which is geared to the follow-up ring and corresponds to the Sperry azimuth motor) is continually reversing the direction of its operation to keep the air vane centrally aligned with the air jet. As soon as the ship begins to alter course to port or starboard, the air jet is carried away from the air vane which is then held over to one contact or the other until the operation of the follow-up motor restores the alignment and the hunting is resumed.

Transmission System. Also operated by the air vane, in conjunction with the follow-up arrangements, is the transmission system (see Fig. II.17). This consists of an induction motor controller, fitted on the supply panel and running at a constant speed to drive a distributor (i.e., transmitter) through reversing gear. A spade armature is held to one or other of two pairs of permanently magnetised pole pieces, having secondary windings alternately energised by the completion of one or other of the air vane's circuits. Impulses from this controller are passed to the step-by-step repeater motors, and in similar manner to the compass follow-up motor which is also of step-by-step construction.

Valve Amplification. The strength of the air blast operating the air vane is comparatively small, so that the contact made with the adjustable contact screws is not very positive. In the past troubles have originated at this point, due to the vicious circle of sparking which resulted in dirty contacts, thus increasing the sparking. The introduction of a modified circuit, utilising a triode valve amplifier, with grid fed at negative potential, has very greatly reduced the current passing at the air vane contacts and, consequently also, the trouble formerly experienced.

Relay transmitters

Relay transmitters are used when it is required to operate a considerable number of repeaters, or repeaters of different voltages. The relay transmitter consists of a large repeater type motor driving one or two camshafts, each of which drives a cam type distributor to which the repeaters are connected on the output side. An adjustable lost motion device introduced between the driving motor and the camshaft eliminates the hunting feature at the repeaters.

Electrical supply arrangements

The ship's voltage is reduced by resistances to 52 volts at which the 50-volt battery, which forms part of the accessory equipment, is kept on "floating" charge while under load, and is also available as an alternative source of electrical supply in the event of a failure in the ship's main supply. This supply of 50-volts D.C. is used for the motor generator of permanent magnet induction type, which runs at a speed of 2,000 r.p.m. and provides 3-phase A.C. at 70-volts, 266-cycles for the operation of the induction motors of the gyro rotor, lower bearing pump and controller.

Latitude, course and speed correction

The errors to which all gyro compasses are subject as the result of the effect of the ship's speed and course, are not mechanically solved and automatically corrected in the Brown compass as is the case with the Sperry compass. Tables showing the error appropriate to the ship's course and speed in navigable latitudes are supplied with the equipment and are applied to the indications of the Brown compass as necessary. Automatic correction can be supplied if required but is not fitted with standard equipment.

The accuracy obtained in the Brown gyro compass with the use of such a small rotor, is in itself a tribute to the design and to the precision workmanship which the manufacturers have at their command. While the directive force is less than that of the Sperry and Anschütz compasses, it has the obvious advantages of simplicity of construction and ease of installation due to its compact design and light weight.

CHAPTER 4

THE ANSCHÜTZ GYRO COMPASS

It will have been apparent from the descriptions of the Sperry gyro compass and Brown gyro compass given in preceding chapters, that friction is the principal disturbing factor with which the designers and manufacturers of gyro compasses have to contend, and this specially applies to friction around the lower vertical axis of the gyro compass system. In the Sperry gyro compass this difficulty is overcome by suspending the sensitive element within the phantom element which is driven round in azimuth to maintain constant alignment. In the Brown gyro compass the sensitive element is supported upon a rapidly pulsing column of oil, reducing friction at the lower vertical bearing to a minimum. In the Anschütz gyro compass, with which this chapter deals, the difficulties connected with friction are overcome by the very novel method of total enclosure of the sensitive element within a complete sphere which is floated within a spherical container of slightly larger diameter. The space between the inner sphere and the outer sphere is entirely filled with an acidulated liquid which serves not only to float the inner sphere, but also as the means of conveying alternating current to the induction motors driving the gyros within the sphere, and, additionally, to the repulsion coil which centralises the sphere within the outer container both vertically and laterally. The centre of gravity of the inner sphere and its contents is located below the normal centre of the sphere, thus making the system pendulous and consequently north-seeking when the gyros are in operation.

Original single-gyro and three-gyro Anschütz compasses

In its original form, as first designed in 1908, the Anschütz compass made use of one gyro but for approximately 15 years from 1912 three separate and independent but similar gyroscopes were utilised, one of which was fixed with its axle parallel with the north/south indications of the compass card, while the two other gyroscopes had freedom in azimuth relative to the card indications, but were linked together so that their axles made equal angles with the meridian. They thus contributed partly to the north-seeking function of the sensitive element and partly to the stabilisation of the gyroscopic system. The three gyros were suspended from a frame carrying the compass card, and this was supported by a hollow sphere made of steel which floated in a container of mercury. By this arrangement freedom within limits corresponding to the movement of the vessel during rolling, pitching and alteration of course, was provided. The system was made pendulous by lowering the centre of gravity of the gyro system to a point below the centre of buoyancy of the steel spherical float, and the three gyros were accordingly spun in the same direction as the rotation of the earth, i.e., clockwise as viewed from the south end. Damping of the oscillation of the gyro axle about the meridian was provided by means of a viscous fluid utilising a pair of vessels interconnected by a small bore pipe, the whole system being attached rigidly to the gyro casing so that super-elevation was acquired with tilting of the gyro axle. The system was partially filled

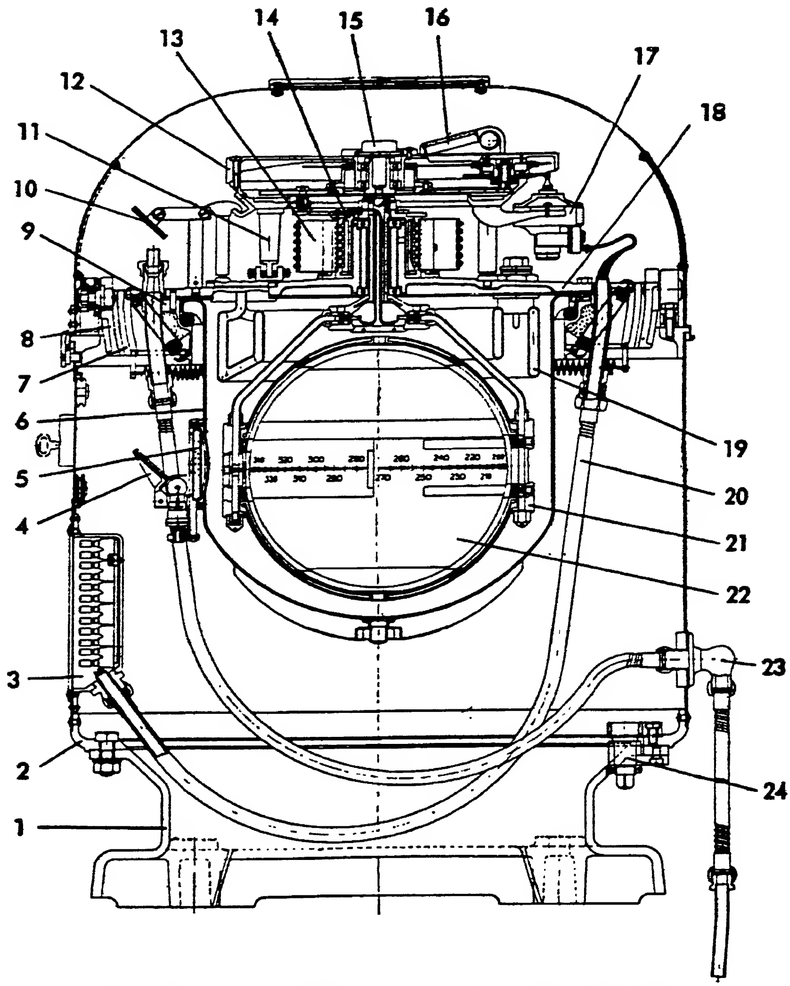


Fig. II.18. The Anschütz gyro compass—sectional diagram.

1. Binnacle bottom
2. Binnacle top
3. Terminal box for ship's connection
4. Reading mirror with bulb, lower
5. Window of liquid container with lubber-line
6. Liquid container
7. Inner gimbal ring
8. Outer gimbal ring
9. Supporting ring with suspension springs
10. Reading mirror, upper
11. Supporting column (3)
12. Gear box with compass cards
13. Brush-rocker
14. Slip ring carrier with clutch
15. Level
16. Lubber line with bulb
17. Follow-up motor
18. Baseplate
19. Ring-cooler
20. Flexible cable
21. Outer sphere (follow-up system)
22. Gyrosphere (sensitive element)
23. Cooling water connection
24. Azimuth adjustment

with oil of high viscosity, which required a period of time to level out after disturbance of the relative elevation of the respective vessels. The operation of the damping system will be described in greater detail later in this chapter.

The two-gyro Anschütz compass

By 1927 the Anschütz compass was completely re-designed and, as manufactured since that date, only two gyros are now employed instead of three, the original gyro which had its axle parallel with the north-south line of the compass card being entirely eliminated and the two other gyros, which contribute both to the meridian seeking and stabilising qualities of the gyro system, being retained. The axles of these two gyros are set at an angle of 45° to the north/south line of the compass card, and while provided with freedom to rotate about a vertical axis, the casings are linked together so that their spinning axles make equal angles with the meridian. These two gyros are rotated, in similar manner to that of the Sperry compass, by A.C. induction motors utilising 120-volt, 3-phase, 330-cycle alternating current providing a speed of about 20,000 r.p.m. The weight of each rotor is approximately 77½ ounces.

Binnacle and gimballing arrangements

The master gyro compass consists essentially of a binnacle, of which the upper portion pivots on the bottom portion with provision for adjustment of orientation relative to the ship's fore and aft line. The compass itself is suspended on springs within a gimbal system, the outer liquid container being of metal, lined with vulcanised hard rubber for protection against corrosion. A window is provided in the outer container for inspection of the contained inner sphere, and also for reading the equatorial markings when required. The liquid container is provided with a top cover which forms the base plate carrying the gearbox, follow-up motor, compass card mechanism, and a thermostat for the regulation of temperature of the contained liquid.

Gyrosphere and outer sphere

The inner sphere, or gyrosphere, contains the sensitive element including the two gyros mounted in the gyro frame, and also the annular damping device and internal repulsion or centralising coil. The gyrosphere is approximately 10 in. in diameter, and is made of vulcanite in two sections which, when joined and sealed, are filled with hydrogen gas.

It will be obvious that the ensuring of correctness of balance and the checking are of the greatest importance before sealing of the gyrosphere takes place. After sealing, the gyrosphere is checked to make sure that its equator line, which is graduated from 0 to 360°, is exactly horizontal when floating. The hermetically sealed ball is then placed inside the outer sphere, which has an internal diameter of approximately 10½ in., and the space between the gyrosphere outer sphere and container is filled with the supporting liquid. This liquid is composed of distilled water and glycerine in the proportion of 13.5 to 1 with the addition of a small quantity of salicylic acid and registers a specific gravity of 1.020 at a temperature of 68° Fahrenheit. At this density the gyrosphere is slightly too heavy to float centrally within the outer sphere, and it will in fact sink gently on to the bottom. However, inside, at the bottom of the gyrosphere when floating, is a built-in repulsion coil whose function it is to maintain the gyrosphere centrally relative to the outer sphere. This repulsion coil consists of horizontal windings which are fed by one phase of the alternating current used for spinning the gyro rotors. The alternating magnetic field thus created produces another alternating current

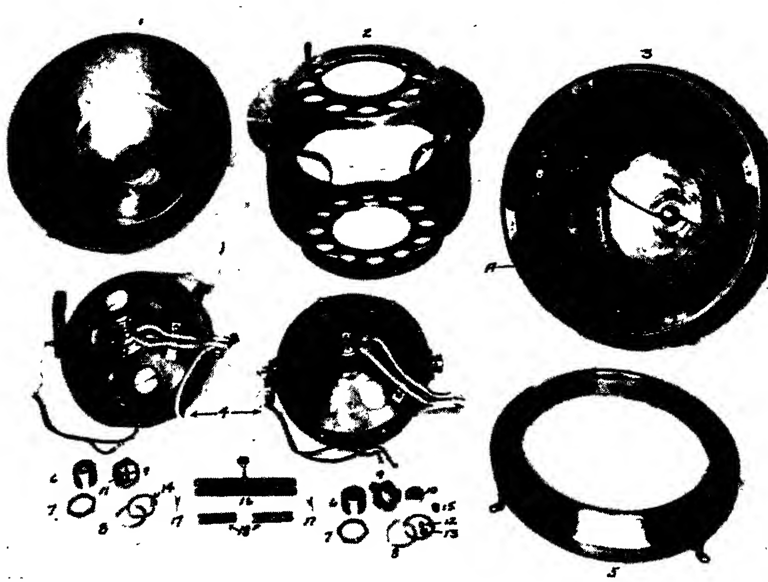


Fig. II.19. The Anschütz gyro compass—sensitive element component parts.

1. Upper half of gyrosphere
2. Frame for gyros
3. Lower half of gyrosphere with repulsion coil "A"
4. Gyro rotors I and II
5. Damping device
6. Upper guide bearing adjustment housing
7. Upper guide housing locknut
8. Locking washer (brass) for upper and lower lock
9. Lower guide bearing adjusting housing with locknut
10. Vertical guide bearing
11. Lower vertical guide ball plate (small)
12. Lower vertical guide ball (large)
13. Lower vertical guide ball plate (large)
14. Lower vertical guide ball (small)
15. Lower vertical guide tip
16. Connecting arm
17. Connecting arm screws
18. Centralizing springs

in the aluminium core of the lower half of the outer container which is in opposition to the primary current. The gyrosphere is therefore repelled and supported within the fluid content of the outer sphere, and the lateral arrangement of the repulsion coil also provides a centering component so that the position of the gyrosphere within the outer sphere is correctly central. In effect the repulsion coil may be considered the primary coil of a monophase transformer, of which the aluminium core of the lower half of the outer sphere represents the short-circuited secondary winding.

Gyro-drive system

The method by which current is passed through the supporting liquid to operate the gyros and repulsion coil within the gyrosphere is especially interesting. From the binnacle terminal block contactors lead through brushes and slip rings at the neck of the outer sphere to contact faces at the poles of the upper and lower hemispheres of the outer sphere, and also to equatorial rings. The inner gyrosphere is similarly fitted with polar contact faces and equatorial rings which are let in to the vulcanite surface of the sphere to avoid projection which would create eddies in the supporting fluid. The acid content of the fluid is such that conductivity ensures the flow of the three separate phases of alternating

Fig. II.20. The Anschütz gyro compass—gyro elements in frame before insertion in gyrosphere.

current from the electrodes of the poles and equator of the outer sphere to the corresponding electrodes at the poles and equator of the gyrosphere. While it is true that the enveloping medium of the supporting fluid does, to some extent, short circuit the currents passing from the outer sphere to the gyrosphere, the amount of short circuiting is so small by comparison with the amount of current passing directly between the electrodes as to be negligible.

Cooling system

The purpose of the addition of glycerine to the distilled water of the supporting fluid is to prevent the freezing of the fluid at low atmospheric temperatures when the compass is not operating. When functioning, however, the electrical energy fed into the gyrosphere leads to a rise of temperature of the fluid. The normal operating temperature of the fluid is approximately 104° Fahrenheit (40°C). Should the temperature rise above 108° Fahrenheit (42°C), a thermostat control operates to produce a flow of cooling water through a tubular cooling system fitted at the top of the liquid container on the underside of the baseplate cover. Any excessive rise of temperature due to failure of the cooling system automatically lights a red lamp on the control panel and sounds a buzzer alarm.

Transmission system

The transmission from the gyrosphere containing the sensitive element to the repeater compass system, is based on the Wheatstone Bridge principle. When the ship is steady on her course, two carbon contacts at opposite ends of a diameter of the outer container are immediately opposite the edges of a semicircular carbon strip at the equator of the gyrosphere. In circuit with solid resistances, the two fluid resistances formed between the contacts and the semicircular strip are equal and no current flows. As the ship alters course the master compass, including the outer container and carbon contacts, moves round in azimuth relative to the gyroscope which remains in the true meridian. The fluid resistance is therefore modified and the generated current is passed to the grid of a thermionic valve and thereby amplified to control an A.C. reversing follow-up motor. This follow-up motor drives round the container in azimuth until alignment of the carbon contacts of the container, and of the ends of the semicircular equatorial strip of the gyrosphere, is again restored. Simultaneously, the follow-up motor, by means of gearing, drives an A.C. transmitter controlling the operation of A.C. motors to rotate the cards of the repeater compasses to the same heading as the master compass.

Fig. II.21. The Anschütz gyro compass—gyrosphere after closing and sealing before insertion in liquid container.

Damping arrangements

The damping device which operates on the Schuler method of damping by means of a surging viscous fluid, consists of an annular vessel, sub-divided into eight equal compartments by partition walls. These compartments communicate by small bore pipes which are further restricted by wires passing through the four compartments on the east and west sides respectively. The damping reservoir contains a special oil of high viscosity, which can only flow very slowly from the north to the south compartments, or in the reverse direction, as the gyro system tilts. The sensitive element contained in the gyrosphere is made north-seeking by the pendulous moment which is provided by the lowering of the centre of gravity below the geometrical centre of the sphere. Without the damping device, therefore, the gyrosphere will be meridian seeking, but will oscillate about the meridian in a manner similar to that of the undamped Sperry compass. Whereas, however, the oscillations of the Sperry compass are damped by a small torque about the vertical axis, progressively reducing the angle of tilt of the gyro axle relative to the plane of the earth's surface, the Anschütz device damps out the oscillation by a small torque about the horizontal axis which is in delayed opposition to the controlling torque provided by the pendulous nature of the gyrosphere. For the purpose of the following explanation of the operation of the damping device of the Anschütz compass, the north-seeking components of the two gyros which are contained within the gyrosphere, and are axially inclined to the meridian, will be regarded in effect as that of one gyro having its axle parallel to the north/south line of the compass card.

Damping of oscillation about the meridian

If the Anschütz compass be started with its gyro axle horizontal and east of the meridian in north latitude, the inertia of the gyro in its balanced state (with the damping fluid level in the annular compartments) will cause the sphere to be stabilised with its north/south axis fixed relative to a fixed point in space. The rotation of the earth from west to east will cause an apparent rise of the north end of the gyro axle, relative to the plane of the earth's surface at a rate which will be proportional to the extent of the easterly deflection and to the cosine of the latitude (see p. 90). The pendulous nature of the gyrosphere will immediately provide

Fig. II.22. The Anschütz gyro compass—the liquid container.

a couple to cause precession to the westward towards the meridian at a rate which will increase as the angle of tilt increases. The rate of tilt of the axle will, however, decrease as the axle approaches the meridian. At the same time oil in the annular damping device will have begun to move slowly from the north compartments to the south. The effect of this, while negligible at first, will slowly take effect in opposition to the controlling torque reducing the rate of precession as the axle passes the meridian. After passing the meridian the gyro axle will still be precessing westward, but the controlling torque will begin to decrease while the opposing torque produced by the flow of oil in the damping ring will continue to increase, thus further slowing up the rate of precession and reducing the extent of the westward excursion. At the maximum westerly deflection the gyro axle will be level and the continued rotation of the earth from west to east will cause the north end of the gyro axle apparently to tilt down relative to the plane of the earth's surface. The pendulous couple will now be reversed, and will cause precession back to the meridian at an increasing rate which will be further increased by the effect of the accumulation of oil in the south compartments of the damping ring. As a direct result the axle will have less tilt on reaching the meridian, travelling to the eastward, so that the rate of precession will be slowed down and the extent of the excursion to the eastward will be diminished. Instead, therefore, of describing an elliptical path in oscillation about the meridian, as it would if not fitted with the damping device, the gyro axle will describe a spiral due to the progressive damping out of the oscillation and will finally settle out steadily on the meridian without error.

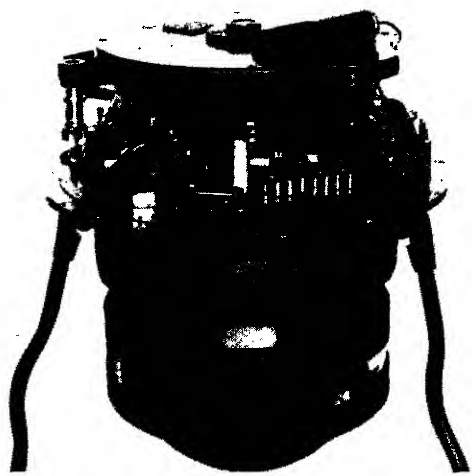


Fig. II.23. The Anschütz gyro compass—view of baseplate cover, ring cooler and follow-up element.

A point which is worth noting in a comparison of the Sperry and Anschütz compasses is that, with the Anschütz system of totally enclosed gyrosphere, the compass must be allowed time to damp out whatever error there may be in the direction of the gyro axle relative to the meridian at the time of starting, as it is not possible to orientate the gyrosphere to the approximate meridian before starting the gyros. A period of at least four hours must therefore be allowed to elapse between starting the gyros and the correct functioning of the equipment providing ability to read off correct indications relative to true north. With the Sperry compass, however, providing the approximate heading of the vessel is known at the time of starting the gyro, the sensitive element may easily be moved around in azimuth by hand until the gyro axle is approximately in the true meridian. The Sperry compass will, therefore, function correctly as soon as the gyro is run up to its normal speed, and the time which must elapse between starting the gyros and correct functioning is reduced from a minimum of four hours to approximately 20 minutes, any small error in the setting of the gyro axle in the true meridian before starting being speedily damped out.

Ballistic deflection

In order to have the correct ballistic deflection for changes of course which involve changes in the course and speed error, a constant proportion must be maintained between the secant of the latitude, the ratio of angular momentum of the gyro rotor and the pendulous moment. In the Anschütz compass the angular momentum of the gyro rotor is varied according to the latitude by regulating the speed of the motor generator which supplies 3-phase alternating current to the gyro rotors. This varies the speed and angular momentum of the gyro rotor to provide the proper ballistic deflection for the particular latitude. While this reduces the rotor speed and consequently the directive force in higher latitudes where the earth's speed and turntable movement is also less, the peculiar method of mounting the sensitive element in the Anschütz compass overcomes frictional effects so completely as to make the effect negligible within navigable latitudes.

The Anschütz compass, manufactured by the firm of Anschütz and Company at Kiel, Germany, was formerly distributed by the Nederlandsche Technische Handel Maatschappij "Giro" of Gravenhage, Holland. The original three-gyro Anschütz compass was patented in Great Britain in 1911, Patent No. 10440, while the new Anschütz compass as described in this chapter, utilising two gyros contained in a gyrosphere, was the subject of Patent No. 193397 of 1922 in Great Britain. Reference to Patent No. 187985 of 1921, in the name of Dr. Charles G. Abbott, of the Smithsonian Institute, Washington, should also be made by students of the gyro compass desiring more detailed information regarding multiple-gyro systems.

CHAPTER 5

THE MARINE GYRO PILOT

There is an old saying among seamen that "the lazy helmsman is the best," implying that the man who steers with the least possible use of the wheel makes a much better course than the man who makes a hard job of steering a ship and uses too much corrective rudder. Ships are designed to steer well but various factors affect their natural steering qualities and it is rarely that any ship will remain steady on her course for long with the rudder amidships. The ship may be well loaded, in good steering trim and steaming in a smooth sea with no wind or swell yet, for no apparent reason, she will begin to swing off her course. If no corrective rudder is applied the rate of the swing, slow at first, will increase quickly until a relatively large corrective rudder angle must be applied to check the swing and return the ship to her original course.

The "lazy helmsman" is the man who quickly senses the initial movement of the vessel away from her course, and by the application of a very small amount of corrective rudder checks the 'off-course' movement before it has a chance to achieve visible proportions.

Effect of wind and weather

It frequently happens that, due to relative directions of wind, sea or swell, or a combination of these factors, the ship will exhibit a tendency to turn off-course constantly in the same direction, either to port or to starboard. Here again the 'lazy helmsman,' instead of waiting for the recurring necessity to apply corrective rudder will, by a series of experiments, ascertain the comparatively small angle of rudder which the vessel will 'carry,' and by keeping that amount of rudder applied, instead of returning his wheel to the amidship position after each correction of off-course movement, he will steer as steady a course as he could with no disturbing factors of weather or sea. As an example we can take the case of a ship steaming north with a strong breeze from the north-east. A ship naturally turns into the wind, in this case to starboard, by reason of the fact that the greater part of her superstructure is aft of the mid-point of her length. If steady on her course the effect of the wind on her superstructure will soon cause her to turn to starboard and by the time the helmsman has noticed the movement and has applied corrective port rudder, as much as 10° of rudder or even more may be necessary to check the swing to starboard and bring the ship back to her course. If now he returns his wheel to amidships a repetition of the swing to starboard will occur within a very short period of time and a comparatively large angle of corrective rudder will again be required. If, however, when the corrective rudder has brought the ship back to her course he 'eases' his wheel, leaving two or three degrees of port rudder still applied, the ship will remain steady on her course, a balance having been struck between the tendency to turn to starboard, as the result of the wind on that bow, and the corrective action of the small angle of port rudder applied. If the balance is not quite correct the tendency to turn to starboard, if insufficient port rudder has been applied, or to port, if too much has been applied, will be much slower than if the rudder had been returned to the amidship position and so a better course will be steered.

Steering by magnetic and gyro compasses

By day, with an occasional glance at his magnetic steering compass, and by constantly watching the movement of the actual ship's head against the horizon or low cloud form, a good helmsman can generally steer a fairly accurate course, but by night, when he is dependent upon his magnetic compass alone, it is a different matter. The magnetic compass, by reason of its small directive force, is sluggish and the compass card tends to follow the initial movement of the ship away from her course so that the helmsman may have no indication that an off-course swing has begun until the ship is actually one or two degrees, or even more, off her course and a substantial swing to port or starboard has started. With a gyro compass the position is very much better as there is no lag in the indication of movement of the ship's head. The gyro compass has a directive force many times that of a magnetic compass—

in the case of the Sperry compass it is as much as 150 times greater—and the repeater compasses indicate movement of the ship's head in steps of $\frac{1}{6}$ of a degree. Even the best of human helmsmen, however, cannot concentrate for long on such a monotonous job as the steering of a ship without losing his precision of judgment—or as the seaman puts it, 'counting up his pay-off'—with the result that the steering becomes erratic, extra distance is steamed and the steering engine is constantly working to correct unnecessary deviations from the course.

Economy of labour and fuel by gyro-pilot

The gyro pilot, which operates in conjunction with the gyro compass system, is designed to do all that the best human helmsman can do in steering a ship and to do it hour in, hour out, without wearying and with the smallest possible use of the rudder and consequently of the steering engine. Besides effecting an economy of fuel per mile made good, by steering a straighter course, the gyro pilot also releases men for useful work about the ship who would otherwise be occupied by steering duties. This is particularly desirable in merchant ships in which the number of crew is limited.

Similarity in principle of single unit and two unit gyro pilots

In its original form the Sperry gyro pilot consisted of a single unit containing a drive motor which was connected by chain and sprockets to the shaft of the existing steering wheel in the wheel house. Clutch arrangements provided for the disconnection and connection of the gyropilot to the normal steering system, and automatic steering was effected by the gyro pilot drive motor turning the steering wheel in a manner exactly similar to that of a human helmsman. Later improved models of the Sperry marine gyro pilot are termed 'two-unit' for the reason that the system includes a bridge control unit installed in the wheel house, and also a power unit, containing the drive-motor, which is installed in the steering engine compartment where it is connected through an electro-magnetic clutch to the control of the steering engine. The two units are connected electrically so that the complete system provides an independent electric steering control from the navigating bridge which is separate from, and independent of, the normal electric, hydraulic telemotor, or rod and gearing, steering control system.

Fundamentally, the single and two-unit Sperry marine gyro pilots are the same in principle so that, in describing technically the later type of two-unit gyro pilot system, the principle and operation of both types should be apparent.

Bridge control unit

This unit is mounted on the navigating bridge in the wheel house, and contains the apparatus for controlling the rudder either by means of the light steering wheel with which it is provided or automatically from the master gyro compass. The stand is provided with a control lever at the left side having three positions marked "Off," "Hand," and "Gyro." When this lever is moved from the "Off" to the "Hand" position a control switch within the stand is closed and power is switched on to energise an electro-magnetic clutch incorporated in the power unit situated aft in the steering engine compartment. This connects the drive motor in the power unit mechanically to the gears and rack operating the control of the steering engine of whatever type, whether electric, electro-hydraulic or steam reciprocating, which may be installed. Any movement of the steering wheel on the gyro pilot bridge control unit results in proportionate operation of the drive motor in the power unit which, by means of the electro-magnetic clutch, and gearing, moves the steering engine control to angle the rudder. It is in effect an electric telemotor control which is immediate in effect and effortless in operation.

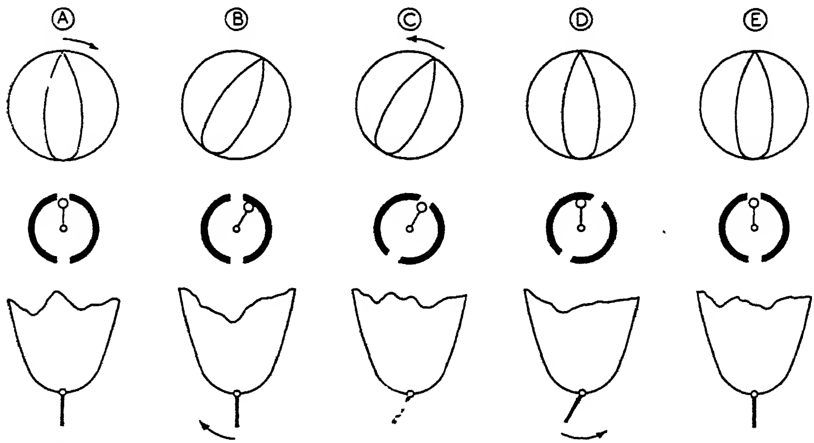


Fig. II.24. The Sperry gyro pilot—successive movement of ship's head, roller contact arm, rudder and contactor ring in automatic steering.

Movement of the control lever at the side of the gyro pilot bridge control unit from the "Hand" to the "Gyro" position performs two further functions. The electro-magnetic clutch in the power unit remains energised while a locking pin is withdrawn to free the armature of a step-by-step motor in the bridge control unit, which is connected electrically to the transmission system of the master gyro compass. At the same time two 'lost motion' devices respectively termed "weather adjustment" and "rudder adjustment" are allowed to become operative.

Principle of automatic steering

In Fig. II. 24 the principle of automatic steering is illustrated. At (A) the ship is steady on her course with the rudder amidships. The roller contact arm actuated by the step-by-step motor in the bridge control unit, shown centrally, is located on the neutral 'island' between the two halves of a contactor ring which is rotated by repeat-back action from the rudder. At (B) the ship has swung to starboard of her course and the roller contact arm, following the movement of the ship's head by means of the step-by-step motor operated from the master gyro compass, has moved over on to the right hand, or starboard, segment of the contactor ring. This completes an electrical circuit which, through electro-magnetic relays, starts the drive motor in the power unit. The drive motor, through the electro-magnetic clutch and gearing, operates the control of the steering engine to apply port rudder. As the rudder moves in response to the action of the power unit the repeat-back system, by electric transmission, rotates the contactor ring in the gyro pilot bridge control unit until the neutral island aligns itself with the position of the roller contact arm, as at (C), when all movement ceases with the necessary corrective rudder applied to return the ship to her course. As the ship responds to the applied rudder so the roller contact arm, following the movement of the ship's head as transmitted from the master gyro compass, moves back off the neutral section on the left hand or port segment of the contactor ring as at (D). The circuit to the drive motor in the power unit is again completed but this time to control the movement of rudder to starboard, i.e., back to the amidships position. The applied rudder angle is thereby progressively reduced until the ship returns to the original course as at (E) with the rudder amidships, while any overswing to port of the course will be met by the application of a 'meeting' rudder movement to starboard.

It has already been stated that the transmission system of the master gyro compass operates in steps of one-sixth of a degree, i.e., the step-by-step motor in the repeater compass, course recorder, and also gyro pilot make six separate and distinct movements for every one degree movement of the ship's head. So sensitive is the gyro pilot in operation for automatic steering that, under ideal conditions of weather, wind and sea the ship has only to deviate one-third of a degree from her course when (at the second movement of the step-by-step motor) a very small movement of the rudder takes place and the initial tendency of the vessel to deviate from her set course is checked and corrected before it can assume any appreciable proportions. If the initial movement of the ship's head is not immediately checked and corrected, as the result of insufficient corrective rudder being applied at this first stage, then the angle of corrective rudder will be increased progressively with each further movement of the step-by-step motor, and the contactor arm roller to which it is geared through the differential, until the off course movement is definitely checked or corrected.

Alteration of course or ship's heading.

As the light steering wheel with which the gyro pilot control unit stand is provided is also geared to the roller contact arm, through the differential, alterations of course or of the ship's heading may be made during automatic steering by movement of the gyro pilot wheel. The wheel is provided with six spokes and the gearing is so arranged that the rotation of the wheel by one spoke, or one-sixth of a revolution, will alter the course, or ship's heading, by half a degree either to port or starboard according to the direction of rotation. At the end of a day's steaming, if, for example, the course to steer is found by observations to differ by three and a half degrees from the course previously being steered, it is only necessary to rotate the gyro pilot steering wheel seven spokes, or one and one-sixth revolutions, when the new course will be steered automatically. This is also useful when, by reason of weather and sea, the ship is 'carrying' rudder. Supposing the weather conditions to be such that the vessel steadies on her course with a small amount of port rudder permanently applied, it will be found, as will be apparent, from the foregoing explanation of automatic steering, that the ship is steering a course which is very slightly 'high' or to starboard of the set course. To correct this it is only necessary to ascertain from the repeaters or course recorder the amount by which the set course is being exceeded, when appropriate movement of the gyro pilot steering wheel (one spoke to each half-degree) will make the necessary correction.

For larger alterations of course, such as may be necessitated in taking avoiding action for other vessels crossing or steering courses which involve risk of collision, it is recommended that the gyro pilot control lever be moved from the "Gyro" to the "Hand" position and the alteration of course be made by normal manual movement of the gyro pilot wheel. Reversion to automatic steering, when it is possible to resume the original course, is effected, when the ship is again steady on her course, by moving the control lever from "Hand" to "Gyro."

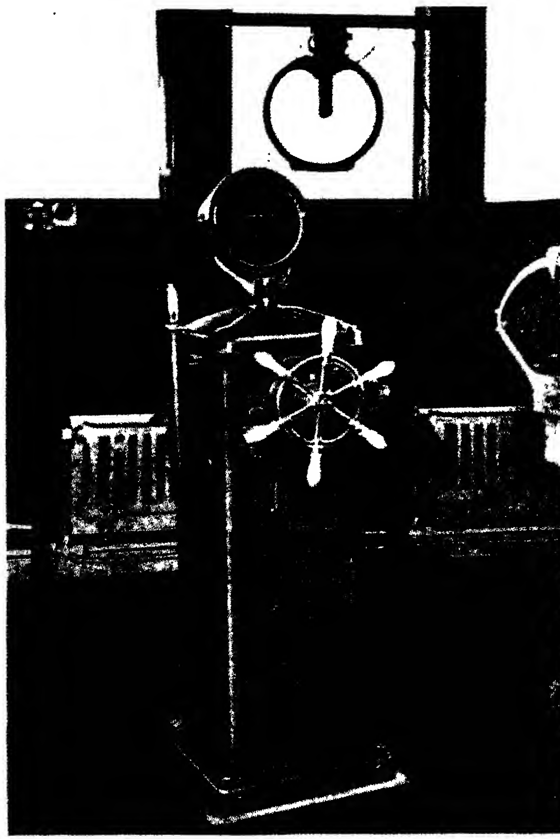


Fig. II. 25. The Sperry gyro pilot—view of bridge control unit.

Weather adjustment

While in perfect, or even good weather, conditions it is desirable that corrective rudder shall be applied as soon as the vessel begins to deviate slightly to port or starboard of her course, there are times when it is not desirable and when it leads to purposeless use of the rudder and steering engine. A good example of this is when a vessel is steaming along with a sea and swell on her quarter. As the stern lifts to the swell the bow will yaw in the opposite direction then steady as the wave form passes under the keel and yaw to the other side as the swell passes under the lee bow. A natural movement of the ship in the seaway results which makes the ship's head deviate from one side of her course to the other without any real off-course movement taking place. This can be allowed for by means of the weather adjustment which introduces variable lost motion between the differential gear and the roller contact arm. According to the setting of this adjustment the ship is permitted to yaw a definite amount either side of her course without any corrective rudder being applied, but so soon as the set amount is exceeded on either side then the normal automatic steering reaction comes into effect.

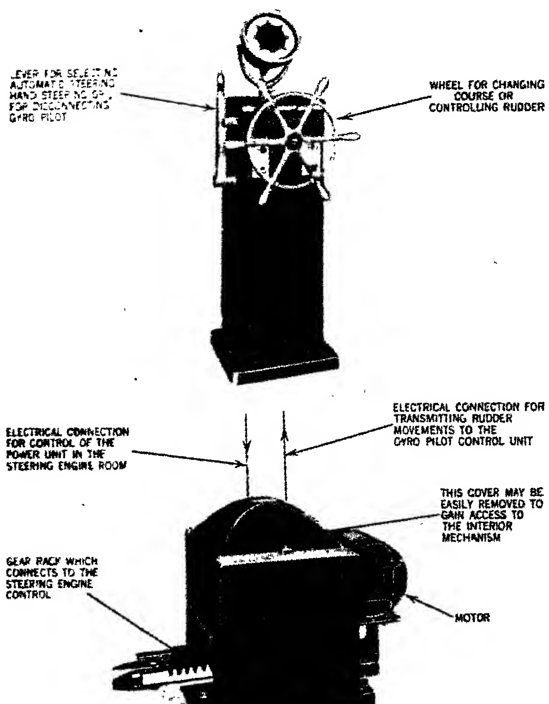


Fig. II.26. The Sperry gyro pilot—showing connections between control unit on navigating bridge and power unit in steering engine room.

Initial Rudder Adjustment

Conditions of loading and trim affect the steering qualities of every ship and vary during the course of a round voyage. A ship outward bound from the British Isles to a far distant port of discharge may start the voyage deeply loaded and in excellent steering trim when rudder movement is fully effective and only small angles of rudder will be required to correct relatively large deviations from her course. On a long voyage, however, large quantities of fuel and water will be uesd, which coupled with the possible discharge of con - signments of cargo for way ports, may alter her draft and trim so considerably that the ratio of applied rudder for off-course movement may require to be very different in the later stages of the voyage from that which was adequate at the beginning. Here again the gyro pilot can be adjusted to suit the changing conditions by means of the initial rudder adjustment which introduces lost motion between the repeat back from the rudder head and the contact rings in the gyro pilot control unit. This lost motion not only varies the amount of rudder angle applied at the initial movement to check an off course deviation, but also provides a means of 'meeting' the ship as she returns to her course after the deviation has been checked. By allowing the steering engine to over-run slightly when returning the rudder amidships, after the application of corrective rudder has been effective, a small angle of 'meeting' rudder will be applied to check the return to course in exactly the same manner as a human helmsman would apply it to steady the ship back on her original course.

The ratio of rudder angle to off-course movement also varies considerably in different classes of ships, but this does not mean that the gyro pilot has to be manufactured individually to suit each vessel in which it is installed. The ratio of movement between the rudder and the contact rings in the gyro pilot bridge control unit can be adjusted at installation or during ship trials to suit the particular characteristics of the vessel.

Self-synchronous feature

In the latest type of the Sperry (two-unit) gyro pilot a great advance on former models has been made by the introduction of self-synchronism between the gyro pilot and the ship's steering arrangements. It was necessary formerly to 'line up', the two systems before interconnection by putting the rudder amidships and the gyro pilot roller contact arm in the neutral position before moving the control lever from "Off" to "Hand" or "Gyro." By a radical re-design of the gyro pilot control arrangements and the introduction of self-synchronous repeat-back from the rudderhead, it is now possible to change over from normal to gyro pilot steering under any condition of rudder angle and gyro pilot indication. As soon as the control lever on the gyro pilot bridge unit is moved from the "Off" position, the rudder will automatically and immediately align itself with the position of the pointer of the rudder angle indicator in the top of the gyro pilot stand, and will thereafter maintain synchronism with that pointer.

So successful have these gyro pilots proved in service, both for hand-electric and automatic steering, that in a great number of ships the gyro pilot has completely displaced the hydraulic telemotor as the primary steering control, while in many new ships the gyro pilot is the only steering system installed. A great advantage of this latest type of self-synchronous gyro pilot is that, by means of controller switches fitted in parallel with the gyro pilot electric steering control at various alternative steering positions, the rudder can, in emergency, be controlled from a variety of steering positions, including the wings of the navigating bridge and in the after steering engine compartment. These steering controllers consist simply of a switching box provided with a small lever which is normally upright when the rudder is at rest. Movement of the lever to port or starboard moves the rudder to port or starboard accordingly, and the movement continues until such time as the lever is returned to the upright position. Rudder angle indicators are naturally required and fitted at these alternative steering positions.

Sperry Two Unit gyro pilots can be adapted to control all makes of steering engines, whether of steam reciprocating, electro-hydraulic or all-electric type. For smaller vessels the Sperry electro-mechanical steering system is supplied in various grades of horse-power and comprises a self-contained steering system in which the power unit motor actually does the work of moving the rudder without the necessity of a separate steering engine.

The Brown automatic helmsman

Marine gyro pilots are also manufactured by S. G. Brown & Co. Ltd., of North Acton, London, for operation in conjunction with the 'Brown' gyro compass, the equipment being known as the 'Brown' Automatic Helmsman. The mechanism, which is totally enclosed within a watertight metal case, consists of :—

(a) Directional controlling element or 'Brains Unit.'
(b) Breaker switches.
(c) Power motor.
(d) Control switches.
(e) Alarm relay.

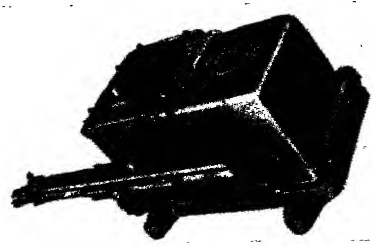
In principle the Brown Auto Helmsman operates to apply corrective rudder for any 'off-course' movement of the ship's head in a similar manner to the Sperry gyro pilot, but as the method employed differs in many respects the following description of its operation is given, and should be read in conjunction with the chapter on the functioning of the Brown gyro compass.

Auto Steering. In the Brown bridge control unit the control switch is in the centre of the unit, and is marked "Off," "Hand" and "Auto." When the automatic helmsman is switched to the "Auto" position a step-by-step motor in the brains unit is connected electrically to the gyro compass transmitter and hunts in step with the gyro compass repeater system. Any movement of the ship's head will now cause this step-by-step motor to turn and, driving through a differential gear on to a split contacting drum in the brains unit, it will move the drum at the same time. This drum will rotate until one of its copper contact segments makes contact with trolley rollers, energising trolley coils and drawing the trolleys over to that side. A complete electrical circuit is now formed through one of the breaker switch coils which will operate the contacts on that particular switch. When the contacts on the breaker switch close current is passed to the power motor, which starts running and in so doing moves the steering engine control to apply corrective rudder for the direction in which the ship's head is moving.

With the vessel moving off course the step-by-step motor in the brains unit drives the drum on to the contacting position, but when the power motor has started turning, a finger type transmitter, also operated by the power motor, sends electrical impulses back to another step-by-step motor in the brains unit. This, through the same differential gearing, rotates the drum back off the contacting position when the correct amount of rudder has been applied. When the drum has rotated back to the 'no contact' position, with the trolleys on the bakelite insulation between the copper contact segments, the breaker switch drops away and the power motor stops. Movement of the ship's head back to the course will turn the split contact drum in the reverse direction, so returning the rudder to the amidship position as the vessel resumes her original heading.

Hand Steering. Placing the main switch on the control unit into the "Hand" position disconnects the unit from the gyro compass transmission system and switches in a finger type transmitter housed in the hand control unit. Turning the hand control will now turn the step-by-step motor driving the contact drum in the brains unit in exactly the same manner as it is done by the gyro compass transmitter when in automatic steering, and the same operations will ensue.

Adjustments. On the front of the brains unit are three adjustments marked respectively "Contact Adjustment," "Rudder Angle Adjustment" and "Contact Roller Adjustment." Movement of the contact adjustment lever to higher readings results in a larger angle of rudder for each application by allowing the trolley contacts to traverse a greater length of the contact segment of the split contact drum. The lever marked "Rudder Angle Adjustment" varies the speed with which the contact drum returns to the neutral position, thus enabling an intermediate setting to be obtained in the angle of rudder applied, but once this adjustment has been made to suit the steering characteristics of each individual vessel no further adjustment is needed. The "Contact Roller Adjustment" allows the vessel when required, to yaw off course a definite amount according to the setting without rudder application. This is desirable under certain conditions as when a vessel is rolling and pitching to a sea on her quarter. By bringing the roller contacts closer together the split contacting drum on which the roller contacts operate has to move a greater distance before contact is made, thus allowing a yaw either side of the course before contact is made and corrective rudder applied. In calm weather this adjustment is kept to the minimum.



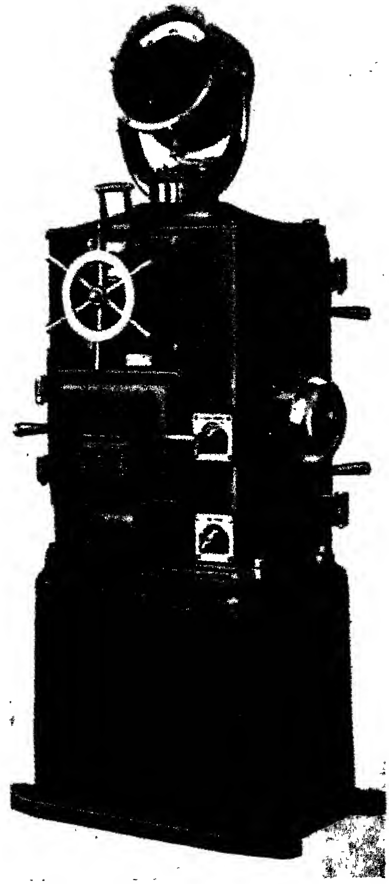


Fig.II.27. The Brown automatic helmsman, bridge control unit, showing small steering wheel for making alterations of course, also (separately) the power or after unit which is connected to the control of the steering engine.

Adaptation for control of all electric steering gear

The Brown auto-helmsman has been specially adapted, in conjunction with Messrs. Harland and Wolff, for control of the Harlandic all-electric steering gear. This method of control permits the automatic helmsman to be greatly simplified and condensed. The power unit with its driving motor, clutch, rack and gears, can be dispensed with and the hand steering control can also be eliminated as the normal hand steering wheel is left in circuit ready for immediate use. The component parts in the Harlandic auto-helmsman are the small control unit mounted on the wheelhouse bulkhead, and a small transmitter for the feed-back system which is mounted on the rudder head.

In principle all types of auto-helmsman are similar and differ only in the means by which the rudder is ultimately moved. With the two-unit type the current is passed by breaker switches to a power motor which in turn moves the rack connected to the steering engine control. With the 'all-electric' type the breaker switches are connected to the control resistances of the electric steering motors at a suitable point for the amount of rudder required, and over half the working parts of the two-unit auto-helmsman are eliminated.

Automatic steering, coupled with hand-electric rudder control, has without doubt come to stay and will be installed as the primary steering control of the ship of the future. That the 'brains' behind the gyro pilot, which acts and almost thinks in a manner similar to that of a highly-intelligent human quartermaster, is the same brain which provides the true north-seeking properties of the gyro compass, is but another example of the versatility of the gyroscope in the service of the modern seaman.

CHAPTER 6

GYROSCOPIC STABILISATION OF SHIPS

There is a mistaken idea, very prevalent among those who have heard vaguely of the stabilisation of ships by means of gyro-controlled devices, and also of direct stabilisation by the use of larger gyroscopes, that such stabilisation is primarily intended to reduce the liability to seasickness of the human beings on board, whether staff or passengers. Another popular fallacy which is prevalent even among those who have closer dealings with ships, is that it is natural and proper for a vessel to roll in a seaway, and that any attempt to reduce the rolling by counter-measures must impose undesirable strains upon the ship's structure.

While concern for the comfort of passengers accounts in great part for the decision to instal gyro stabilisers in a 41,000-ton passenger liner, and also in smaller passenger vessels and in many hundreds of power yachts, it does not account for the stabilisation of large numbers of vessels of other types and classes in which the comfort of the ship's personnel can be regarded as a minor consideration. In the matter of strains and stresses imposed upon the structure of a stabilised ship by the stabilising installation, experience has amply proved the theory and conviction of the designers of such equipment that stabilisation, in actual fact, greatly reduces the strain to which a ship is subjected in a seaway, and that the stress delivered to the hull by the stabiliser is very considerably less than the rolling, twisting, hogging and sagging stresses to which a ship is normally subjected in heavy weather, and for which the naval architect has to make due allowance in design.

Why a ship rolls

Before describing the principal methods of gyro and gyro-controlled stabilisation, it will be as well to consider what it is that makes a ship roll at sea, and also at the outset to make it clear that it is the rolling, not pitching, which is counteracted by stabilisation. Roll stabilisation, it is true, also allows a reduction in pitching to be effected by permitting a course to be steered in heavy weather which could not otherwise be made good by reason of the very heavy strains which would thereby be thrown upon the hull, coupled with the risk of taking aboard heavy water which would endanger hatches, deck fittings and superstructures.

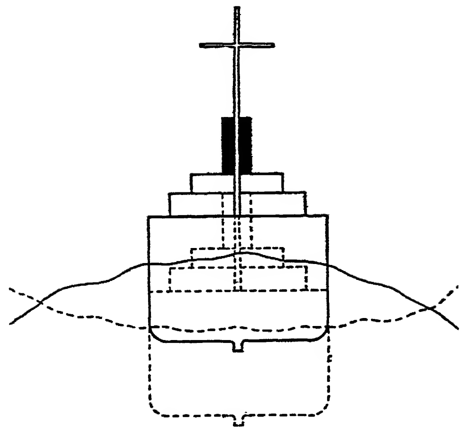


Fig. II.28. A floating ship rises and falls but does not move horizontally to wave motion.

Wave motion

Let us first consider wave motion, and take the case of a ship or other object floating on a smooth sea in deep water in which a swell is running. The terms 'sea' and 'swell' are frequently used erroneously even by seamen of considerable experience. It is quite possible for a swell, which has originated as the result of conditions which prevail, or have prevailed, many hundreds of miles away, to be running in one very definite direction with a 'sea,' resulting from local conditions of wind and weather, superimposed from quite another direction. The wave form moves horizontally but the actual movement of the water is confined to small circular orbits within the wave, and the water in the wave is not itself translated horizontally. The simplest way to understand wave motion properly is to demonstrate it by taking a length of rope, making fast one end to a post or other object and then, after slackly extending the rope, rhythmically raise and lower the other end by hand. A series of

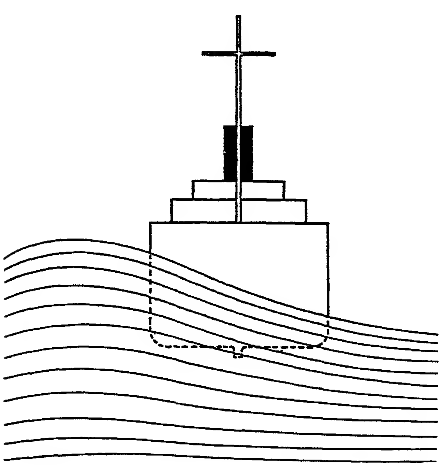


Fig. II.29. The initial cause of rolling of a ship is the sloping surface of the wave form (see also figures 30 and 31).

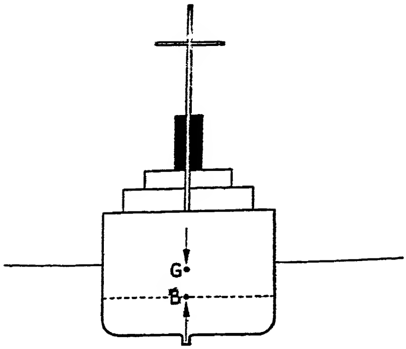


Fig. II.30. When floating, the weight of the ship, acting vertically downwards through G, the centre of gravity, is exactly equal to the pressure of the water acting vertically upwards through B, the centre of buoyancy.

undulations will run along the rope simulating wave motion, but it will be observed that the rope itself is not translated horizontally. So with a swell, the originating cause of which may have occurred at a great distance. The water in the stretch of sea intervening is not actually moving towards the point of observation, although it may frequently appear to be when the wind is from the same direction as the swell, and a 'sea' is superimposed, tending to turn over the head of water lifted by each succeeding undulation.

If a ship or other object be floating in the path of a swell, it will rise and fall with each succeeding undulation, but will not be moved in a horizontal direction unless influenced by local wind or sea. The term 'sea,' to a seaman, may be defined as the curling over of water in the form of a 'whitecap' which results from the sustained action of wind of moderate breeze strength and over, i.e., of force 4 and upwards of the Beaufort scale. On the coast, a swell coming in from seaward and advancing towards the beach or shore, has all the appearance of definite forward movement of the water, although this is followed immediately by a back-run. Shoaling, or gradual decrease in depth, produces this breaking of a wave by reason of the friction of the bottom which distorts the movement of the water particles, tends to decrease the velocity of the wave form, and the distance from crest to crest, and to increase the height of the crest above the hollow, until the upper part of the wave, having greater velocity than the lower part, literally falls over itself with a consequent breaking of the crest and a shoreward run of actual water. This does not occur, however, in deep water where the only effect of wave motion upon a floating object is in the vertical plane.

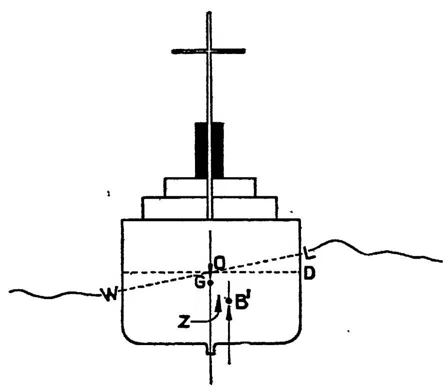


Fig. II.31. When a wave form causes the water to rise on one side of the ship's hull, and to fall on the other side, the centre of buoyancy is displaced from the centre line and a couple is exerted causing the ship to roll towards the side having the smaller wetted surface.

G Centre of gravity
B′ Centre of buoyancy (displaced)
Z Heeling lever
WL Water line

Ship stability characteristics

As to how wave motion causes a ship to roll, we must first consider the stability characteristics of a ship. Any floating object, including a ship, will sink into a fluid until such time as the force of gravity acting vertically downwards is opposed equally by the force of buoyancy acting vertically upwards. These two forces may be said to be concentrated at two points within the hull of a ship termed centre of gravity and centre of buoyancy respectively (see Fig. II. 30). The centre of gravity is determined by the disposition of the weights of the hull itself, and of all cargo, fuel, water and consumable stores located therein. The centre of buoyancy is determined by the shape and area of the "wetted" surface of the hull. In the normal ship, in smooth water when upright, both centres are located on the central vertical line, and there is no tendency to list the vessel either to port or starboard. When subjected, however, to wave motion as in Fig. II.31, the shape and area of the wetted surface of the hull are altered, and the centre of buoyancy moves out towards the side having the greater wetted area. A couple is now effected by the force of gravity acting downwards through the centre of gravity, and the force of buoyancy acting upwards through the new centre of buoyancy, tending to roll the vessel towards the side having the smaller area of wetted surface. As the wave passes under the keel the centre of bouyancy shifts to the other side, and a reversing couple is exerted tending to roll the vessel back in the opposite direction. If the natural rolling period of the ship is coincident, or nearly coincident, with the period of the wave impulses, a roll of increasing angular amount will be built up until aperiodic factors intervene, when the roll will die down only to be built up again in like manner.

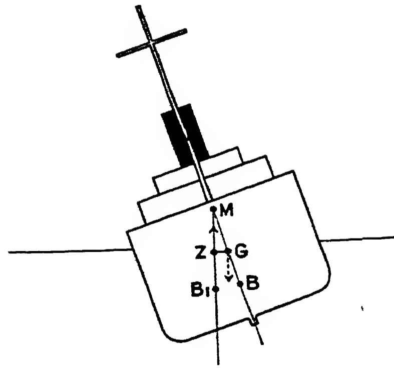


Fig. II.33. In this figure G is the centre of gravity, B the centre of buoyancy when vessel is upright and B_1 the centre of buoyancy when listed. M, the metacentre, is the point where the force of buoyancy acting vertically upwards through B_1 intersects the centreline. GM is the metacentric height and GZ the righting lever.

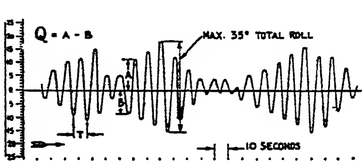


Fig. II.32. The rolling of a ship builds up from a small initial movement to a point where aperiodic conditions intervene. The roll then quickly dies away only to be built up again by succeeding wave impulses. This figure shows a typical rolling record in which Q is the rolling increment by which successive oscillations, B and A, are increased or decreased.

Rolling characteristics

No ship rolls steadily, without variation of angular amount, even if the periods of wave impulse and natural roll are virtually coincident, because the roll period increases slightly as the amplitude of roll increases. This is due to the water friction becoming greater as an increasing area of the hull is wetted. The result is, as already stated, that a ship's rolling characteristic is one of building up gradually, due to succeeding wave impulses, then of dying away comparatively quickly when out-of-phase conditions intervene. A contributing factor to the damping down of a built-up roll is the fact that wave periods are rarely constant for long and synchronisation of periods of both wave and ship is therefore of short duration. Nevertheless it can, and frequently does, exist for long enough to build up a dangerous degree of rolling, especially in a "stiff" ship having a large righting lever. The fact still remains, however, that even a heavy roll is built up from a small beginning, the initial wave impulse being small, and if the initial and succeeding impulses can instantly be suppressed by some means then rolling can be reduced to a negligible minimum by a small expenditure of power.

Stabilisation in relation to metacentric height

It will be appreciated that the amount of stabilisation necessary for any given ship depends upon the relative positions of the centre of gravity, and the metacentre, or position on the midship vertical line through which, when the vessel is inclined, a vertical line passes upward from the new centre of buoyancy. This distance, termed "metacentric height," is the measure of the ship's stability, and determines the extent of the righting lever drawn through G at right angles to B′M to the point Z (Fig. II.31). Seamen refer to a ship having a large metacentric height and righting lever, as a "stiff" ship. Though safe from the possibility of capsizing, such a vessel rolls heavily and violently when wave and rolling periods coincide and, apart from the discomfort to those on board, may shift and damage cargo and semi-permanent fittings, including boilers in their seatings. On the other hand a ship having a small metacentric height, and consequent small righting lever, is termed a "tender" ship. While very much more comfortable for those on board, and less likely to damage cargo and fittings by excessive rolling, a ship which is tender to the point where the positions of the centre of gravity and metacentre virtually coincide, may be a dangerous ship from the point of view of capsizing when the effects of loose water on deck, or in double bottom tanks, or of other unforeseen conditions, are experienced.

Both from the viewpoint of comfort and safety the metacentric height should be as small as is consistent with prudence, and the same factors should be borne in mind when considering the matter of stabilisation, for obviously the stabiliser, to be effective, must be capable of counteracting the maximum increment of roll to which the vessel is subjected by wave impulses. The period of a vessel's roll lengthens in inverse proportion to the square root of its metacentric height, so that the stabiliser will have less work to do in the act of stabilisation of a vessel with a moderate metacentric height, than of a vessel having a large measure of stability. With the Sperry gyro stabiliser a large ship having a reasonable metacentric height can be stabilised efficiently with an installation weighing only 1.5% of her displacement tonnage.

Early forms of ship stabiliser

The earliest form of stabilisation of seagoing vessels was that indirectly provided by the sail area of a sailing ship which, with a steady wind of a suitable force and direction, was sufficient to overcome the rolling tendency so that the ship, heeling to leeward, merely rose and fell to the wave motion. The introduction of mechanically propelled vessels, without steadying sail area, necessitated greater thought being given to anti-rolling measures and modifications to the under-water shape of deep seagoing ships were followed by the fitting, in about 1870, of bilge keels in addition to the bar keel then customary. While fairly efficient in the reduction of rolling in heavy weather, bilge keels are not nearly so effective in moderate weather. They involve a definite drag on the propulsive power, amounting to approximately a quarter of a knot for a 10-knot ship rolling moderately, and to much more when the ship is pitching and a vertical component is introduced.

Stabilisation has also been attempted by means of anti-rolling tanks in which the flow of water between large tanks placed athwartships was controlled to produce aperiodic effects. Such anti-rolling tanks were

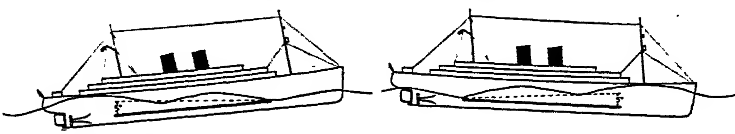


Fig. 11.34. Bilge keels assist in reducing the amplitude of a ship's roll but also reduce the ship's speed particularly when pitching causes the introduction of vertical components.

originally tested out in a British warship at about the same time that bilge keels were first being fitted, but while a certain measure of stabilisation was effected under favourable conditions, the flow of water from tank to tank was most difficult to control, and under unfavourable conditions synchronism of water oscillation and the ship's rolling period occasionally obtained, resulting in an increase instead of a decrease of the amplitude of roll. A later form of anti-rolling tank was introduced in the early years of the present century by a German engineer, named Frahm, utilising two main tanks of inverted syphon type, one on either side of the ship, having a restricted communicating channel. The flow of water between tanks was controlled by air valves from above, and such tanks were found to be a great improvement upon the earlier types. With all types of anti-rolling tanks, however, the stabilising effect lags considerably behind the actual rolling of the vessel, and the inter-relation of the periods of the ship, the waves and the flow of water to produce the stabilising effect is too complicated and unpredictable to produce really satisfactory stabilisation, though partial suppression is often possible.

The gyroscope as a ship stabiliser

In the gyroscope, however, we have a ready means of determining immediately when the initial rolling movement of a vessel begins, and also a means of stabilisation, either by control of a larger gyroscope which can exert a couple to counteract the roll, independent of gravity, or by the control of stabilising fins projected under water from the sides of the ship, and oscillated, in a manner similar to that of the horizontal rudders of a submarine, or the ailerons of an aeroplane, to produce the stabilising effect. In this latter method, utilising gyro-controlled stabilising fins, it will be appreciated that stabilisation can only be effected when the ship is making way through the water so that the action of the water on the fins, when appropriately angled by the electro-hydraulic mechanism under the control of the gyroscope, exerts the necessary righting moments to counteract the tendency of the vessel to roll. In the case of the gyro stabiliser, in which the stabilising moments are provided by the inertia and precessional movements of a large gyroscope located within the hull, under the control of a small gyroscope, the stabilising torques are provided quite independently of the forward motion of the ship, and can also stabilise the vessel when "hove to," or not making way through the water.

CHAPTER 7

THE SPERRY GYRO-STABILISER

The Sperry gyroscopic stabiliser derives its stabilising properties from a heavy rotating wheel which exerts the stabilising effect without any transfer of weight, and independent of gravity. Every pound weight of the rotor multiplied by its angular velocity can be brought into action almost instantaneously to counteract an incipient roll, so that it is possible to stabilise even large ships with a comparatively small installation.

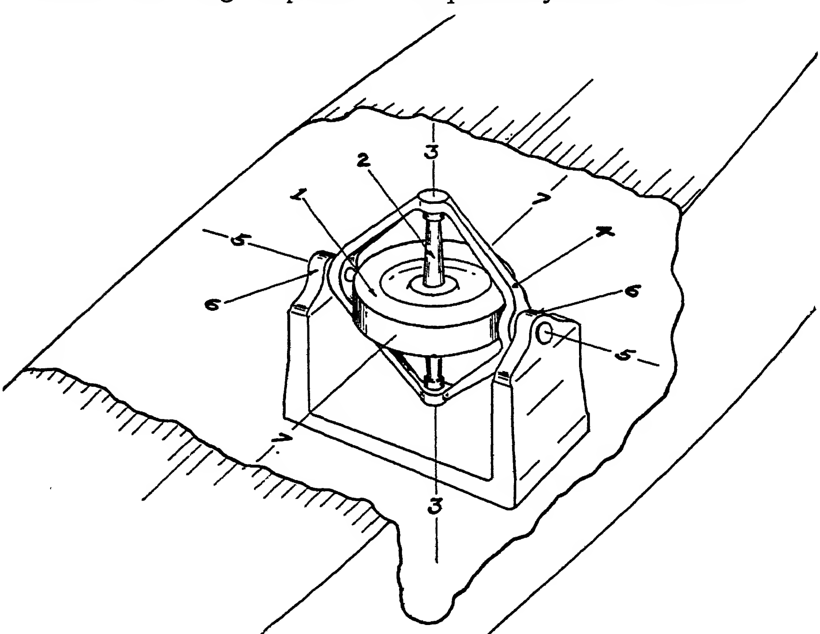


Fig. II.35. The gyro stabiliser shown in schematic diagram. (1) The gyro rotor, (2) Gyro rotor axle, (3) Gyro rotor bearings, (4) Gyro rotor casing, (5) Athwart ship gudgeon bearings, (6) Pedestal, (7) Fore-and-aft axis of ship. When the rolling of the ship about its fore-and-aft axis (7) subjects the gyro to torque the resistance of the stabilising gyro is proportional to the rate at which the gyro turns or precesses about the athwart ship axis (5).

The passive gyro as a stabiliser

In Fig. II. 35 a simple gyro is shown with which the action of the stabiliser may be described. A spinning wheel or rotor is mounted on an axle in bearings, the axle being normally vertical and the plane of the rotor horizontal. The bearings are mounted in a casing supported on athwartship gudgeon bearings, which are normally horizontal when the ship is upright and are secured to the ship's hull by pedestals. From this description it will be seen that the gyro rotor has freedom of the spin axis, and also about the horizontal axis in the vertical plane. The freedom about the fore-and-aft line of the ship is restricted by the ability

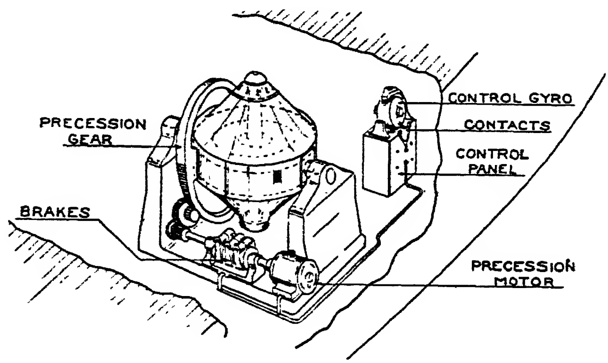


Fig. II.36. In the Sperry gyro stabiliser a small but sensitive control gyro controls precession of the stabilising gyro by starting and stopping the precession motor in circuit with which are electrically operated brakes on the precession motor shaft. Irregular wave action is continually opposed by stabilising torque exerted by the stabilising gyro.

of the ship to roll. It is fundamental that when subjected to a couple around an axis at right angles to the spin axis such a gyroscope will resist that couple, and that the degree of resistance will be proportional to the velocity with which the gyro precesses about a third axis at right angles to the other two axes. In this case the axis of precession is the horizontal axis when a couple is exerted by rolling about the fore-and-aft axis. For the moment let us assume that friction and inertia are non-existent in the precessional axis, i.e., the athwartship gudgeon bearings. Under such conditions the rate of precession about this axis would be such that no movement of roll, about the fore-and-aft axis could take place because the reaction about the same axis would exactly equal the applied couple exerted by the tendency to roll. This situation would continue until such time as the gyro had precessed through a quarter of a circle and the plane of rotation had become coincident with the plane of the applied couple, when precession would cease together with all resistance to the applied couple.

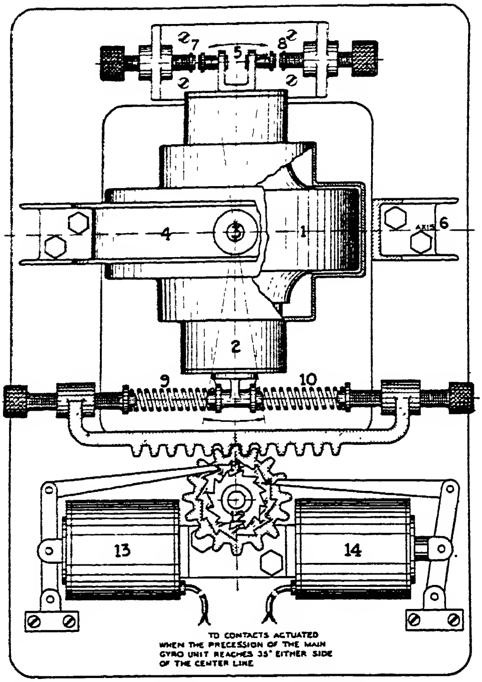


Fig. II.37. The control gyro of the Sperry gyro stabiliser.
1. Control gyro rotor 2. Rotor bearing housing
3. Vertical axis 4. Gyro casing
5. Gyro contact 6. Horizontal axis
7 & 8. Fixed contacts 9 & 10. Centralising springs
11 & 12. Ratchet wheels 13 & 14. Electro magnets

Control of precessional movement

A simple passive gyro, such as illustrated in Fig. II. 35, could stabilise a ship efficiently if its angular momentum were sufficient, so that no single wave impulse would use up its precessional movement. This can be accomplished, but there are two other qualifications which also apply, the first being that all inertia and friction about the precessional axis must be eliminated, and, secondly, that the wave impulses would have to be perfectly symmetrical in amount and period so that the average position of the spin axis would remain in the vertical. Neither of these additional qualifications can be met by an uncontrolled gyro. It is necessary, therefore, to control the precession in order to provide stabilisation against irregular wave action and overcome the precessional inertia and friction.

Operation of precession motor and brakes

Referring to Fig. II. 36, it will be noted that the shaft of the precession motor is provided with a set of electrically-operated brakes. When no current is passing through the coils operating these brakes, the precession motor shaft is gripped firmly in the brake shoes by the action of heavy helical springs. The brake coils are connected electrically in series with the precession motor circuit, so that when the motor starts and a heavy current passes through the coils the brakes lift off the shaft. As the motor speeds up and current lessens a slight braking effect is apparent until the current again increases, and when the motor stops, full braking is applied by the springs. The brakes may therefore be regarded as floating on the shaft during the cycle of precession, and by these means the precession of the stabilising gyro is accelerated at starting, retarded when about to stop and controlled as to velocity by the prevention of overrunning of the precession motor by the stabilising gyro.

Control gyro

In Fig. II. 37 it will be seen that the precession of the control gyro around the vertical axis by any angular (rolling) movement about the horizontal axis will cause the gyro contact to close on to either one or other of the fixed contacts. The gyro casing is normally kept centrally located by springs, the tension of which is controlled by ratchet wheels. The ratchets engaging these wheels are operated by electro-magnets in circuit with contacts on the main or stabilising gyro which close when the main gyro precesses more than 35° from the vertical. Magnets acting on the ratchets will then cause one of the centraliser springs to be compressed, and the other to be extended, making the control gyro less sensitive in the direction in which the main gyro has precessed more frequently, thus causing it to average equal precessions on each side of the normally vertical position. This simple arrangement automatically controls centralisation of the main gyro even though the wave impulses, against which stabilisation is effected, are not symmetrical.

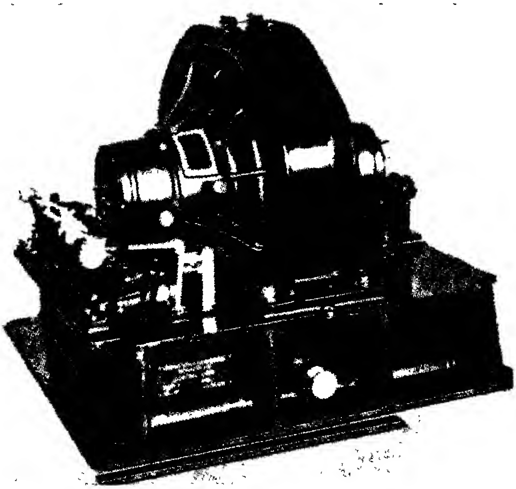


Fig. II.38. Control gyro, shown diagrammatically in Figure 37.

Gyro stabilising installations, unlike gyro compasses, have to be designed and constructed individually according to the characteristics of the vessel in which they will operate. The stabilising action of the gyro is, however, the same in whatever part of the ship it may be installed, as the effect of a couple in causing rotation of a body is independent of the axis about which the couple is applied. This is fortunate in that the stabiliser may be located in a part of the ship which is of little use from the point of view of earning capacity, and need not even necessarily be located on the fore and aft line, or in the vicinity of the centre of gravity.

"Conte di Savoia" stabilising equipment

Sperry gyro stabilisers have been fitted in a great variety of ships from men-of-war to small luxury yachts, but possibly the most interesting installation was that made in the 41,000-ton Italian liner *Conte di Savoia*, employed in the transatlantic trade. In this vessel the gyro stabilising equipment is not only remarkable for its size in that, with all its auxiliaries, the total weight is in the neighbourhood of 660 tons, but also for the fact that stabilisation is effected by three complete and quite independent units which may be operated singly or together according to the degree of stabilisation necessary. Each of the three stabilising units utilises a gyro rotor having a diameter of 13 feet, a periphery width of 44½ inches, and a weight of 100 tons. The normal rotor speed is 800 r.p.m. with a maximum of 910 r.p.m. With K, the radius of gyration in feet, and W the weight of the rotor in pounds, each unit has a K^2W of 4,700,000. and the maximum gyroscopic stabilising torque of the three units combined is 7,860 foot tons. These figures are remarkable as pertaining to the largest gyroscopic stabiliser yet constructed, but by comparison with the data for the ship herself it will be seen that proportionally they are exceedingly small. The *Conte di Savoia* is a vessel of over 800 feet in length with a beam of 96 feet and draft of water of 30 feet. In her loaded condition the metacentric height is 2·2 feet, and in still water the rolling period is 25 seconds. With a displacement of 41,000 tons the total weight of the combined stabilising units amounts to less than 1½% of the displacement, while at 1,900 h.p. the normal power consumption of the stabilising plant in operation again approximates 1½% of the main engine horse-power of 120,000 for a cruising speed of 27 knots.

Another point of great interest in connection with this stabilising equipment is that the wave action twisting torque for which the ship's structure had to be designed, whether stabilised or not, was approximately 1,600,000 foot tons, or more than 200 times the stabilising torque exerted by the combined gyros. These facts certainly bear out most fully the opinions given in consultation, before any large gyro stabilisers were installed, by two internationally famous naval architects, Sir William White of Great Britain, and Admiral Taylor of the United States. These, and other experts, concluded, after careful examination of the problems involved, that the stresses delivered in the process of stabilisation by gyroscopic equipment would in all cases be small by comparison with the hogging, sagging and twisting stresses for which every naval architect must provide when designing a ship. So small in actual fact are the stresses delivered to the hull by a gyro stabiliser in operation, that they may be taken safely by a single frame of the ship.

Bearing load problems

This is not to say that the construction of such large gyros as those used in the *Conte di Savoia*, and in certain stabilised aircraft carriers, did not involve considerable problems in the matters of bearing loads, lubrication and the provision of safety factors. The Sperry Gyroscope Company had of necessity to carry out a great deal of research into these problems before the larger units could be constructed with any guarantee of efficient operation in service. These investigations resulted in many interesting facts becoming known, including the necessity for the bearing load to be entirely borne on an oil film, and that if the greatest accuracy be not used in the manufacture of bearings and journals, allowing high spots to occur in their surfaces, then it is only these high spots which will be useful in providing the oil films. Pressure on such spots may amount to as much as 3,000 lb. to the square inch when the bearing is supporting a load of only 150 lb. to the square inch of its total surface.

This load had previously been regarded as a maximum which it would not be safe to exceed. As the result of this research, however, stabilisers are now constructed which will safely carry gyroscopic loads of as much as 1,000 lb. to the square inch of their total bearing surfaces or approximately seven times the previously considered maximum. Other interesting points disclosed by preliminary investigation into bearing problems were that the white metal lining ordinarily used in plain bearings, while not by any means deserving its popular description as "anti-friction"

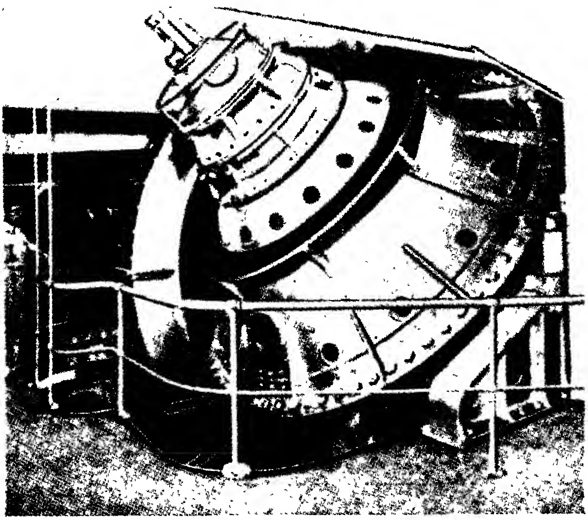


Fig. II.39. One of the three gyro stabilising units of the transatlantic liner *Conte di Savoia* shown in operation. The stabiliser is in the act of precessing about the thwartship axis providing a stabilising torque opposing the roll about the fore and aft axis.

metal, nevertheless has sufficient resilience to "give" to oil pressures, thus facilitating the uniformity of the oil film in the bearing. A bearing is inefficient when the oil film is thick, as turbulence within the oil increases friction and heat losses, and is most efficient when the oil film is just sufficiently thick to prevent any high spots of journal bearing surfaces from projecting through it.

The high bearing load of a gyro stabiliser with axis normally vertical is unavoidable because of the necessity to support the heavy gyro rotor when starting, and also when running, and because of the heavy gyroscopic stabilising couple delivered through the main bearings. While the gyro is being started its weight is taken by a roller bearing at the top of the gyro casing (Fig. II.40). When the gyro is running, and has reached a speed of 100 to 180 r.p.m., this roller bearing is lowered by a hydraulic jack so that the weight is taken on a pivoted shoe step-bearing at the lower end of the gyro axle. The main bearings therefore are relieved of practically all loads except the radial stresses involved, but, as previously stated, the gyroscopic load on these bearings may reach values approximating 1,000 lb. to the square inch so that the greatest care in manufacture is necessary.

The oil circulation system of the Sperry gyro stabiliser performs the two functions of lubricating and cooling the bearing surfaces and of cooling the surrounding parts. Since the entire input of power to the gyro rotor is solely to overcome friction, a considerable amount of heat is generated which has to be dissipated by radiation; and the forced circulation of air and oil.

Main gyro rotor and casing

The gyro rotors used in gyro stabilising equipments are made of low carbon steel forgings having a yield point of 40,000 lb. to the square inch, and an elongation characteristic of approximately 20%. To ensure that the forging is as nearly homogeneous as possible, and that no impurities remain, the most modern methods of forging, heat treatment and testing are used, and more than half the weight of the original ingot is discarded. The rotors in the smaller equipments are composed of single discs, but for much larger rotors two discs are used, abutting against each other only over a narrow ring of the same radius as the circle of bolts which hold the discs together, the bolts being required to resist tension only. The two discs are held against relative radial displacement by a series of curved keys constituting the ring. The shaft stubs are made separately, and are secured to the discs by the extensometer method. The casing is built up of welded and riveted structural steel with reinforcing beams extending between the gudgeon bearings and the end caps housing the main bearings. The trunnions rest on roller bearings in the pedestals which are secured to the ship's structure.

Electrical system

The main gyro is driven by an alternating current induction motor of which the stator is attached to a bracket within the gyro casing on the lower side. The "squirrel-cage" rotor is secured to the lower shaft stub of the main gyro rotor. Ventilating fans attached top and bottom of the squirrel cage rotor draw cool air in through the bottom of the gyro casing over the stator and rotor windings of the gyro drive motor, and over the gyro rotor itself, to exhaust through orifices at the top of the casing.

The power for this spinning motor is provided by a motor generator set (or in special cases a turbo-generator) which, besides supplying an output of three-phase A.C. for the gyro drive, also provides a D.C. supply for the precession motor. The precession motor is controlled by the Ward Leonard system by which the motor field is continuously excited in one direction and the motor is started, stopped and reversed, by control of the field of the generator which supplies the motor.

When the control gyro contacts are closed two relays are simultaneously actuated, one closing the generator field circuit with correct polarity of current, while the other closes the circuit between the armatures of the generator and precession motor respectively. A third relay, termed a field forcing relay, is automatically operated by voltage rise in the armature circuit as the precession motor speeds up, and assists maximum acceleration by strengthening the generator field.

When the control gyro contacts open, the relay connecting the D.C. generator to the precession motor automatically opens and simultaneously connects the precession motor armature across a heavy resistance, thus assisting dynamic braking in the stopping of precession.

Buffer locks

The Sperry gyro stabiliser is provided with a precession buffer and lock which protects the gyro against the results of a possible failure of precession control or braking systems. In the remote event of such a failure, involving freedom to precess to the end of the precession arc with considerable velocity and energy, a spring hammer on the gyro casing engages a plunger of the buffer lock. Movement of the plunger

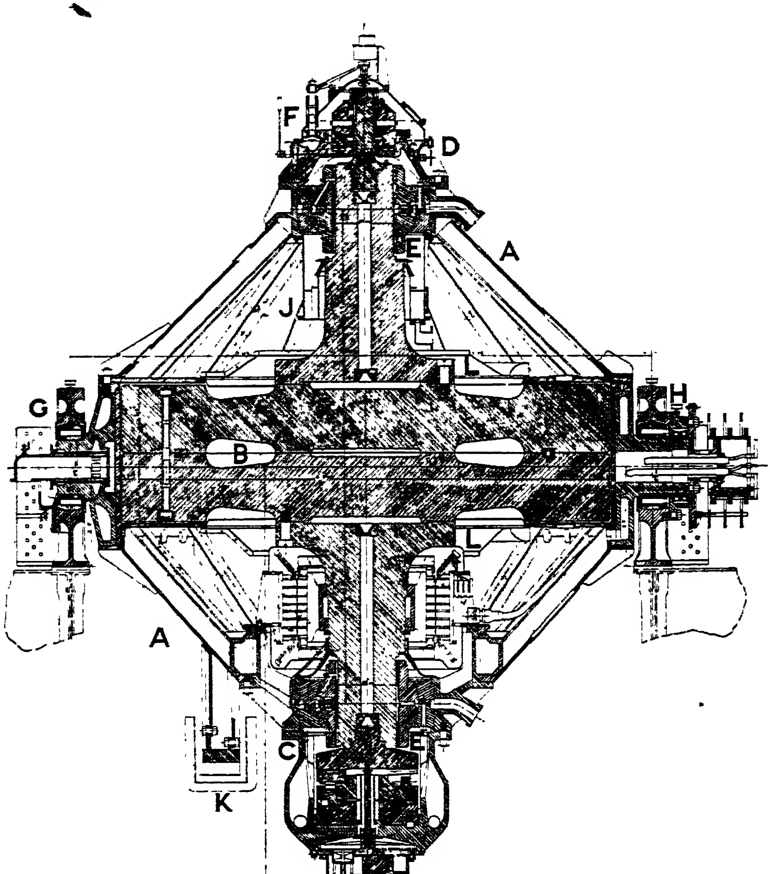


Fig. II.40. One of the three stabiliser units of the *Conte di Savoia* shown in elevation section. (A) Gyro casing, (B) Gyro rotor, (C) Lower cap with pivoted shoe step-bearing, (D) Upper cap and roller bearing, (E) Main journal bearings, (F) Hydraulic jack and collar, (G) Gudgeon bearing, oil side, (H) Gudgeon bearing, electric side, (J) Upper oil chamber, (K) Precession gear, (L) Ventilating directors.

displaces oil from one end of a cylinder to the other with progressive reduction of the area through which the oil escapes, thus absorbing the energy. When the spring hammer has moved the buffer lock plunger a short distance, a ratchet on the buffer unit is released and engages with teeth on the hammer body, thus locking the gyro against movement in the opposite direction, and also opening the buffer cut-out switch and disconnecting the precession control system.

Balancing

To obtain from the gyro rotor the maximum stabilising torque, which is proportional to its mass, speed of rotation and square of its radius of gyration, the rotor must be spun at maximum speed and have as large a radius as possible. The greater the speed, and larger the radius, the more pronounced will be the effect of small eccentricities of weight at the periphery of the rotor. The matter of balancing is therefore of the greatest importance, and is carried out by a precision balancing

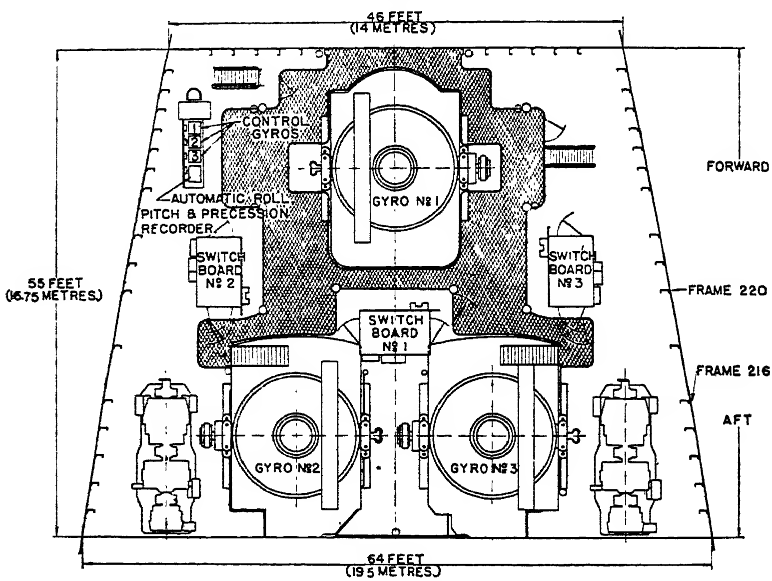


Fig. II.41. Plan layout of the *Conte di Savoia* gyro stabilising plant showing location of the three stabilising gyros, control gyros, switchboards, and automatic roll, pitch and precession recorder.

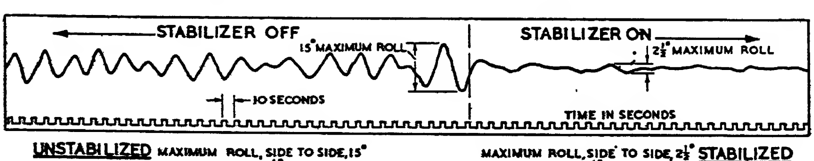


Fig. II.42. Section of record taken in *Conte di Savoia* showing the effect of stabilisation. With stabiliser not in operation the vessel averaged a roll of 7½° with maximum 15°. With the stabiliser in operation the average roll was reduced to less than 2° with maximum of 2½°.

machine. The rotor is mounted and rotated in this machine with the axle horizontal and supported at each end by cradles, either of which may be clamped while the other "floats." The deflections of the floating end are then precisely measured, and by means of formulae the exact value and angular location of changes necessary to the disposition of weight in the rotor can be determined. So accurate are these methods in practice that a virtually perfect balance can be obtained, resulting in complete absence of vibration and noise in operation.

CHAPTER 8

THE DENNY-BROWN SHIP STABILISER

By contrast with the Sperry gyro stabiliser, described in the preceding chapter, the Denny-Brown ship stabiliser, while utilising the gyroscope to control the means of damping out the amplitude of roll, does not use the precessional effect of a comparatively large gyro to do the actual work. With this apparatus stabilisation is obtained by the use of fins projecting from the hull and oscillated in somewhat similar manner to that of the ailerons of an aeroplane. The suggestion to use oscillating fins in such manner was first made by A. Wilson in 1890 and was the subject of Patent No. 19516. A Japanese, Dr. S. Motora, made the first installation of an oscillating fin stabiliser and a few Japanese ships were so fitted. The method of operating the fins was, however, unsatisfactory and little progress was made until the idea was taken up by Messrs. Brown Bros. & Co. Ltd., of Edinburgh, hydraulic engineers and steering gear manufacturers, in conjunction with the well-known firm of Wm. Denny & Bros. Ltd., Dumbarton, shipbuilders and naval architects.

The result was a completely re-designed and much improved version of the original fin stabiliser which has given very satisfactory results. Due to the fact that the stabilising effect is dependent upon the speed of the ship through the water and the area and angling of the fins employed, stabilisation will be much more effective in fast vessels with small metacentric heights than in slow vessels with a bigger measure of stability, though any type of ship can be stabilised by fin oscillation, provided that increase of weight of the equipment is not of importance.

Operating principles

Nearly every ship afloat is permanently fitted with what are termed bilge keels, to reduce the amplitude of roll. These consist of angle bars riveted at right angles to the hull at the turn of the bilge and extending for a considerable part of the vessel's length. While presenting little resistance to the forward motion of the ship, nevertheless they reduce the rolling motion of the vessel, though this is only effected with a resulting slight decrease in speed.

The Denny Brown stabiliser consists of fins or planes which can, when required, be projected from the turn of the bilge, and which can be oscillated so that the action of water upon the fin on one side of the vessel produces an upward force while the action upon the fin on the other side produces a downward force. It will be appreciated that, in addition to the upward or downward force exerted upon the fins, there is also a slight tendency to impede the forward motion of the ship, but for the time being this will be disregarded. The fins, of which there is one or more on each side of the vessel, are situated at a convenient position in the fore and aft length where the beam is greatest, thereby obtaining the maximum righting moment with the minimum area of fin, and they are designed to oscillate about an axis which is located at the centre of pressure on the fins when the ship is steaming ahead. As a result the torsion moment required to angle the fins is comparatively small, and rapid oscillation can be effected by the operating gear which is similar in design to that of an electro-hydraulic steering gear. This

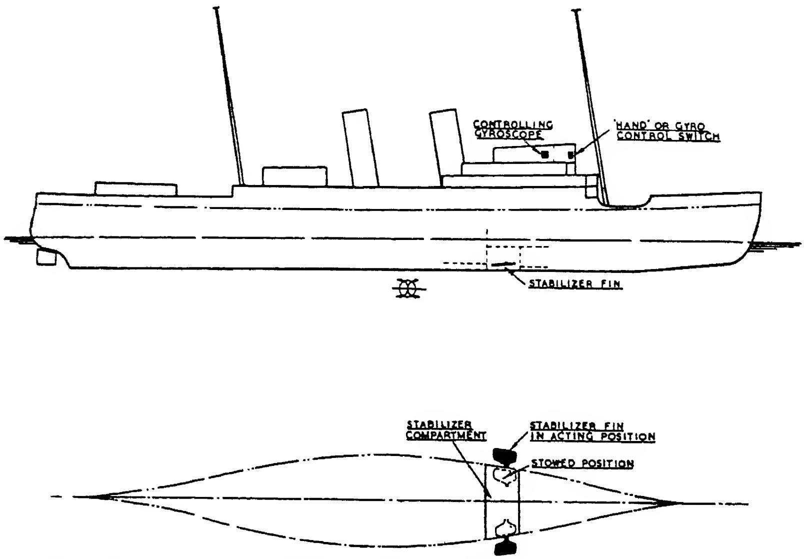


Fig. II.43. T.S.S. *Isle of Sark* showing location of controlling gyroscope and of stabilising fins in both stowed and operating positions.

rapidity of oscillation is necessary by reason of the comparatively quick "swing-swang" or rolling period of certain types of vessel in a seaway. In a cross-Channel vessel, for instance, the period for the complete port-starboard-port roll may be less than 10 seconds.

Control gyro

A small gyroscope is used to control the oscillating operation of the fins. The gyroscope is conventionally mounted in ball bearings with the spin axis athwartships in a rotor casing which is free to move in the horizontal plane about a vertical axis. The gyroscope is spring constrained and any angular movement of the vessel, and consequently of the gyroscope mounting, will produce a precessional movement about the vertical axis which is used to close one of the two contacts of a relay. This closes a switch which energises a solenoid which in turn moves a balanced valve controlling the operation of the electro-hydraulic gear which angles the fins.

It will be apparent that the control gyroscope only precesses when the ship has angular velocity about her fore-and-aft axis, i.e., when she is actually in process of rolling. When there is no rolling velocity the control gyro is kept in the central or neutral position between the two contacts by means of centreing springs and the stabilising fins on both sides of the ship remain in the horizontal or zero position. They then lie in the natural streamline and are so designed and shaped that no appreciable resistance is offered to the progress of the ship through the water. This is an important point because not only do the fins, when extended but not in operation, act in a similar manner to that of conventional bilge keels, but also, should the vessel develop a permanent list to one side or the other, the fins do not attempt to correct this list so long as

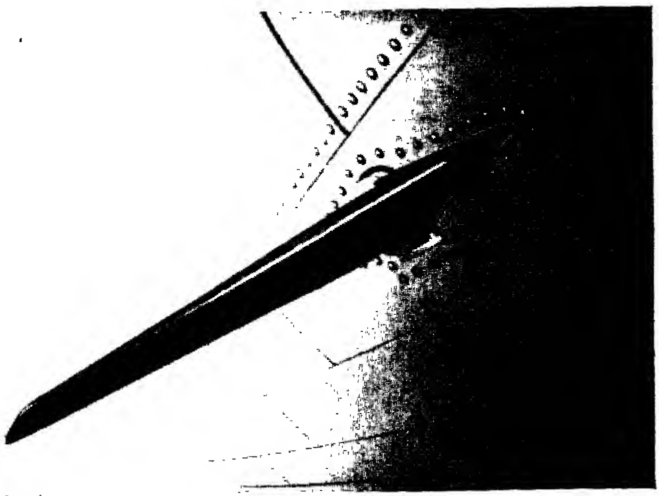


Fig. II.44. T.S.S. *Isle of Sark*—view of starboard stabilising fin in operating position.

there is no velocity of roll. When there is velocity of roll and the fins are put into operation under the control of the gyroscope, they tilt alternately upwards and downwards, in opposition, so that the stabilising moments set up by the forces on the port and starboard fins respectively are combined in a total roll damping effect.

Anticipatory mechanism

From the foregoing it will be appreciated that angular velocity of roll is necessary to bring into operation the gyroscopic control closing the contacts which lead to the angling of the fins. When angular velocity ceases at the extreme angle of roll the fins would return to the horizontal and would not reverse the angle of their surfaces until velocity of roll in the opposite direction becomes appreciable. However sensitive the control gyro may be there is bound to be a slight lag in the exertion of the stabilising force as compared with the tendency to roll. This is overcome in ingenious manner by the use of anticipatory mechanism which utilises the centering movement of the gyro axle at cessation of roll velocity to reverse the angle of the fins in preparation for the stabilisation of the roll in the opposite direction before the return roll actually begins. This is effected by mounting the operating contacts on a sliding carriage which is moved by the gyroscope in the act of precession to a point beyond the normal centre position, so that when the angular velocity of the roll ceases at the extreme angle of roll, the centering springs take charge and close the opposite contact, thus reversing the aspect of the fins in preparation for, and in advance of, the return roll. The centering springs are augmented by what are termed anticipation springs which are adjustable to suit the various conditions of sea against which stabilisation is desired. Under certain conditions, as for example with a following sea, the anticipatory mechanism serves no useful purpose and provision is made for locking the sliding carriage, carrying the operating contacts, in the mid position by the movement of a small lever at the side of the control gyro. The control gyro consists of a small rotor which is spun at about 6,000 r.p.m. by twin D.C. induction motors, one on each side of the rotor. Each of the twin motors is alone capable of maintaining a speed of 4,500 r.p.m. which is sufficient for the correct functioning of the gyroscope, but normally both are in operation.

Single and multiple fin installations

The fins are extended from, and retracted into, their housing within the hull by electro-hydraulic machinery which also performs the function of tilting or angling the fins during stabilisation. The stabilising installation may be of single fin or multiple fin type. In the former the leading portion of the fin is stationary relative to the hull with hinged trailing edge, while in the latter type the fins angle in unison and are hydrodynamically balanced.

An interesting feature of this type of gyro-controlled stabiliser is that the stabilisation effected is an almost constant figure for any given speed and degree of fin operation irrespective of the angular amount of free or unstabilised roll. This was predetermined by tank experiments and confirmed in actual practice when a vessel, steaming at 19 knots, with a fin operation of 17° up and down, effected a reduction of roll of 16°. With a free roll of 16° the operation of the stabilising fins completely eliminated the roll, while with a free roll of 26° the operation of the fins reduced the amplitude of roll by 16° to a total of 10° or 5° from the vertical on each side. In similar manner a free roll of 36° would be reduced, at the same speed and angle of fin operation, to one of 20°, or 10° from the vertical on each side.

Installation in T.S.S. "Isle of Sark"

The first practical installation of the Denny Brown stabiliser was made in the Southern Railway Company's cross-Channel steamer *Isle of Sark* in 1936. Prior to the installation experiments had been carried on for many months in the Dumbarton experimental tank on a model of the vessel carefully ballasted to give the natural rolling period and correct metacentric height. Tests with fins extended but not oscillating showed that the resistance to propulsion was not increased by more than 5 per cent, while the with fins oscillating 15° each way a total of 16° roll could be eliminated.

During actual sea tests after installation of the stabiliser in the *Isle of Sark*, it was found that the fins could be extended in two minutes and housed in one minute. Reduction of speed due to the action of the fins in stabilisation was calculated at approximately a quarter of a knot, while with a free roll of 20° the action of the fins reduced the amplitude to less than 4°. These very satisfactory results in service confirmed the tank tests and added much to the comfort of passengers on subsequent voyages.

Other applications

A large number of subsequent installations have been made, but particulars are not available at the present time though the matter is of considerable interest to operators of medium-sized fast passenger vessels from the point of view of future construction. The matter of stabilising naval vessels for aircraft landing purposes, and for anti-aircraft gunnery, has no doubt been one of interest for the Allied naval authorities during the period of the war.

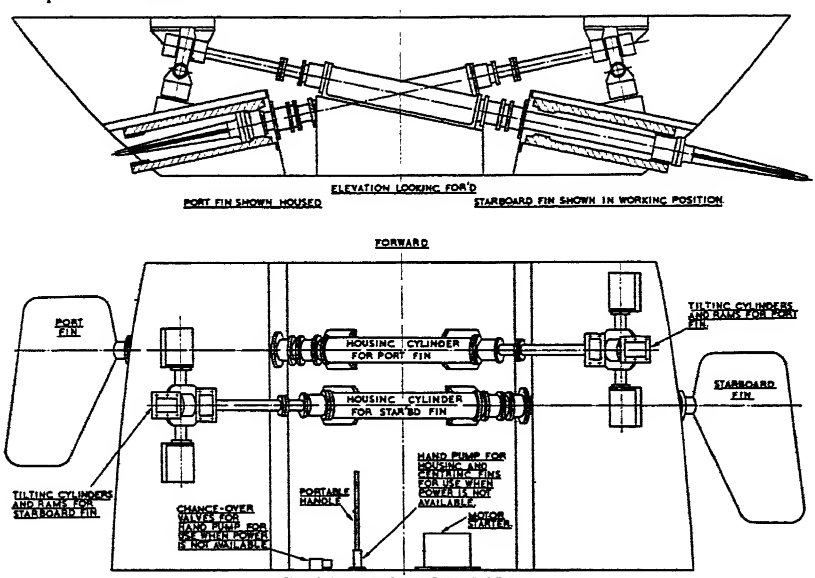


Fig. II.45. Typical arrangement of Denny-Brown stabilising equipment in plan and elevation.

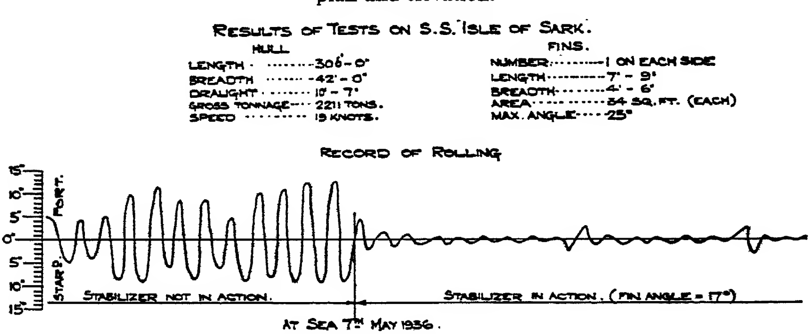


Fig. II.46. Record of rolling, in T.S.S. *Isle of Sark* at sea on May 7th, 1936, showing effect of putting Denny Brown gyro-controlled fin stabiliser equipment into operation.

CHAPTER 9

THE GYROSCOPE IN THE TORPEDO

A torpedo may be described briefly as an instrument designed to carry a large explosive charge at a required depth, and in a required direction, and to detonate that charge upon hitting the enemy target. The torpedo is unique in that it has, of necessity, to carry its own supply of oxygen, as well as fuel for combustion, whereas other machines have only to carry the fuel, the oxygen being obtained from the air. The air vessel, containing air under very high pressure due to the limitation of size, is actually the largest and most expensive part of a torpedo, and when it is remembered that the prime object is the destruction of the enemy target, involving the largest possible explosive charge in the warhead, it will be appreciated that the space available in the torpedo for the engine, fuel, buoyancy chamber and depth and direction-keeping mechanism, is very limited by the overall dimensions as also are the range and speed.

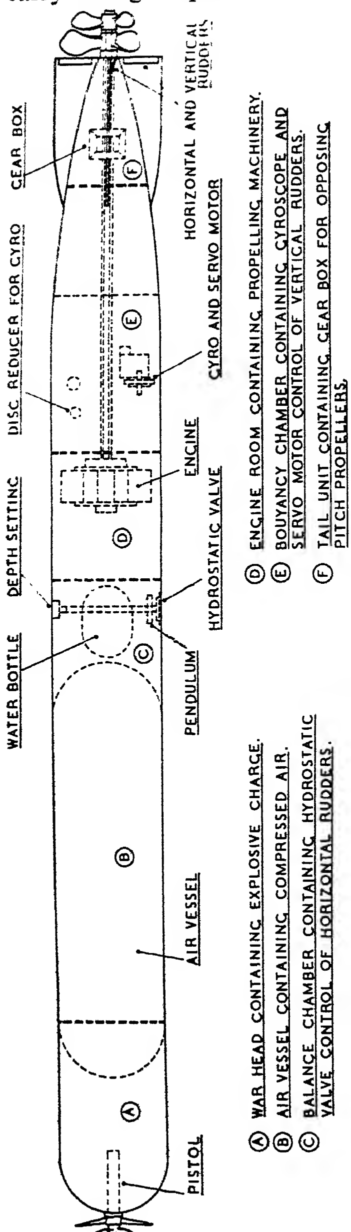


Fig. II.47. Layout diagram of a torpedo showing relative position of gyroscopic control of vertical rudders.

Gyroscopic control of direction-keeping mechanism

While the various parts and functions of the torpedo are of sufficient interest to justify a whole section for their description, for the purpose of this chapter the direction-keeping mechanism only will be dealt with as this is the only mechanism which is controlled by the gyroscope. The depth at which the torpedo travels is controlled by hydrostatic valves which operate horizontal rudders corresponding to the elevators of an aeroplane and their control is in no way gyroscopic.

Before giving a description of this gyro-controlled steering mechanism it may be as well to make it clear that in this case we are concerned only with gyroscopic inertia and not also with the precessional properties of a gyroscope as is the case with the meridian-seeking gyro compass and the gyroscopic stabiliser. It should also be realized that the limitations of space and weight in the torpedo have imposed restrictions on the design of the gyro-controlled steering mechanism, with the result that features desirable in the ideal gyroscope have had to be sacrificed in favour of practical considerations, in view of the fact that the steering mechanism must be kept as small and light as possible.

The course of a torpedo can only be set just prior to discharge as the course and speed of the target must be determined before it is possible to estimate how far ahead of the target it is necessary to aim the torpedo in order that the torpedo and the target will meet. To enable the torpedo to be placed in the correct position for discharge, the gyroscope rotor must be stationary, but at the moment of discharge the gyroscope rotor must be running at sufficient speed to maintain the set course.

It will be clear, therefore, that the necessity of imparting sufficient energy to the rotor to give the maximum speed in the minimum time must limit the size and weight of the rotor, which receives its initial spin from a spring-driven toothed sector which engages with teeth cut on the rotor axle, the sector being released by a trigger when the torpedo is discharged. As the sector swings clear of the rotor it automatically frees the gimbal system, which is kept rigidly locked during the initial spin. When the rotor is in the locked position its axis is parallel to the longitudinal axis of the torpedo; it will therefore take up this position when it receives its initial spin on release. In some designs the initial spin is given by the compressed air used to drive all torpedo gyros throughout the run of the torpedo, irrespective of whether starting is by air or spring.

The mounting of the rotor is such that, on the release of the gimbal system, it is given freedom of movement, If therefore, the torpedo rolls, pitches, or is deflected from its course by an external force, gyroscopic inertia will ensure that the axis of the rotor will remain in the position it occupied at the moment of release. Any relative motion between the longitudinal axis of the torpedo and the axis of the rotor in the horizontal plane is used to operate the vertical or steering rudders of the torpedo.

Rotor and gimbals

The rotor and gimbals are mounted in a frame or housing which incorporates the starting mechanism, controlling and relay valves, and the steering engine.

The rotor consists of a bronze wheel and axle weighing approximately 1½ lb., one end of the axle having teeth cut on it to engage with the starting mechanism, while the opposite end is screwed and fitted with nuts for balancing. Each end of the axle terminates in a hardened steel centre, ground to suit ball bearings in the inner gimbal. Equidistant holes are drilled around the periphery of the rotor to form buckets for the air drive.

The inner gimbal is fitted with ball bearings to accommodate the rotor axle, the ball races being cup-shaped to enable the rotor to align itself without undue friction or lateral play. This gimbal is mounted horizontally in the plane of the rotor axis, on pivots fitted in the outer gimbal, the axis of the pivots being at right angles to the rotor axis.

The outer gimbal is mounted vertically and turns on pivots on an axis at right angles to those which carry the inner gimbal. This gimbal is also fitted with two air nozzles which are set one at each side at an angle so as to direct air jets on to the buckets of the rotor. The nozzles are connected by pipes to the source of air supply through the lower pivot which is hollow, the air pressure passing through the pivot helping to overcome the weight of the gimbal system and rotor and making an almost frictionless bearing. The top of the gimbal carries a disc on which is mounted a small actuating pin.

Controlling valve

The controlling valve is situated at the top of the frame and consists of a small rotary valve working in a valve chest connected to an air supply. Ports cut in the valve and valve chests are so arranged that a movement of $\frac{1}{4}$ deg. in either direction by the valve will open a port on one side to supply, and on the other side to exhaust. A forked lever attached to the top of the controlling valve engages with the actuating pin on the outer gimbal, movement of the gimbal being thus transmitted to the valve. The supply ports are also arranged so that the valve itself is balanced and frictionless, thus imposing no load on the actuating pin.

Relay valve

The relay valve is a small piston valve contained in a cylinder the ends of which are connected to the ports of the controlling valve, the valve piston being forced to one end or other of the cylinder according to which port is open to supply. The object of the relay valve is to allow a much larger quantity of air to be admitted to the steering engine than it would be possible to pass through the small ports of the controlling valve. The valve piston is reduced in diameter in three places to correspond with three ports on one side of the cylinder; two of these ports being connected to the air supply and one to exhaust. On the other side of the cylinder are another two ports which connect with either end of the steering engine cylinder. The ports are so arranged that movemen of the valve piston admits air pressure to one end of the steering engine cylinder while opening the other end to exhaust.

Steering engine

The steering engine consists of a cylinder fitted with a piston and piston rod which is connected by a rod and cranked lever to the steering rudders of the torpedo. The piston is a lapped fit in the bore of the cylinder and has no intermediate position so that when one end is open to supply the other end is open to exhaust, each stroke being the full length of the cylinder.

Starting mechanism

The starting mechanism consists of a toothed sector carried on a spindle mounted vertically in bearings in the gyroscope frame. The teeth on the sector are designed to mesh with the teeth cut on the rotor spindle. The spindle is surrounded by a powerful coil spring which is anchored at one end to the frame and at the other end to the toothed sector. The lower end of the spindle protrudes through the frame and is fitted with a cam, a square hole being provided in the base of the cam to take the cocking key. A trigger lever is kept in contact with the cam by a light spring, and, when the cam is revolved during cocking, the trigger lever drops behind a step in the cam and holds the starting mechanism in the cocked position. A spring-loaded lever mounted on a vertical spindle carries a centering pin. This lever is so arranged that the first movement of the cocking spindle brings the centering pin into engagement with a hole in the inner gimbal and holds the gimbal rigid all the time the sector is in engagement with the rotor axle.

A lever attached to the toothed sector of the starting mechanism, and connected to a small dashpot piston, acts as a cushioning device to bring the sector to rest without shock when it is released.

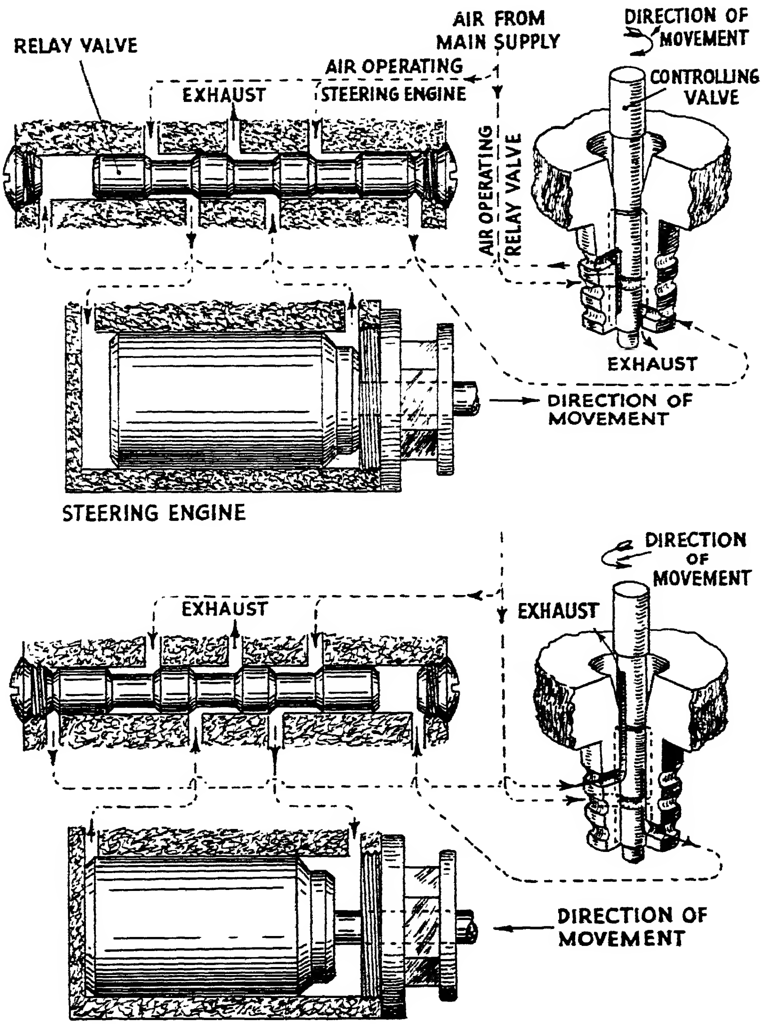


Fig. II. 48. Action of controlling and relay vales and of steering engine under gyroscopic control.

Rectifying clutch

The gimbal system is brought into the central position by a rectifying clutch, which is operated separately by hand before the gyroscope can be cocked. The clutch consists of a spring-loaded lever pivoted to a lug which rises from the bottom of the unit frame. At the end of the lever is mounted a light spring-loaded fork arranged to swivel in a vertical direction. When it is desired to centralise the gimbal system, the clutch is pressed upward against the spring until a small slot at the extreme end is brought into contact with one or other of two pins projecting from the underside of the vertical gimbal, the sides of the slot being so shaped that contact with either of them will force the gimbal into its central position. Further movement of the clutch causes the spring-loaded fork to swivel until it is brought into contact with the underside of the horizontal gimbal, bringing this gimbal into the central position.

When the gimbal system is centralised, and the centering pin is in position, the rectifying clutch is released and is returned by the spring to its former position clear of the gimbals.

Air supply

The air supply for the gyroscope unit which is obtained from the main air vessel through a small disc reducer, is connected to a nipple on the frame, whence it is taken through separate passages to the controlling valve, to the relay valve and the gimbal nozzles. A filter is fitted in the supply passage to prevent dust or grit from being carried into the valve chest or cylinder, and causing damage to the valve surfaces.

Operation

When the gyroscope unit is fitted into a torpedo it is secured to a shock-absorbing mounting with the axis of the rotor parallel to the longitudinal axis of the torpedo. The steering engine piston rod is coupled to a rod attached to the steering rudders of the torpedo. An air supply pipe is connected to the supply nipple on the frame and the starting mechanism cocked.

When the torpedo is discharged, the trigger of the starting mechanism is tripped ; this allows the starting spring to uncoil, turning the toothed sector and spinning the rotor to about 2,000 revolutions per minute, in about one-third of a second.

During the initial spinning, the inner gimbal is held rigid by the centering pin, but immediately the toothed sector has completed its full travel, and is clear of the teeth on the rotor axle, the centering pin is withdrawn, and the rotor and gimbals are then free. Simultaneously with the release of the starting mechanism, an air supply valve is opened, admitting air pressure to the supply nipple on the gyroscope frame.

After passing through a filter, the air separates into three passages, one leading to the controlling valve, one to the relay valve cylinder and the third to the gimbal nozzles. The air jets from the gimbal nozzles are directed on to the buckets formed on the periphery of the rotor and cause the rotor to accelerate. After about five minutes it reaches a steady speed of approximately 27,000 revolutions per minute.

The ports of the controlling valve are so arranged that air is admitted to either one end or other of the relay valve cylinder; there is no neutral position, one end being open to supply and the other to exhaust. The relay valve piston is thus forced to move, and in doing so opens a supply port to one end of the steering engine cylinder at the same time allowing the other end to exhaust. It will be clear therefore that the action of the controlling and relay valves will cause the steering engine piston to move one way or other, according to which way the controlling valve is moved, thereby causing the steering rudders to follow suit.

On starting its run the torpedo will turn to port or starboard, depending upon which side the steering rudders happen to be or upon any other forces acting upon it ; when it has swung about $\frac{1}{4}$ deg. away from the line for which the gyroscope has been set, the forked lever attached to the controlling valve will be moved by the actuating pin on the outer gimbal and turn the controlling valve. This action will reverse the position of the ports, thereby causing the relay valve piston to move to the opposite

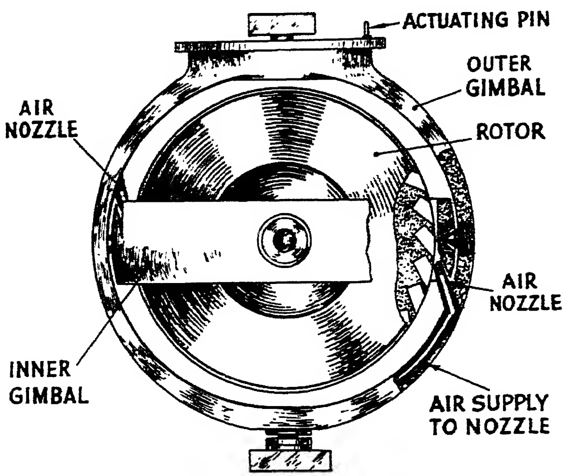


Fig. II,49. Sensitive element of gyroscopic control of vertical rudders showing compressed air supply to turbine type rotor.

end of its cylinder ; this movement of the relay valve piston will reverse the supply and exhaust to the steering engine and cause the steering rudders to move to the opposite side.

The movement of the steering rudders from port to starboard, or vice versa, occurs each time the longitudinal axis of the torpedo passes $\frac{1}{4}$ deg. beyond the line for which it is set, that is, the set course of the gyroscope. The torpedo therefore follows a slightly zig-zag course the mean line of which corresponds to the set course.

Modifications have, however, been introduced which permit an alteration of course of predetermined angular amount to be made by the torpedo immediately on entering the water, after which a steady course is maintained. This obviates the necessity of altering the course of the vessel under certain circumstances in order to bring the tubes to bear on the future position of the enemy target. The torpedo can also be made to zig-zag a definite angular amount on either side of the set course in laps of equal distance, or to run straight for a predetermined distance after leaving the tube and then to zig-zag for the remainder of the run in the target area. Whatever the arrangement dictated by tactics may be, however, the gyroscope remains the "brain" controlling the mean course steered from the tube to the target, and upon its efficiency as a direction keeper may depend the outcome of the engagement.

Conclusion

While the gyroscope in the torpedo may be said to be used for an offensive purpose, as also are the gyroscopes used in the aerial torpedo or in the "flying bomb," the main uses to which the seamen put the gyroscope in ships, and especially in merchant ships, are essentially of a pacific nature. As the heart of the navigation system in the modern vessel, the gyroscope is as vital in peace as in war.

The descriptions of the gyro compass, gyro pilot, gyro stabiliser and gyro-controlled fin stabiliser given in the preceding chapters, will have provided some indication of the extent to which the seamen of this generation depend upon the gyroscope. While there are still many ships which depend upon the magnetic compass alone for their navigational needs, the number decreases from year to year, and the many modifications necessitated by wartime measures to counteract the magnetic mine and dive-bomber at sea have resulted in the conversion of many seamen of the previous generation, who had hitherto looked upon the gyro compass as possibly a desirable innovation but certainly not as a necessity.

These chapters have dealt with the main functions only of the gyroscope at sea, and are not intended to form a comprehensive survey of all adaptations for marine, and particularly for naval use. There are various adaptations which make use of the "rate of turn" function of the gyroscope in precessing. It will be recalled that when a gyroscope is subjected to a couple around an axis at right angles to the spin axis, the degree of resistance to the couple is proportional to the velocity of precession about a third axis at right angles to the other two. This function of the gyroscope is employed in various ways which cannot be described here, but the instruments concerned have played a notable part in the events of the last few years at sea, and will prove of interest to the student of the gyroscope in due course when publication of the technical data becomes possible.

SECTION III—AERONAUTICAL APPLICATIONS

CHAPTER 1

INTRODUCTORY

The gyroscope has many applications in aircraft, and the number of gyroscopic instruments, differing in design but accomplishing with varying success the same object, is even greater. Such instruments used on aircraft can be divided into two broad classes, namely, those which provide a fixed artificial datum and those which measure angular velocity and angular acceleration. This chapter is devoted to an appreciation of the elementary problems involved with a general description of the principles of the various forms of gyroscopic apparatus employed on modern aircraft. Before proceeding further it is essential that the reader should be familiar with the aeroplane and its controls and should appreciate the need for the various instruments to be described.

An outline drawing of a typical modern aircraft is shown in Fig. III. 1. Since an aircraft operates in three dimensional space it has freedom of angular and linear motion in any direction. In this section we are concerned primarily with its angular movements and these will be referred to three axes mutually perpendicular and passing through its centre of gravity. Angular motion about the lateral axis PS is known as pitching. Control of this motion is accomplished by the elevators and is known as longitudinal control. Angular motions about the normal axis VV′ and the longitudinal axis FA are known as yawing and rolling respectively. The corresponding directional and lateral control can be effected by rudder or ailerons. Yawing about the normal axis should not be confused with turning about a vertical axis remote from the aircraft. In normal flight the axis VV′ is vertical and hence the axes PS and FA are in the horizontal plane. On early aircraft directional control was accomplished primarily by means of the rudder, as with a ship, but on modern aircraft the ailerons play a more important part. If either the rudder or the ailerons are operated separately the aircraft will turn and bank but it should be noted that for a given airspeed and radius of turn there is only one correct angle of bank. At any other angle the aircraft will sideslip. For correct curvilinear flight rudder, aileron and elevator controls are necessary. Depending on the stability and control characteristics of individual aircraft it is possible to maintain straight and level flight by using the elevators in conjunction with either the rudder or the ailerons.

Suppose that rudder control is applied to turn the aircraft to starboard, that is, towards the reader in Fig.III. 1. As the turn starts the velocity of the airflow past the port wing increases and hence the lift on the port wing increases. Conversely the air velocity past the starboard wing, and hence the lift also, are decreased. Thus a couple is applied about the longitudinal axis FA and the aircraft banks as it turns.

If the ailerons are used to turn the aircraft it first banks and sideslips in towards the centre of the turn and the resultant side thrust on the rudder and tail fin causes a turn. It will be seen therefore that finally the rudder and tail fin, and not the ailerons, actually bring about the turn.

The effectiveness of rudder and aileron control during turns depends on the aircraft. For example, aircraft with a large rudder and tail fin surface can be turned more effectively by aileron control than those with a smaller surface. There are of course other factors and the reader should remember that the design of modern aircraft differs very much from the designs of ten years ago. This is particularly important to remember when reading the chapter on automatic control.

In simple types of aircraft it would be possible for experienced pilots to accomplish local flying under conditions of good visibility without the use of any instrument whatsoever. For any degree of safety, however, certain instruments are always essential and on large modern aircraft many additional instruments fitted are indispensable. These instruments can be divided into four groups :—

1. Flying instruments.
2. Navigational instruments.
3. Engine instruments.
4. Miscellaneous instruments.

Flying and navigational instruments

Here we are concerned with the gyroscopic instruments which are used for flying and navigational purposes only, and their relation to the other instruments used for this purpose. We shall assume first that the aircraft has no gyroscopic instruments and consider the limitations which ensue.

The flying instruments are the air-speed indicator, the altimeter, the inclinometer, the cross level and the "rate-of-climb and descent" meter. Of these the first two are also used for navigation. The only other navigational instrument which we need consider is the magnetic compass.

As its name suggests, the air-speed indicator gives a measure of the speed of the aircraft relative to the air. It does not, of course, indicate ground speed and the indicated reading is not the true air speed* ; various corrections such as for barometric pressure and air temperature must be applied to obtain the latter. For flying purposes alone the air-speed indicator serves as a stall indicator and provided that the engine speed is constant, it also indicates by an increased reading that the aircraft is diving and by a decreased reading that it is climbing. Thus to some extent it indicates a pitching movement about the lateral axis. It should be noted, however, that this indication is not sufficient to enable the pilot to maintain proper control about the lateral axis. A definite divergence from horizontal flight must occur before any indication is shown and the disturbance cannot be checked at an early stage.

The rate-of-climb meter and the altimeter will both indicate a change in the height of the aircraft. The former instrument shows the instantaneous rate of change of height and the latter shows the height—subject to corrections—at which the aircraft is flying and the amount of any change in height. An aircraft can lose and gain height without change

*True air-speed indicators have been designed but are not included as part of the instrument equipment of the normal aircraft.

of attitude, which means that neither of these instruments can be used to give indications of angular motion about a horizontal axis.

The inclinometer is essentially a liquid level which shows the fore-and-aft attitude of the aircraft. Similarly, the cross level shows the lateral attitude of the aircraft. Unfortunately, neither of these instruments can be used to indicate the attitude of the aircraft except when it is flying at uniform speed in a straight line. They are both gravitational devices and are affected by accelerating forces during both straight and curvilinear flight. In a correctly banked turn the cross level remains central and is useful in that it shows whether the aircraft is correctly banked or is sideslipping. When sideslipping occurs the bubble in the instrument is displaced from zero. Neither instrument is now used as an attitude indicator. The cross level is still used as a sideslip indicator.

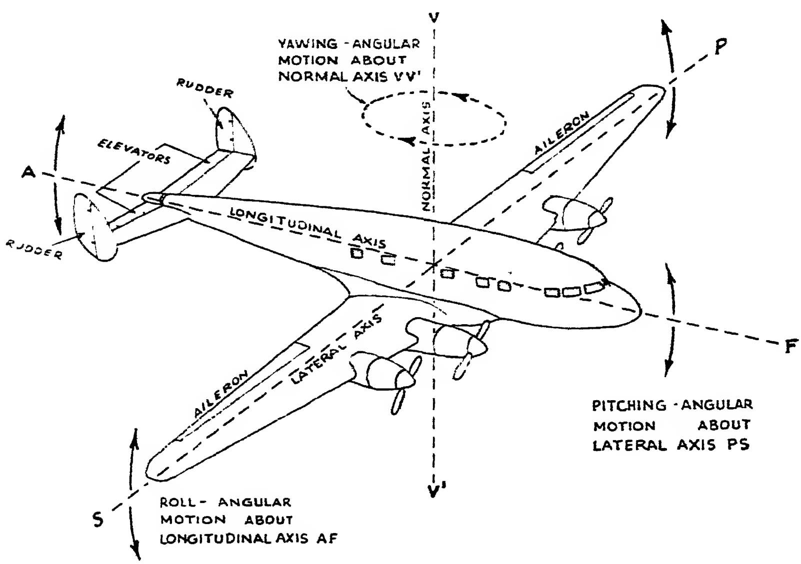


Fig. III. 1. The aeroplane. The amount and control of angular movements are referred to three mutually perpendicular axes.

The magnetic compass. If an aircraft is in unaccelerated and level flight the magnetic compass will indicate the magnetic heading on which it is flying and the amount of any small turns which it makes. Under any other conditions the compass is subject to errors of a magnitude dependent on the design of the individual compass and the nature of the aircraft's manoeuvres. It is not proposed to discuss fully the defects of the magnetic compass but the principal errors will be described briefly.

As will be known to most readers, the direction of the earth's magnetic field, except at the magnetic equator, is not in the horizontal plane. A magnet freely suspended at its centre of gravity and not subject to local intreference, will align itself with the earth's field, that is, in the magnetic meridian, and at an angle to the horizontal known as the magnetic dip. This varies with the latitude of the place and in England is approximately 70°. For a suspended magnet to be useful as a compass it must be approximately in the horizontal plane. On aircraft compasses three methods are used to accomplish this :—

(i) The point of suspension of the magnet system is placed well above its centre of gravity.

(ii) The point of suspension is displaced horizontally from the centre of gravity of the magnet so as to counterbalance the effect of dip. Or in other words, a weight is added to one end of the magnet—to the south seeking end for compasses in the northern hemisphere and to the north seeking end for compasses in the southern hemisphere.

(iii) The magnet system is supported in double pivots so that it has freedom about an axis normal to the aircraft only.

Unfortunately, although these devices limit the tilt of the compass card to a tolerable value, they introduce serious errors when the aircraft is in a turn or is accelerating in straight flight.

In a turn the error can be caused either by centrifugal force on the unbalanced mass, that is, acceleration error, or by dip, that is, if the aircraft banks the compass will act partially as a dip circle and will cease to indicate the true direction in azimuth. Alternatively, in the latter case the earth's field may be considered to be split into horizontal and vertical components and, when the card is displaced from the horizontal during a banked turn, the vertical component displaces the magnet so that during the turn the compass gives a false indication. These errors occur when the aircraft is turning on a northerly or southerly course and are known as northerly turning errors. All three methods of suspending the compass magnet will introduce either one or both forms of the error. The "weighted" magnet is subject to acceleration error. The magnet with low centre of gravity is subject to both forms of northerly tuning error. It is pendulous and hence the magnet does not remain in the horizontal during a turn. Also, since the magnet is displaced slightly from the horizontal by dip when the aircraft is flying horizontally, a turning moment is produced by centrifugal force during turns. The double-pivoted magnet is not susceptible to acceleration errors and is only affected if the aircraft is banked when heading in a N-S direction, as in a turn through north. Both methods of suspension, using a single pivot, are affected also by linear acceleration in an E-W direction.

Since the compass magnet is subject to the disturbances mentioned, its movements have to be heavily damped as otherwise the magnet would be in a continuous state of oscillation and it would not be possible to take a reading. This is done by immersing the complete magnet and pivot assembly in a bowl of liquid, usually a mixture of alcohol and water. The damping thus provided varies with different compass designs and unfortunately introduces a further error, known as liquid swirl. This is caused by the liquid being dragged round by the compass bowl when the aircraft turns. The magnet system is then dragged round by the liquid. The bowl is normally completely filled with liquid and the error is not serious unless air bubbles are allowed to remain. However, the error is always present to some extent and is aggravated by continuous turning in one direction.

The magnitude and duration of the errors described will of course vary with the particular compass design and the manoeuvres made by the aircraft. However, it is of interest to note that the compass indication can be a complete 180° in error, that is, when the aircraft turns in one direction the compass may indicate that a turn has been made in the opposite direction (see Chapter 2, Fig. II. 15), and finally, always supposing the pilot is able to fly the aircraft straight and level, it may be two or three minutes before a correct indication is available.

When natural reference data are visible, such as landmarks, the horizon, a star, etc., an aircraft can be flown approximately straight and level without difficulty. In cloud and fog and in bad visibility at night no such visual references are available and if a substitute were not provided aircraft would be limited to fine-weather flying.

The pilot's sight is the only one sense on which he can rely. His sense of balance, that is, of the vertical, is dependent on gravity. When an aircraft is in a banked turn this sense is subjected to the apparent vertical which is the resultant of gravity and centrifugal force, the only noticeable effect being an apparent increase in weight.

To summarize, the air-speed indicator offers a delayed indication of movement about the lateral axis. Of movement about the longitudinal axis there is no indication at all. Thus the aircraft cannot be flown level, which means that the compass will not function correctly and hence the aircraft cannot be flown straight. It is not difficult to imagine the confusion which could arise and pilots frequently lost control of their aircraft when flying in cloud and fog.

The gyroscopic instruments

The use of gyroscopes in aircraft has made flying possible and safe in cloud and fog conditions. This means also that aircraft can operate at their most economical altitude and are not forced to fly under low cloud to maintain visual contact with the ground. The gyroscope has by no means completely solved the problem of blind flying. Radio devices may eventually solve the problem of obviating collisions with obstructions such as hills and other aircraft. Progress has been made on the problem of blind landing and automatic landing, and gyroscopic instruments will be an essential part of any final solution.

Gyroscopic datum. In Section I of this book the reader will have learnt that one property of the gyroscope is that the axis of spin tends to remain fixed in direction. Hence if a spinning wheel is supported in gimbals so that it is free from angular restraint in all directions, it will be possible to detect any angular movement of the supporting frame with the exception of movements which take place about the spin axis. Thus by installing a single gyroscope in the aircraft, the pilot would be able to detect angular movement of the aircraft about any two axes. Such a gyroscope would, however, have a very limited use, as is explained later.

The gyroscope's property of rigidity, as it is sometimes called, is its most important property as applied to aircraft, but in every case the gyroscopes used are subject to constraint in some form or other, that is, they are subject to corrective couples which precess them in a predetermined manner.

To detect movement of the aircraft about all three axes two gyroscopes are required. Possible arrangements are shown in Fig. III. 2.

Usually a gyro with a vertical axis of spin, known as a gyro-vertical, is used to detect movement about the lateral and longitudinal axis as shown in Fig. III. 2 (a). This is, however, purely a matter of convenience.

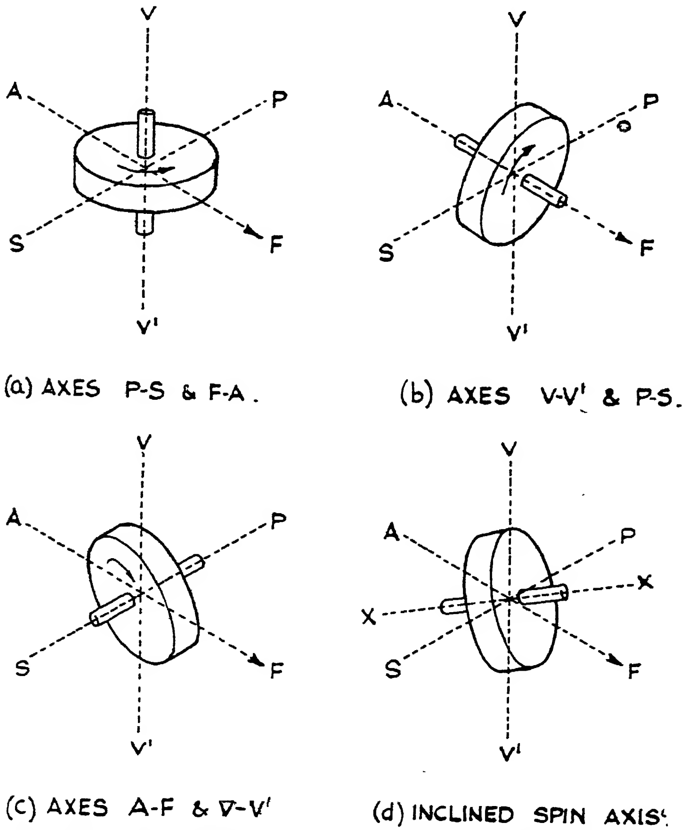


Fig. III.2. Gyro datums. Two gyroscopes are required to define three mutually perpendicular axes.

Movements in azimuth are detected by means of a gyro with its spin axis horizontal. This instrument is known as a directional gyro or gyro azimuth.

The important point to note is that the pilot of an aircraft wishes to know the vertical and his direction on the earth's surface, and the reader should have a clear conception of the limitations of the simple free gyroscope in this respect. The factors which must be considered are :—

(i) The rotation of the earth.

(ii) The speed and direction of the aircraft's flight.

(iii) Mechanical imperfections.

At normal temperature and atmospheric pressure the effect of mechanical imperfections, on commercial gyroscopes, is approximately equal to the sum of the effects of earth rotation and the speed of the aircraft.

However, if we include variations of temperature and atmospheric pressure as mechanical imperfections the latter become more serious. The effect of temperature and pressure variations is to change the rotor speed and, in most cases, the expansion caused by temperature changes will displace the centre of gravity of the gyro. The magnitude of the precessional errors depends on whether attempts have been made in the design to maintain a constant rotor speed and to provide temperature compensation. Random precessional errors are always present because of wear of bearings and the inevitable damage of the delicate parts which are an unavoidable feature of all gyroscopes.

Earth rotation and speed of aircraft. As explained in Section I, a perfectly balanced gyroscope would tend to maintain a fixed direction in space and consequently it has an apparent angular movement because of the rotation of the earth. It has also been shown in Section I that if the gyroscope has a linear motion of its own, as when it is carried on a ship or an aircraft, the apparent angular movement depends also on the speed and direction in which it is moving.

When the gyroscope is in a fixed position on the earth it has an angular velocity $\omega \sin \lambda$ about a vertical axis and $\omega \cos \lambda$ about a N-S horizontal axis, where ω is the angular velocity of the earth and λ is the latitude of the place at which the gyroscope is situated. Before proceeding further it should be appreciated that an aircraft in flying from a point A to a point B on the earth's surface would normally do so in one of two ways, as shown in Fig. III. 3. It can fly either along a great circle track or along a rhumb line. The shortest distance between two points A and B would be the arc length of the great circle which passes through them. This corresponds to a straight line on a plane surface. But in practice there is no direct reference which will enable the pilot of an aircraft to fly a great circle track accurately. It will be seen that except when the track of the aircraft is along a meridian, or along the equator, a great circle makes a constantly changing angle with the meridian, i.e., the track of the aircraft would be constantly changing. If the aircraft flies on a constant compass course, that is, at a constant angle to the meridian, its track is known as a rhumb line. Fortunately the rhumb line distance between two places is not much greater than the great circle distance for journeys up to approximately 500 miles. For longer journeys the aircraft is flown over a series of rhumb line tracks which approximate the great circle track required.

It will be obvious that since the gyro does not detect any angular movement which takes place about its axis of spin it will, if set spinning with its axle parallel to the earth's axis, continue to point to the celestial pole irrespective of the earth's rotation and any motion of the aircraft. The gyro would then always be inclined at an angle to the horizontal equal to the latitude of the place. If we then desired to use the gyro to indicate direction it would be necessary to project the axle vertically on to a horizontal plane. In the case of the gyroscope with three degrees of freedom, that is, with two supporting gimbal rings, this means that the axis of the outer gimbal ring must always be vertical. The practical objections to the use of such a gyroscope are discussed later under "Directional Gyro."

It has been shown in Section I, Appendix 6, that if a space gyroscope is carried on an aircraft flying on a track θ with consequent angular velocity ω_a about an axis through the earth's centre the instantaneous angular velocity of the gyro relative to the aircraft is given by the following equations, ω being the angular velocity of the earth about its axis:

Angular velocity about the vertical $= \omega \sin \lambda$

Angular velocity about N-S horizontal $= \omega \cos \lambda + \omega_a \sin \theta$

Angular velocity about E-W horizontal $= \omega_a \cos \theta$.

These velocities are however only instantaneous values and since the latitude λ is constantly changing during flight on any great circle course, except along the equator, there is an angular acceleration about the vertical and about a N-S horizontal axis.

If a couple could be applied to the gyro, which at any instant was just sufficient to cause it to precess at the rates given by the above equations, it would be possible to use the gyro as a reference for flight along a great circle. This would however require a continuous knowledge of the latitude λ and/or the ground speed, and automatic application of this information to produce the desired precessing torque would be extremely difficult.

In practice, mechanical imperfections in the gyroscope often produce gyro precession of the same order as the "apparent precession" resulting from the rotation of the earth. Further, the ground speed of an aircraft cannot be determined either accurately or automatically. In general, because of the indeterminacy of the corrective couples necessary, it is not practicable to use a "space gyro" as a reference for the vertical or for direction on the earth's surface.

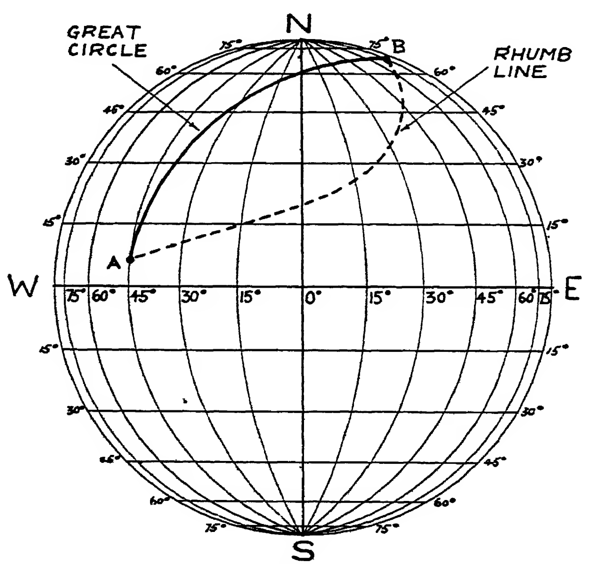


Fig. III.3. The shortest distance between two points on the earth's surface is the arc length of the great circle which passes through them. In practice, an aircraft has no reference datum for flying an exact great circle track. It flies a set course and its track is along a rhumb line, that is, a line which makes a constant angle with the meridian.

Use of gyroscopic compass. The various gyroscopic compasses used on marine vessels have been described in Section II. These instruments are "north seeking" and depend on the rotation of the earth for their operation. Unfortunately they are unsuitable for use on aircraft because of the relatively high speed of which the latter are capable and the greater accelerating forces which obtain. The various errors of the gyro compass would be difficult to compensate.

In addition, there is the fundamental defect that if the compass is moving at a linear speed equal to the peripheral speed of the earth, and in the opposite direction, it will have no meridian seeking torque. As explained in Section I, this occurs when $v_a = 900 \cos \lambda$, where v_a = ground speed of aircraft in knots and λ = latitude in degrees. It has been shown in Section I* that the meridian-seeking torque of a gyro compass is given by :—

$$K = H_s \, \omega \cos \lambda \sin \alpha$$

where H_s = moment of momentum of rotor about its axis of spin
ω = angular velocity of earth
α = angle between meridian plane and a vertical plane containing the gyro axle

If the aircraft is moving with a velocity v_a from east to west the foregoing expression is modified to :—

$$K = H_s \, (\omega \cos \lambda - \omega_a) \sin \alpha$$

where $\omega_a = \dfrac{v_a}{R}$ = angular velocity of aircraft about centre of earth (of radius R).

On a ship the meridian-seeking torque is too small to be effective at latitudes above 85°. Thus if we assume the maximum ship's speed on which this limit is based to be about 40 knots and the maximum aircraft ground speed (airspeed + windspeed) to be about 400 knots, the maximum useful latitude at which the compass can be used on an aircraft can be obtained from the foregoing equation. Expressing all angular velocities in min. of arc per hr., i.e., in knots, for convenience, we have :—

$$H_s \, (900 \cos 85° - 40) \sin \alpha = H_s \, (900 \cos \lambda - 400) \sin \alpha$$

$$900 \times 0{\cdot}0872 - 40 = 900 \cos \lambda - 400$$

$$\lambda = \cos^{-1} \frac{78{\cdot}48 + 360}{900}$$

$$= \cos^{-1} 0{\cdot}4872$$

$$= 60° \text{ (approx.)}$$

It will be agreed that a compass which is limited to latitudes between 60° N. and 60° S. would be of little use on aircraft. As previously mentioned, however, the various errors (*see* Section I) and the stringent conditions under which the mechanism would be required to function on an aircraft are of even greater consequence.

Before proceeding further it is important to note that although the free gyroscope is by no means perfect, and is also affected by the motion of the earth and the aircraft, it will give no serious error over a short period of time. For example, if a space gyro with a vertical spin axis

*See Section 1, Appendix 2, equation (16). The second term in (16), $H \omega \cos \lambda \sin \alpha$, is the meridian seeking torque of the gyro.

is situated at the equator it will after twenty seconds be inclined at an angle of 0° 5′ to the vertical. If this angle is trebled as a result of mechanical faults the effect is still not serious. Further, if the gyroscope's centre of gravity is coincident with the intersection of its three axes of support it is unaffected by accelerations of the aircraft in which it is carried. With a total weight of a few ounces only, the gyro-vertical will serve the same purpose as a long-period pendulum, a device which because of its weight and/or length cannot be carried on an aircraft. A pendulum indicator when limited to a practical size is of no use as an indicator of the vertical except when the aircraft is flying with uniform speed in straight flight. Under any other condition it will be displaced from the vertical by accelerating forces. The bubble indicator (spirit level) is subject to the same limitation.

Similarly, the error given by a directional gyro is small over a short period of time. Thus if either a continuous or an intermittent short-period correcting couple is applied to the gyroscope errors can be reduced to a negligible quantity.

Fig. III. 4 is a diagram showing how a free gyroscope is used as a directional gyro and as a gyro vertical. The gyro rotor is supported in gimbal rings which are free to turn about horizontal and vertical axes. The outermost ring is supported in a frame and it will be seen that the frame can be turned about the rotor in any direction, except when all three axes are in the same plane.

With the directional gyro, angular movement about a vertical axis is detected by fixing a compass degree scale to the vertical gimbal and a pointer to the outer frame, the latter being rigid with the aircraft. In Fig. III. 4 the pointers are shown fixed to the gimbal ring for convenience in illustration. With the gyro-vertical, pitching movements are measured by the relative movement between the frame and the horizontal gimbal, and rolling movements by relative motion between the frame and the vertical gimbal. The N-S line of the compass scale on the directional gyro is usually aligned with the rotor axle (see Chap. 3), so that the latter is parallel to the longitudinal axis of the aircraft only when the course is due north or south. In the gyro vertical the axis of the vertical gimbal is set parallel to the longitudinal axis of the aircraft and remains in this relationship for all directions of flight. The axle of the gyro is vertical as shown in Fig. III. 4.

The directional gyro. The requirements of a directional gyro are (a) that the gyro axle shall remain horizontal and (b) that the gyro axle shall continue to point in a fixed direction in the horizontal plane, say, north. The reader will remember from Section I, Appendix 6, equation (63) that the rate at which the gyro will move away from a set course is given by the expression $\omega \sin \lambda + \omega_a \sin \theta \tan \lambda$, and the gyro must be constrained to precess at this rate about the vertical if a north heading is to be maintained. It will be observed that unless the course θ is due W or E the lattitude λ is continuously changing and hence there is an angular acceleration as in the case of a gyro which is intended to define a reference for a great circle track. If the course is due E or W the angular velocity of the gyro is $\omega \sin \lambda + \omega_a \tan \lambda$ and is constant since the latitude λ does not change. In this instance the gyro could be constrained to maintain its heading by applying a simple gravitational torque, that is, the gyro can be balanced so that it maintains its northerly heading at a given latitude and ground speed v_a, in either an east or a west direction. This arrangement would obviously have a very limited application.

In practice a compromise is made both in the method of keeping the gyro axle horizontal and in maintaining its direction. To keep its axle in the horizontal plane the gyroscope assembly is provided with an automatic device which tends to keep the axle perpendicular to the axis of the vertical gimbal. Thus if the horizontal gimbal moves from the perpendicular position a couple is automatically applied about the axis of the vertical gimbal. This precesses the gyro back to the perpendicular position where the precessing couple is zero. It will be seen therefore that this method of keeping the gyro axle horizontal is dependent on the

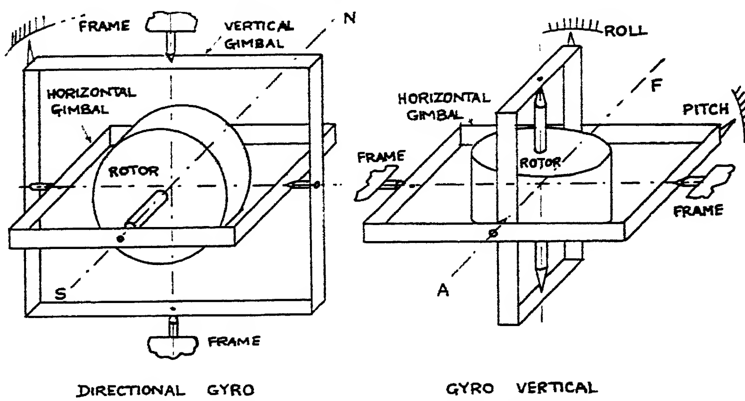


Fig. III.4. The directional gyro and the gyro vertical have freedom about three mutually perpendicular axes. The axle of the directional gyro is horizontal while that of the gyro vertical is vertical.

outer gimbal axis being vertical. Actually the gyroscope is so installed that the outer gimbal is vertical when the aircraft is in level flight, and the correct functioning of the instrument is therefore dependent on a mean horizontal flight attitude. Temporary variations from the horizontal are of no consequence since the control torque, though sufficient to correct the gyro movement resulting from precession or other causes, is insufficient to cause any serious error from disturbances of a transient nature. Since this method of corrective control is in common usage with gyroscopic instruments it is desirable that the reader should appreciate it fully. For example, if the maximum value of the free precession* of the gyro about a horizontal axis is 0·5° per min., the maximum precession produced by the correcting torque might be designed to be 3° per min.

If the aircraft is in straight and level flight transient disturbances may have a period of 3 to 10 seconds and furthermore these disturbances are always oscillations about a mean attitude so that the effect of a displacement to one side of the vertical is followed by a displacement in the other direction. Hence in level flight the gyro axle may oscillate, from this

*The term free precession will in future be assumed to include all relative movement of the gyro when no external torque is intentionally applied. During flight this may have a maximum value of $\omega \sin \lambda + \omega_a \tan \lambda \pm$ (resultant precession caused by applied and random gravitational torques).

cause, through an angle of approximately 0·15° to 0·5° about the horizontal. Larger disturbances of the gyro will occur when the aircraft is in a slow glide, or a climb with the axis of spin fore and aft which, if of sufficient duration, would cause the inner ring of the gyro to precess until it was at the same inclination to the horizontal as the longitudinal axis of the aircraft. Once level flight conditions are resumed it will again be precessed towards the horizontal. Thus to summarize, free precession about the horizontal axis is suppressed by a slow rate of control. This ensures that the gyro axle is always approximately in the horizontal plane. If the free precession were not corrected the axle would eventually reach the vertical, in which case the gyroscope would obviously be of no use as a direction indicator. In fact the instrument does not function correctly as a direction indicator unless the three axes are mutually perpendicular and the outer gimbal axis is maintained in the vertical. Since the outer gimbal axis is rigid with the aircraft it follows, therefore, that a correct indication is not given while the aircraft is in the banked, climbing or gliding attitude, but only after the aircraft is again in horizontal flight.

These errors are not concerned with gyro precession but are a result of the geometry of the gimbal system in that, unless the gyro frame, i.e., in effect the aircraft, is rotated about one of the gyro axes, the outer gimbal ring must itself move if the direction of spin is to remain undisturbed. Since we are relying on the outer gimbal ring to remain fixed in azimuth, the indication of the amount of the turn will be in error. It should be noted that the angle turned through in azimuth is required and not the rotation of the aircraft about its normal axis. If the directional gyro were stabilized in the vertical it would give the azimuth component of any turn made by the aircraft.

It will be seen, therefore, that the indication of the directional gyro can be incorrect under the following conditions :—

(a) For flat turns and straight flight, if the outer gimbal is displaced from the vertical.

(b) For banked, climbing or gliding turns, but during the turn only except in cases as in (a) above.

The magnitude of the error is dependent on the bank angle and the direction of the gyro axle relative to the longitudinal axis of the aircraft, i.e., the course angle. From similar considerations, unless the gyro axle is horizontal, rolling and pitching movements of the aircraft will be indicated as changes in course ; or if the aircraft dives, without turning and depending on the heading, a turn may be indicated.

It is not proposed to analyse all possible errors due to banking, climbing and/or tilting of the gyro axle but the indication of the directional gyro during banked turns can be shown to be :—

$$I = \tan^{-1} \tan \varphi \cos \delta$$

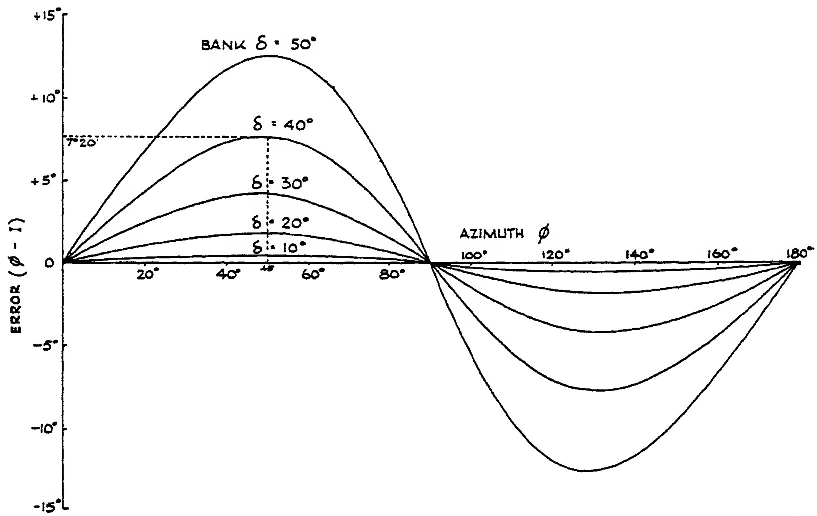
where I = indicated course

φ = true course or azimuth heading

δ = bank angle of aeroplane

Thus the error in the indicated reading is equal to $\varphi - I$. The error during a complete 180° turn starting from north, for various bank angles, is shown in Fig. III.5. It will be seen that the maximum error for banks up to 30° is less than 5°, while for a 40° bank it is about 7°. When the aircraft is level, or nearly so, the error is negligible and it is of no practical consequence during moderately banked turns.

As mentioned previously, the errors are also affected by any tilt of the gyro axle. It should also be noted that the error is due to an angular



Crown Copyright

Fig. III. 5. Banking error of directional gyro. The indicated angle of turn is not correct unless all gyro axes are mutually perpendicular. Thus when the aircraft turns and banks the angle of the turn is not shown correctly until horizontal flight is resumed.

movement of the vertical gimbal relative to the fixed frame. Thus if a directional gyro is spinning in the fore and aft plane of the aircraft, but with its axle tilted, a roll of the aircraft about its fore and aft axis will result in a movement of the vertical gimbal. This effect is made use of in gyroscopic equipment to be described later.

In practice the freedom of the gyro on each side of the horizontal is usually limited by unavoidable features in the design of the instrument. Thus a directional gyro may have $\pm 60°$ of freedom in pitch instead of complete freedom as shown in the diagram in Fig. III. 4. It will be seen that if the axle is allowed to deviate too far from the horizontal, normal pitch or roll movements of the aircraft may cause the limit stops to abut with the horizontal gimbal ring, which results in a torque about the horizontal gimbal axis, and precession takes place about the vertical gimbal axis, thus causing the gyro axle to lose its set heading.

The second requirement of the directional gyro is that the gyro axle shall maintain its azimuth heading. This condition cannot be met entirely. In practice the free azimuth precession is reduced to the lowest practical limit to suit that part of the world in which the instrument is to be used. This is done by adding weight to one side or the other of the horizontal gimbal axis so that the resultant gravitational torque produces a precession in the opposite direction to the relative notion due to earth rotation. By this means the free azimuth precession may be limited to say 15° per hr. for any locality in which the gyro is likely to be used. Obviously, therefore, such an instrument is only of use as a direction indicator for specified time limits. But it should be noted that even so it can be used for making accurate turns since it is not subject to the turning errors of the magnetic compass and gives no appreciable error over a short time.

In the past the directional gyro was reset manually to the correct headings at regular intervals. The pilot of an aircraft would fly straight and level, thus enabling the magnetic compass to give a correct heading, and then set his directional gyro to the same heading. Some modern instruments are designed to apply a correction automatically and thus combine the true mean heading of the magnetic compass with the instantaneous true heading of the directional gyro. The same control principle is employed as with pitch control of the inner ring on the directional gyro, that is, a slow constant control. Automatic correction of the precession is usually done by means of air pick-offs or electromagnetic devices, and examples of the various designs are described in later chapters.

As mentioned earlier in the chapter, if the gyro axle is inclined in the meridian plane at an angle equal to the latitude of the place, the gyro will not be affected by rotation of the earth. However, from the foregoing paragraphs it will be seen that such an arrangement is not practicable with the simple directional gyro. Suppose that the aircraft is flying at a latitude of 60° N. or S. The gyro would then be inclined at 60° to the horizontal with the following disadvantages :—

(i) Depending on the heading of the aircraft, rolling or pitching motion of the aircraft would, because of "gimballing effect," cause a continuous oscillation of the vertical gimbal and hence of the heading indication.

(ii) If the aircraft, during manoeuvres, were inclined at 30° to the vertical on an East or West heading, the gyro axle would be aligned with the axis of the vertical gimbal (*see* Fig. III. 4), and in this position it would have no directional properties. Furthermore since all the axes would then be in the same plane, "gimbal lock" would cause the gyro to topple if the aircraft either pitched or rolled in the plane of the vertical gimbal. As mentioned, in practice alignment of the gyro axes is prevented by stops which would topple the gyro before the attitude of the aircraft had reached a 30° inclination to the horizontal.

Such a gyroscope could be used only if it were stabilized in the vertical. However, at the present time it has not been possible to manufacture a directional gyro of sufficient accuracy to justify this additional complication.

The gyro-vertical. The only requirement of the gyro vertical is that the rotor axle should remain vertical irrespective of earth rotation, motion of the aircraft and mechanical defects. This requirement, although simple in conception, is not easy to satisfy, and it is only in recent years that some measure of success has been achieved. Before proceeding further it should be remembered that other arrangements of the spin axis may be used for indicating the vertical, but a vertical spin axis is the only possible arrangement with a single gyroscope. Reference to Fig. III. 4 will show that roll of the aeroplane will be indicated by the vertical gimbal, and pitching will be indicated by the horizontal gimbal, relative to a supporting frame fixed to the aircraft.

The gyro-vertical is, of course, not sensitive to rotation about the vertical. As shown in Section I, Appendix 6, equations (60) and (62), the angular velocities which affect it are: $\omega \cos \lambda + \omega_a \sin \theta$ about a N-S horizontal axis and $\omega_a \cos \theta$ about an E-W horizontal axis. Or expressing this in another way, the resultant rate of deviation from the vertical is given by the vector sum of $\omega \cos \lambda$ (due to rotation of the earth) and ω_a (the angular velocity of the aircraft about the centre of the earth). In the foregoing formulae $\theta =$ the track angle and $\lambda =$ the latitude. The "apparent" (but nevertheless effective) precession, given by the foregoing expressions, is present on all gyro verticals.

If the gyro axle moves from the vertical a correcting torque must be applied which will precess it back to the vertical. Also if the gyro axle is initially displaced by a considerable angle, say 40°, it must reach the vertical within a reasonable space of time. The rate at which the gyro axle seeks the vertical is known as the erection rate. Ideally this should be as fast as possible. Unfortunately the only means of knowing the vertical is by the direction of gravity, as given for example by a pendulum, which of course will not give the vertical if any accelerations are present. Over a period, however, the pendulum will oscillate about the mean vertical and, as in the previous instances, a slow rate of control can be employed so that during turns, when it will be displaced for an appreciable time, the couple causing precession of the gyroscope will not introduce a serious error.

Thus we have a pendulum controlling a gyroscope and if the gyroscope is, for example, displaced by 2° from the vertical about its lateral axis, the pendulum is arranged to operate a device which applies a couple about a perpendicular axis and thus precesses the gyro towards the vertical. Similarly, of course, if the pendulum moves from the vertical, as it does when the aircraft turns, the gyro will be precessed to follow it. Thus in practice the maximum erection rate we can use is limited by the maximum error which can be tolerated during turns. The minimum erection rate is decided by the rotation of the earth, the speed of the aircraft and by the degree of perfection attained in the manufacture of the gyroscope.

For small angular displacements from the vertical the couple tending to erect the gyro is usually proportional to the displacement, but for larger displacements it is arranged to remain constant. It is desirable also that the couple should give the same erection rate when the spin axis is displaced by any angle in any direction, and this object is achieved, within limits, by some of the mechanisms in use on modern instruments.

The use of a constant control rate, in all directions, is required to minimise and reduce the duration of errors which are caused by turns during flight. If the aircraft completes a turn lasting half a minute with a 30° bank, the erecting control on the gyroscope will be as though the axle were displaced from the vertical by 30°. Consequently, if the erection rate is made proportional to the displacement, a rate appertaining to 30° is active during the turn. When the aircraft levels out after the turn, however, the mean rate tending to restore the axle to the vertical is only half that applicable to the initial inclination of the axle to the vertical. For example, if we require the gyro to return to within $\frac{1}{3}$° of the vertical, the minimum control rate we can use might be, say, 5° per minute. If this rate is constant for all displacements the error in the vertical will, for practical purposes, disappear after a period of level flight equal to the time of the turn. With any other arrangement both the magnitude and the duration of the error are increased. A numerical example will make this clear :—

Case 1. *Constant control rate of* 5° *per min.*

Error at end of ½-minute turn $= 0{\cdot}5 \times 5 = 2{\cdot}5°$
Duration of errors $= 2{\cdot}5 \div 5 = 0{\cdot}5$ min.

Case 2. *Control rate increases from* 5° *per min, at* 0° *to* 15° *per min. at* 20°, *and is then constant.*

Error at end of ½-minute turn $= 0{\cdot}5 \times 15 = 7{\cdot}5°$
Duration of errors $= 7{\cdot}5 \div \frac{8{\cdot}75}{2} = 1{\cdot}7$ min. (approx.)

Equal erection rates for displacement in any direction are required to reduce the possibility of a slow cumulative error during manoeuvres. For example, suppose the aircraft flies a mean straight course but makes alternate right and left-hand turns. If the mean erection rates are equal during each turn there will be no permanent error. If they are unequal, however, the gyro axle will deviate from the vertical at a rate given by $\frac{1}{2}t(l_1—l_2)$, where t is the time of the manoeuvre and l_1 and l_2 are the mean erection rates.

Note. Balancing of the two control rates on a compass-monitored directional gyro is necessary for similar reasons. (*See* Chapter 2.)

In practice there will always be a small difference in the erection rates of a gyro-vertical, even if the design itself gives equal rates. This is because the free precession of the gyro will always oppose the erection in one direction and assist it in the other. The free precession of a gyroscope, in addition to being dependent on the latitude and the speed and direction of flight, is subject to random changes because of mechanical wear, varying temperature and varying rotor speed, as mentioned earlier.

The gyro-vertical may be used in three ways on an aircraft :—

(a) to give an indication of rolling and pitching of the aeroplane ; in this application it is known as an artificial horizon,

(b) as the detector element for measuring the amount of roll and pitch in an automatic control, and

(c) to stabilize other instruments, or components of other instruments, in the horizontal plane.

Functions (a) and (b) are sometimes performed by the same instrument. Function (c) includes the stabilisation of sighting planes for cameras, drift sights, bombsights, gunsights and navigational octants, etc. It is also used to stabilize the magnetic element of some types of distant-reading compass. That is, the magnetic detector element, be it a magnet or a "flux gate," is maintained in a horizontal plane so that it is not subject to banking errors as described earlier in this chapter.

It should be noted, however, that fundamentally, such a gyro-stabilized compass is subject to larger maximum errors than a compass-monitored directional gyro. If the gyroscopes used in the two cases are of equal mechanical quality the two control rates will be the same, that is, the precessional control maintaining the directional gyro in the magnetic meridian is the same as that keeping the gyro-vertical in the vertical. Thus for disturbances of equal duration each gyro would be precessed from its true position by an equal angle. In the case of the directional gyro this angle is the total error in heading, but in the case of the stabilized compass it is the inclination of the gyro-axis to the vertical. The actual error introduced in the compass heading depends on the direction in which the gyro axle is tilted and the magnetic dip angle at the latitude concerned. It is a maximum when the gyro axle, and hence the magnet-pivot, is tilted due east or west, when it can be shown to be :—

$$e = \tan^{-1} \tan d \sin t$$

where e = error in heading

d = dip angle

t = tilt angle of magnet axis

Thus in England, where the magnetic dip is about 70°, the compass error may be about three times the tilt angle of the magnet axis, the latter being equal to the tilt of the gyro axis.

The comparative performance of commercial instruments working on the two different principles will of course depend on the relative control rates used, which in turn will depend on the degree of accuracy attained in making the gyroscopes.

Angular velocity meters. If the aircraft turns about any of its axes the direction in which it turns and the rate of the turn can be shown by making use of the gyroscope's properties of precession and gyroscopic torque. The most common application is to measure rate of yaw, that is, movement about the normal axis. It will be obvious that the directional gyro does not give an indication of rate of turn but only of the angle by which the course has changed. The angular velocity meter, used as rate-of-turn indicator, is particularly useful in that it gives a large indication when it is most needed. Thus if the aircraft starts to diverge very rapidly from its set course, the directional gyro at first gives a small indication only, but the rate-of-turn indicator, since it is measuring rate-of-turn and not angle of turn, may give a full-scale deflection before the course has changed appreciably. The pilot is thus able to correct the disturbance before it reaches serious proportions.

The principle of a rate-of-turn indicator is shown in Fig. III. 6. The gyro rotor is mounted in a single gimbal ring supported on pivots in a fixed frame. The gimbal axis may be athwart the aircraft or fore and aft, as shown in Fig. III. 6. The rotor, in this case, has freedom of spin about the lateral axis and can precess about the longitudinal axis only.

If the aircraft turns a torque is applied about the vertical axis and the rotor precesses about the longitudinal axis. Thus if the direction of spin is as shown in Fig. III. 6, a left-hand turn causes the gyro to precess in a clockwise direction and a right-hand turn causes it to precess in an anti-clockwise direction. If the precession were not checked in some manner the gyro would precess until the rotor was spinning about the same axis and in the same direction as the turn of the aircraft.

In Section I it has been shown that the gyroscopic torque K is given by :—

$$K = I_s \omega \Omega$$

where ω = rotor speed

Ω = angular velocity about a perpendicular axis in the plane of spin

I_s = moment of inertia of rotor about axis of spin

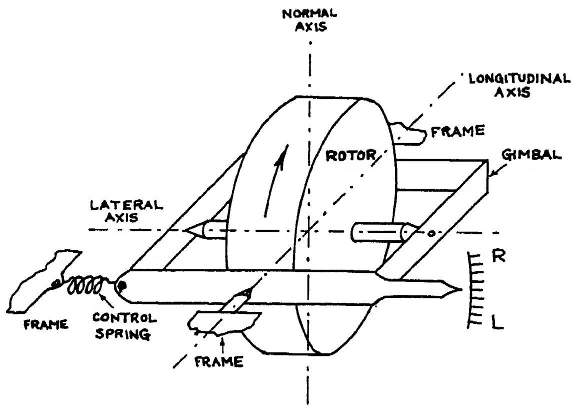


Fig. III.6. Angular velocity meter. Turning of the aircraft produces a torque about the normal axis. Precession takes place about the longitudinal axis—in a sense tending to align the direction of rotor spin with the direction of the applied torque—and ceases when the gyroscopic torque equals the control torque.

The moment of inertia is fixed and therefore if the rotor speed is constant the gyroscopic torque is directly proportional to the angular velocity Ω about a perpendicular axis.

The precession of the gyro is opposed by a torque which is proportional to the deflection of the axis of spin from the lateral axis of the aircraft. As shown in Fig. III. 6, the control is usually in the form of a spring constraint on the gimbal ring. Thus when the aircraft turns at a uniform rate the gyro precesses about a fore-and-aft axis and indicates the direction of the turn, and at the same time extends the spring until the spring torque is equal to the gyroscopic torque, when precession about the fore-and-aft axis ceases. In this condition the spring torque is just sufficient to cause the rotor to precess about a perpendicular axis at the same rate as the component of the aircraft's turn about that axis. Or alternatively it may be said the rotor wheel precesses about the vertical at the same rate as the aircraft. The inclination of the gyro axle to the lateral axis is therefore a function of the rate of turn. If the spring torque were directly proportional to the inclination of the gyro axle, we have $\theta u = I_s \omega \Omega$ where θ = inclination of axle and u = control torque for unit angle. It should be noted that in the above expression θ is directly proportional to the rate of turn Ω about an axis which is always perpendicular to both the axis of spin and the gimbal axis. Consequently, although it is proportional to the angular rate at the start of a yaw, during a turn it is not proportional to the rate of turn about the normal axis of the aircraft, because when the turn starts, the gyro axle is immediately deflected from its initial alignment with the lateral axis, that is, perpendicular to the normal axis. Also, the angle θ is not proportional to rate of turn in azimuth except when it is equal to the bank angle of the aircraft, that is, when $\tan \theta = \tan \varphi = \frac{\omega_a^2 r}{g}$ where

φ = correct bank angle of aeroplane (for no sideslip)
r = radius of turn
ω_a = angular velocity of turn in azimuth
g = 32·2

The sense of rotation of the gyro rotor is usually such that when the aircraft turns the rotor tilts in the opposite direction to the bank of the aircraft. This will occur in the case of the instrument shown in Fig. III, 6, and tends to keep the plane of spin towards the vertical ; hence the tilt θ, for a given rate of turn, is a maximum.

Since the correct bank angle of the aircraft depends on the angular rate of the turn and also on the radius of turn, while the deflection of the gyro axle depends on rate of turn only, it is not possible to calibrate the indication of the instrument so that it is correct for all flight conditions, even if we assume that all turns will be correctly banked.

In practice, rate-of-turn indicators do not show the actual rate of the turn in degrees per minute. They merely give a relative indication of whether the aircraft is turning fast or slowly. The control force on the gimbal ring is designed to give a large initial deflection of the pointer which can easily be seen by the pilot. The dials of some instruments are marked with numbered divisions, e.g., 1-2-3-4- on each side of zero, but the numbers have no real meaning during continuous turns except as relative rates of turn under specified conditions of bank and airspeed. They are provided for adjusting the sensitivity of the instrument, and correspond to certain rates of turn when the instrument is rotated about a vertical axis. This corresponds to a flat turn and since the aircraft never does flat turns in normal flying the rates of turn allocated to the numbers do not apply to flight conditions. In applications other than as an indicating instrument the angular velocity meter may be designed to measure quantitative rate of turn at a specified airspeed.

The oscillations natural to the gyro system are damped by an air dashpot or other suitable means.

Angular accelerometers. In some types of automatic control it is necessary to know the angular acceleration of the aircraft about one or more axes. This is done by using an angular velocity meter and measuring either the torque about the axis of the turn or the precession rate of the gimbal ring.

Thus in the first case, while angular acceleration is present there is a torque about the turning axis, viz.,

$$K = \alpha I_v = I_s \omega \Omega$$

where α = angular acceleration about axis of applied torque, i.e., axis about which aircraft is turning.

I_v = moment of inertia of gyroscope assembly about axis of applied torque.

This torque which normally results in increased bearing pressure can be measured approximately by mounting the angular velocity meter in a second gimbal with a spring constraint as shown in Fig. III. 7. The angle through which this gimbal moves is proportional to the torque acting about the gimbal axis and providing that the deflection is small it is proportional to the angular acceleration $\frac{d\Omega}{dt}$. In practice the gimbal deflects through a small angle which is amplified by suitable means.

Since in a rate-of-turn indicator the deflection θ of the gyro axle against the control spring is proportional to the angular velocity Ω, it follows that the angular acceleration $\frac{d\Omega}{dt}$ is given by $\frac{d\theta}{dt}$ which is the precession rate of the gimbal ring in the angular velocity meter. In practice this is sometimes measured by pneumatic means, using a differential pressure diaphragm as explained in a later chapter (see Fig. III.65).

Automatic pilots

The object of an automatic pilot is to relieve the human pilot of the monotonous routine of flying the aircraft straight and level, and to fly it with greater accuracy. Modern aircraft have less aerodynamic damping and journeys are longer, thus the need for relieving the pilot's fatigue is greater than in the past. More accurate pilotage of both civil and military aircraft is required for a number of reasons among which may be mentioned: comfort of passengers, more economical operation and the provision of a stabilised platform for photographic aerial surveys and sextant navigation. A further military application is the "pilotless" aircraft, which is used either as a target aeroplane for gunnery practice or as an aerial torpedo. Most readers who were in Southern England during 1944 will be familiar with both uses.

It is beyond the scope of this book to deal with automatic control and the stability of aircraft, but a brief outline is necessary to clarify the part played by the gyroscope. It is important to realize first that an aircraft automatic pilot does not stabilise the aircraft by means of gyro-

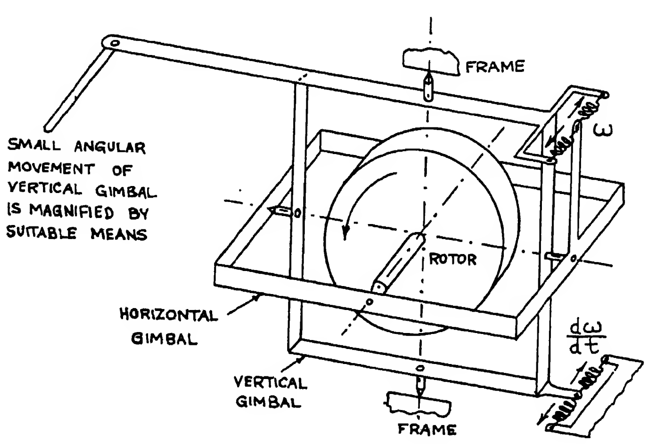


Fig. III. 7. Angular accelerometer. Displacement of the vertical gimbal, provided it is small, is proportional to angular acceleration about the vertical axis.

scopic torque in the manner of the Sperry ship's stabiliser described in Section II. The gyroscope, or gyroscopes, are used to define two or more reference lines or axes, to detect any angular movement of the aircraft away from these reference lines (*see* Fig. III, 1) and to control a servo-mechanism which operates the aircraft's controls, as the human pilot would under similar conditions. The gyroscope therefore provides a "brain" for the automatic pilot (see Chapter 5) but it does not provide "muscles." For the latter, the weight of the gyroscope required would be prohibitive on aircraft, and in addition, the direction of the reference lines defined by the gyroscope would be changed by the precession caused by the torques imposed on the gyro.

The human pilot controls an aircraft with an accuracy which depends on his individual experience and skill as a pilot. In general, the accuracy of control achieved depends on the pilot's ability to interpret correctly, with the aid of the various instruments, the angular and linear motion of the aircraft during a disturbance. For accurate control, that is, for a minimum change in attitude under any conditions of flight, it may be necessary for an automatic pilot to take note of the amount, velocity and acceleration of any angular disturbance and also of the aircraft's airspeed and linear acceleration. In most existing designs of automatic pilot, because of the otherwise complex nature of the control apparatus, only angular disturbances of the aircraft are considered, and the necessary measurements are made entirely by gyroscopic means. On future apparatus, as with a modern German auto-pilot described in Chapter 5, it may be desirable to include terms of linear motion, and possibly terms of height or of barometric pressure.

Under manual control, if the aircraft yaws the pilot applies rudder and/or aileron control, and in doing so he takes account of the rate of the yaw as shown by the turn indicator, and he returns the aircraft to its original course as shown by the directional gyro. Control about the other two axes is similar, except that no indication of rate is normally provided.

In an automatic pilot the vertical axis and two horizontal axes are defined by gyroscopic means, any of the arrangements shown in Fig. III. 2 being used. For example, the directional gyro and the gyro-vertical may be used, but instead of their providing a visual indication, the relative movement between gyroscope and aircraft is detected mechanically and used to set in motion a motor coupled to the appropriate control surface, viz., rudder, elevator or aileron.

The angle through which the control is moved for a given disturbance is regulated by a follow-up system which progressively removes the motive power as the control is operated. (The gearing or ratio of the follow-up is usually made adjustable to suit the aerodynamic characteristics of different aircraft.) As the aircraft returns to its original attitude under the action of the control the motor operates in the reverse direction and progressively reduces the control to zero. The aircraft, however, overshoots its original attitude, that is, its alignment with the axis defined by the gyroscope. This results in a damped oscillation of the aircraft about the aligned position. The character of the oscillation, which is actually the sum of a long and a short period motion, and the damping vary with individual aircraft. It is desirable, however, that the oscillations should be critically damped.

With an automatic pilot which takes account of angle of disturbance only, the long period motion can be effectively damped by using a suitable follow-up ratio, but to damp out quickly the short period oscillation an angular velocity meter (turn indicator) is necessary and in some cases an angular accelerometer is also used.

Thus the amount and/or the rate at which the aircraft's controls are operated may be governed by the amount, velocity and acceleration of the disturbance. In practice the angular velocity meter compensates for any lag in a simple direct control and also damps out the oscillations. It is often known as a "damping gyro" in its application to automatic pilots.

Some automatic pilots control the aircraft by means of the elevators with either the rudders or the ailerons. These are known as two-axis controls and they make use of a gyroscope with an inclined axis of spin. As mentioned earlier in this chapter, if the spin axis is inclined to the horizontal relative motion can be detected about all three axes. This fact is utilised as follows. In an elevator-rudder control, opposite rudder is applied if the aircraft rolls. In an elevator-aileron control, aileron control is applied if the aircraft yaws.

Chapter 5 is devoted primarily to the gyroscopic mechanisms used on different automatic pilots. This includes the mechanisms used to detect relative motion between gyro and aircraft and also those used for curvilinear automatic flight. A brief description of the complete equipment of a typical automatic pilot is also given.

Note.—In the chapters which follow one instrument in each chapter is described in more detail than the remainder. Instruments serving the same purpose obviously have many common features and subsequent descriptions are limited to essential differences in design only. The choice of a particular instrument as an example of a type is of course no suggestion or indication of its superiority over others designed for similar work.

CHAPTER 2

DIRECTION INDICATORS

The first successful directional gyro designed for use in aircraft is due to Dr. Elmer A. Sperry. This instrument, known as the azimuth direction gyro, was produced in 1913, together with a "gyro inclinometer" and an "aeroplane stabiliser."

Sperry directional gyro

To-day, the modern development of the 1913 Sperry instrument is the best known of the directional gyros. It is the same in principle as the early instrument but modern methods of manufacture and details of design have resulted in greatly improved accuracy and appearance.

A complete instrument, and also the mechanism removed from its case, is shown in Figs. III. 8 and III. 9. The gyro rotor is mounted in special spring loaded ball bearings in the inner gimbal ring. These bearings are designed to prevent movement of the rotor due to changes in temperature. The inner and outer gimbal rings are also mounted on ball bearings. The inner gimbal has ± 55° freedom while the outer gimbal has complete freedom and carries a vertical compass card which is read against a lubber mark behind the cover glass. The rotor is $1\frac{7}{8}$ in. in diameter and weighs 11 oz. It is rotated at 10,000 r.p.m. by means of two side-by-side air nozzles carried by an arm inside the outer gimbal. The instrument case is airtight and the two nozzles are connected to outside (atmospheric) pressure by an air passage which passes through the lower bearing of the outer gimbal. The instrument case is connected by tubing to a source of suction, 2 lb./sq.in. below atmospheric, usually from an engine-driven pump but sometimes from a venturi tube on older types of aircraft.

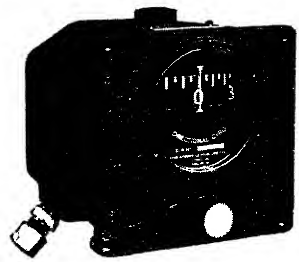


Fig. III.8. Sperry directional gyro. A standard aircraft instrument for many years, it consists of a free azimuth gyro with a compass rose fitted to the vertical gimbal.

When the pump is in operation air is sucked into the instrument case and the jets of air from the two nozzles spin the rotor by impinging on buckets cut in its periphery.

The air jets, in addition to rotating the rotor, are also designed to keep the axis of spin perpendicular to the outer gimbal axis. The buckets are cut round the centre of the rotor periphery while the rim on each side is of a reduced diameter. When the rotor is upright relative to the outer gimbal the air jets strike the buckets at points equidistant from their centres. If the rotor tilts due to precession, one air jet strikes the rim instead of the buckets while the other jet strikes the sides of the buckets. This results in a torque which instead of merely spinning the rotor, has a component about the vertical gimbal axis which precesses the rotor back into its original position.

There is also a component of this torque which acts about the inner gimbal axis. This is so small for normal displacements of the rotor that it can be neglected but for larger displacements it may cause the gyro to precess appreciably in azimuth. This occurs during a slow banked turn. For example if the aircraft starts on a turn with a 20° bank the rotor axle will at first be displaced by 20° relative to the outer gimbal, The control torque due to the jets is such that as the aircraft continues in the turn with a 20° bank, the rotor will after three minutes have precessed through about 5° to 6° towards alignment with the outer gimbal and also by about 1° in azimuth. Thus if the aircraft flattens out of the turn after three minutes there will, from this cause, be an azimuth error of 1°. However, this will disappear after three minutes of level flight since the gyro will then be precessed in the opposite sense. It will be seen that the error is small because normally a turn is of relatively short duration; three minutes would be exceptionally long. But it is important that the rotor be kept with its axis perpendicular to the outer gimbal to within certain set limits as otherwise the driving jets produce an undesirable azimuth precession during level flight. In practice it is usually controlled to within at least 3° of the perpendicular position.

A similar model of this instrument made by Messrs. Reid and Sigrist uses a different method of keeping the gyro axle horizontal. The inner gimbal is in the form of an airtight case which carries the air nozzles for spinning the rotor. In this instance the air passes through the lower bearing of the outer gimbal, through one of the inner gimbal bearings to the air nozzles, spins the rotor and then exhausts into the instrument case through two ports in the gimbal casing. If the rotor is not tilted the two exhaust ports are each half covered by a plate attached to the outer gimbal. If the rotor tilts one port is covered and the other is uncovered. The unequal reaction from the two exhaust ports results in a torque which precesses the gyro back to the aligned position. This method of erection suffers from the same fault for large angles of tilt as does the first method, that is, it produces unwanted azimuth precession proportional to the tilt angle and the time for which it is tilted.

The maximum free azimuth precession of these instruments when functioning within the limits of latitude for which they are designed is from 12° to 20° per hr. irrespective of any manoeuvres made by the aeroplane. This degree of accuracy is accomplished by careful design of bearings, etc., and is adjusted during manufacture by means of two balance weights attached to the inner gimbal. A weight on the reverse side to that shown in Fig. III. 9 can be adjusted towards or away from the inner gimbal axis. The small weight shown in Fig. III. 9 can be adjusted up and down. The two weights between them enable the centre of gravity of the inner gimbal and gyro assembly to be moved to one side or the other of the gimbal axis, in a plane containing the axis of spin. Thus a gravitational torque can be introduced to act in one direction or the other as necessary. The balance weights are locked in position after manufacture and the free precession of the gyro cannot be adjusted when the instrument is in use.

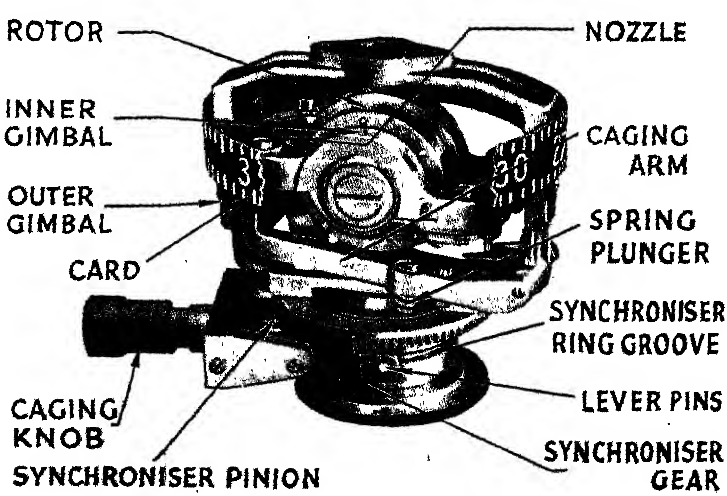


Fig. III. 9. Sperry directional gyro. View of mechanism showing gyro and caging device. The gyro axle is constrained to remain at right angles to the vertical gimbal axis by the action of the driving air jets which produce a corrective precession if the axle is displaced.

The lower portion of the mechanism (see Fig. III. 9) is used to cage and reset the gyro by hand. When in use, this operation will be necessary every 10 to 15 minutes. The outer gimbal carries a bevel gear at its base which can be engaged by a pinion attached to the spindle of the caging

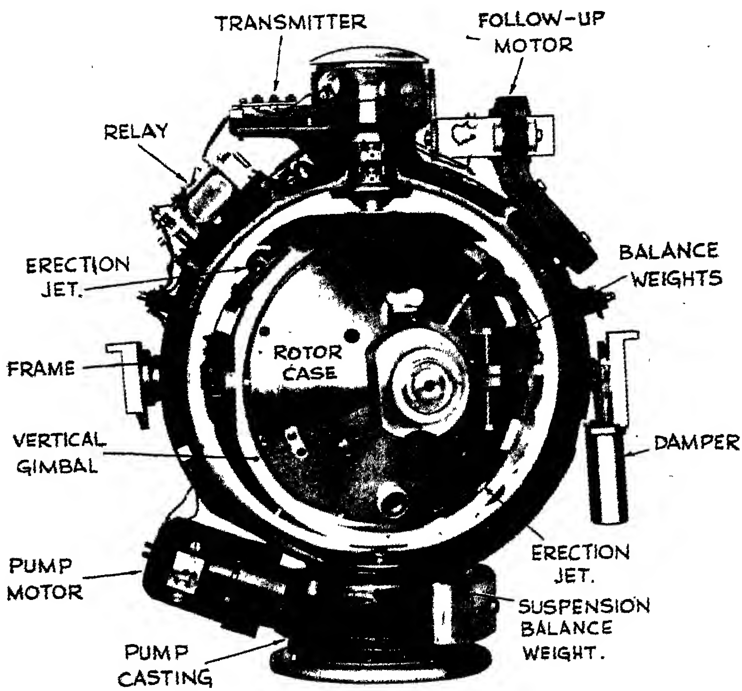


Fig. III. 10. Brown static compass, master unit removed from binnacle. The complete unit is pendulously suspended in an outer binnacle. Swinging of the unit in its binnacle is damped of means of the dashpots shown on the right. The follow-up motor rotates the top bearing of the vertical gimbal through an angle equal to the angle turned by the aircraft and also drives a transmitter for operating the repeaters. The pump motor supplies a pulsating column of oil to the lower bearing of the vertical gimbal. (See Brown gyro-compass, Section II.)

knob by pushing in the latter. The interior of the pinion is conical and when pushed in it raises the forked member carrying the two lever pins. The two pins raise the synchronizer ring and thence the caging arm by means of a small spring-loaded plunger which works in a hole in the base of the outer ring. The caging arm clamps the inner gimbal in a horizontal position, and by turning the caging knob the gyro assembly can be set to the correct bearing without toppling the inner ring. When the caging knob is pulled out the gimbals are freed and the gyro is spinning with its axle horizontal.

The instrument weighs about 4 lb. and its dimensions are approximately $4\frac{1}{2} \times 4\frac{1}{2} \times 4\frac{1}{2}$ in. The scale markings are luminized for use at night.

Brown static compass

This instrument is interesting in that it probably embodies the most accurate gyroscope yet designed for use in aircraft. This was not easily achieved and has resulted in a relatively heavy and costly instrument. Mr. S. G. Brown spent many years experimenting with different bearings and rotor sizes. The reader will appreciate that a good gyroscope should have a minimum of friction in rotor and gimbal bearings. There is a practical limit to any reduction in friction and the random precession which results from friction in gimbal bearings can be reduced by employing a high moment of momentum ($\frac{W}{g} \cdot k^2\omega$, see Section I) which effectively means a heavy rotor or a high speed of rotation. Unfortunately, a high rotational speed increases the wear of the rotor bearings thus allowing uncontrolled axial movement of the rotor and consequent random precession of the gyroscope. Hence one of the problems was to find the most suitable ratio of rotor speed and weight, bearing in mind that excessive weight was undesirable in a gyroscope to be used on aircraft.

The Brown aeroplane static compass is shown in Fig. III. 10. Briefly, the instrument is a very accurate directional gyro which transmits its reading by electrical means to one or more repeaters placed in front of the pilot and the navigator, etc.

The gyro rotor is electrically driven from a 12-volt battery and is enclosed by a close-fitting steel case which forms the inner gimbal. A sectional drawing of the complete assembly is shown in Fig. III. 11. The rotor shaft runs in roller bearings and has ball thrust bearings at each end. The thrust bearing at the south end (the left-hand end in

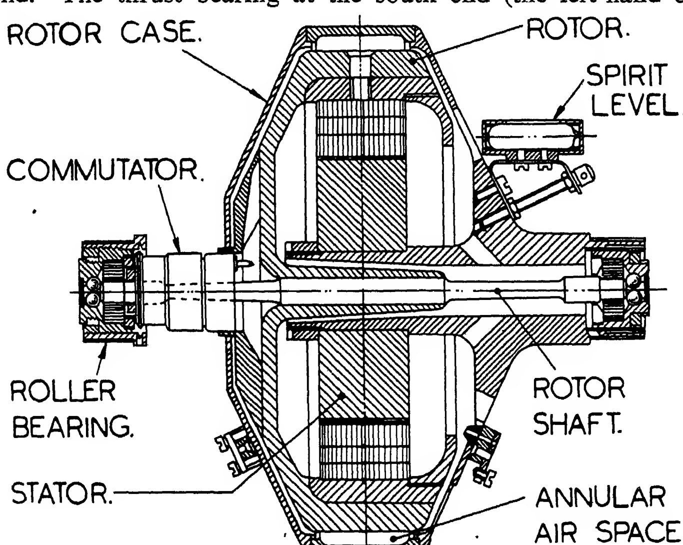


Fig. III. 11. Brown static compass, section through gyroscope and casing. Air pressure developed in the annular space between rotor periphery and case is used to keep gyro axle at right angles to the vertical gimbal axis. (See fig. 13.)

Fig. III. 11) is spring-loaded to eliminate the development of end play due to wear and expansion at different temperatures. Any axial movement of the rotor mass would, of course, result in azimuth precession. The rotor weighs $3\frac{3}{4}$ lb. and rotates at 12,000 r.p.m. When the gimbal assembly is balanced for a particular latitude the precession rate is of the order of 1 degree in 12 hours but, as explained in Chapter 1, will of course vary with the latitude and the speed and direction of flight.

The steel case is supported in the outer gimbal ring on special knife-edge bearings. These consist essentially of a knife edge, attached to the steel gyro case, resting in V blocks supported in ball bearings carried by the outer gimbal ring. It will be appreciated that in addition to preventing axial movement of the rotor it is also important to reduce friction of the inner gimbal bearings to a minimum since both these factors will produce azimuth precession. Knife-edge bearings give a minimum of friction but suffer from the disadvantages that they only allow a limited angular movement and are very susceptible to failure because of vibration and temperature changes which result in a sawing action on the supporting V blocks. The addition of a ball-bearing support for the latter enables full angular movement of the inner gimbal while the continuous small angular movement obtaining when the instrument is carried on an aeroplane is taken on the knife-edges. The ball bearings also permit slight axial movement of the gimbal, thus tending to minimise the sawing action of the knife edges. A sectional diagram of the bearing is shown in Fig. III. 12. In practice the useful life of these bearings on aircraft is dependent on the provision of efficient anti-vibration mountings.

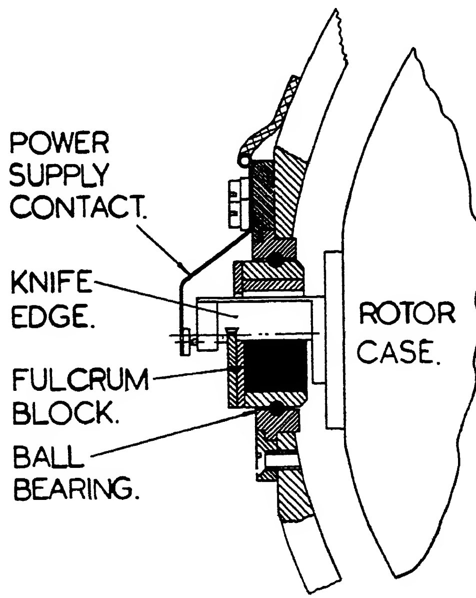


Fig. III. 12. Brown static compass, section of horizontal gimbal bearing. Knife edge bearings minimize friction during normal angular movements while ball bearings permit complete rotation of gimbal.

As shown in Fig. III. 11, an annular space is formed between the periphery of the rotor and the steel case. With the rotor rotating at high speed an air pressure generated in this space is used to keep the gyro axle horizontal as follows. The pressure is released from the gyro case through two rectangular slots, on opposite sides and one above and one below the gimbal pivots. In the vertical gimbal ring and opposite the two slots are two other slots which are partitioned in the centre and connected to two ports which exhaust the air in opposite directions. Fig. III. 13 is a diagram of this device. When the gyro case and the vertical gimbal are aligned, that is, when the gyro axle is horizontal, an equal mass of air is exhausted through each port and there is no resultant couple about the vertical gimbal axis. If the gyro axle moves relative to the vertical gimbal, because of earth rotation, a greater mass of air

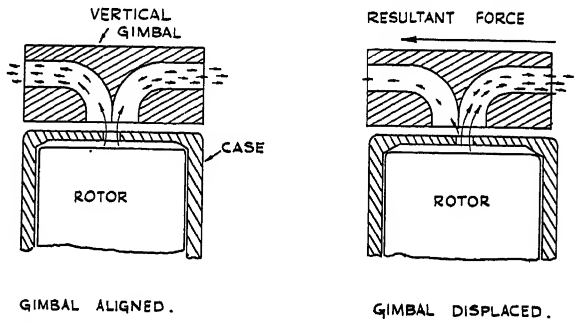


Fig. III. 13. Brown static compass, diagram showing principle of erection device. If rotor case and vertical gimbal are not aligned jet reaction torque on vertical gimbal will precess the gyro into correct alignment.

escapes from one port than from the other and the resultant couple precesses, or erects, the gyro axle back to the horizontal. A small spirit level is attached to the gyro case to check the erection in the laboratory.

Weights are provided for adjusting the centre of gravity of the gyro assembly. A weight on the side opposite to that shown in Fig. III, 10 enables the instrument to be balanced to suit the latitude in which it is to be used. Thus in England where the azimuth movement, 15°/hr. × sin latitude, due to earth rotation is about 12°/hr. the balance weight is moved out so that the gyro precesses at 12°/hr. in the same direction, with the result that it appears to be stationary. The corresponding movement in pitch, 15°/hr. × cos latitude, which is about 9°/hr., is automatically corrected by the air exhaust ports on the vertical gimbal, as previously mentioned.

The lower bearing of the vertical gimbal is similar to that used on the Brown gyro compass for ships described in Section II. The journal is, in effect, supported on a column of oil which is made to pulse up and down about three times per second by means of a small pump. Here the pump is driven by a small permanent-magnet motor as shown in Fig. III. 10. The upper journal has an extension which carries an electrical brush contact. This normally rests between two metal segments and comprises the follow-up device for operating the repeaters.

The follow-up comprises a small permanent-magnet D.C. motor which is geared to drive an assembly consisting of two contact segments and the top bearing of the vertical gimbal. The action of the follow-up is described with reference to the electrical wiring diagram in Fig. III. 14.

If the aircraft changes course the outer frame of the gyro moves with it and one of the segments makes contact with the brush, thus energizing one coil of a double-acting relay. This allows current to pass through the armature of the follow-up motor in a direction such that the contact ring and upper bearing assembly is driven into its previous alignment with the outer gimbal where the brush breaks contact with the metal segment. If the aircraft changes course in the opposite direction the other relay coil is energized and the armature current of the follow-up motor is reversed, thus causing it to turn in the opposite direction. The brush only just clears the two contact segments when in the aligned

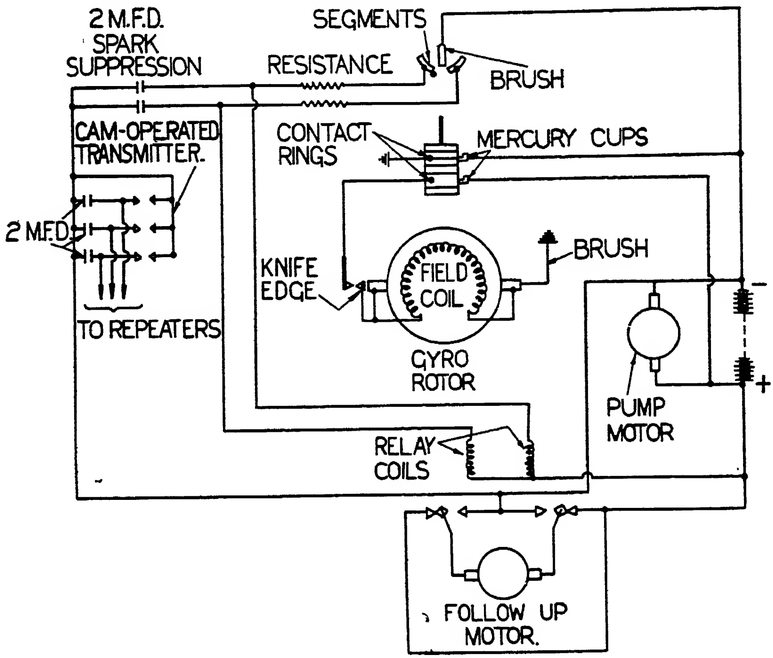


Fig. III. 14. Brown static compass, schematic wiring.

position and consequently the follow-up assembly makes a continuous small oscillation about the aligned position. It will be seen, therefore, that except for this small oscillation there is no relative movement between the vertical gimbal and its bearing and consequently no effective friction. Also, the follow-up motor makes a definite number of revolutions depending on the change in the aircraft's heading. The follow-up movement operates the repeaters by means of a small cam-type transmitter geared to the motor. The repeaters are of the step-by-step geared type similar to those used with a ship's gyro compass.

The electrical supply to the gyro and the follow-up brush is taken through contact rings on the journal of the vertical gimbal via mercury cups carried by the follow-up assembly. The latter is provided with a light alloy dust cover as shown in Fig. III. 10. Electrical connection between the vertical gimbal and the gyro case is made by means of spring contacts which press axially, as shown in Fig. III. 12, and thus introduce very little friction.

The outer-frame casting is pendulous and is supported in ball bearings in a spherical-shaped binnacle (not shown in Fig. III. 10). The movements of this suspension are damped by two small dashpots. The compass card carried by the vertical gimbal is viewed through a circular glass window in the binnacle. From Fig. III. 10 it will be noted that the gyroscope has three degrees of freedom and that the possibility of this freedom being dependent on the direction of the gimbal axes ("gimbal lock") is practically eliminated by the provision of the additional axis for the frame, and the fact that the frame itself is pendulous.

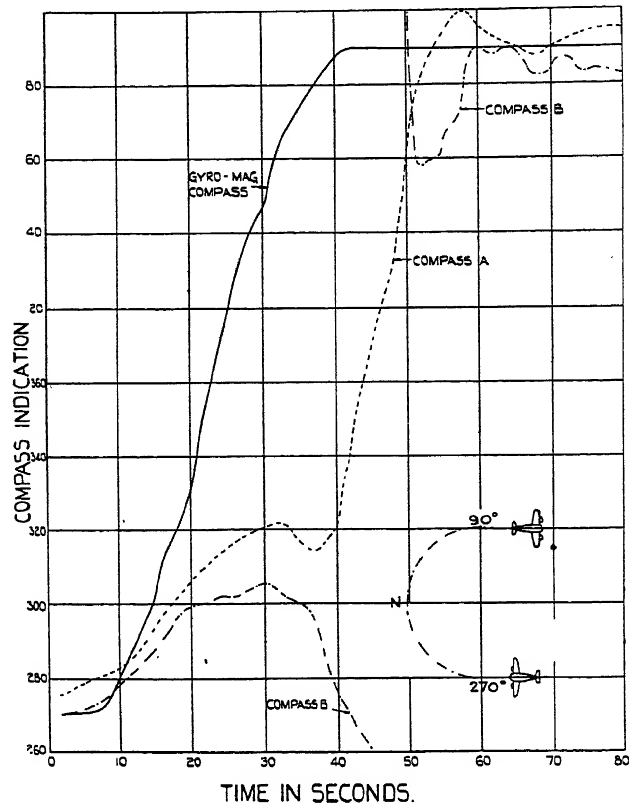
The instrument is not North seeking and in a minor degree is subject to all the precessional errors of the normal directional gyro. Neglecting errors due to friction in bearings, its accuracy is affected by change in latitude during flight and also by the speed of the aircraft, as explained in Chapter 1. As designed, the instrument was supplied with a chart which gave the rate at which the gyro would precess from the correct heading at different latitudes and at different speeds in an E-W direction. No provision was made for N-S or intermediate courses. Thus the cumulative error due to the speed of the aircraft would only be known to the pilot when the aircraft was flying east or west and he would then have to add or subtract from the indicated heading an amount depending on his flying time. No means of resetting was provided and in a long flight the actual true heading would be rather doubtful. The principal advantage of the instrument was that, since it is not subject to turning errors, it would enable very accurate turns to be made during local flights. As with all directional gyros which are not stabilised in the vertical, it does not give a correct indication *during* a turn.

Gyro-magnetic compasses

A gyro-magnetic compass comprises essentially a compass-monitored directional gyro. This should not be confused with a gyro-stabilised magnetic compass, such as the "Pioneer" Gyro-Fluxgate Compass mentioned in Chapter 5, in which a gyro-vertical is used to prevent a magnetic compass from tilting when the aircraft is banked. As previously mentioned, with a simple directional gyro it is necessary for the pilot constantly to check its reading against that of a magnetic compass and reset the gyro manually. The gyro-magnetic compass does this operation automatically, either continuously or at frequent intervals.

There are a number of these instruments in use, differing in design but similar in principle in that a magnetic compass is made to correct the free precession of a gyroscope. As described in Chapter 1, if a slow rate of control is used the directional gyro will indicate the true mean magnetic heading. The errors of the magnetic compass are of a transient nature and the gyroscope can be said to delay their effect, that is, the gyroscope precesses slowly and the error of the magnetic compass has either ceased or changed in sense, before the gyroscope shows any appreciable change in heading.

The principle of control is similar to that used with the gyro-vertical which is gravity-controlled. Similarly, the errors which are possible with these instruments result from the same fundamental cause as with the gyro vertical, that is, the apparent vertical is not the true vertical when the aeroplane banks and turns. Thus, as with the gyro-vertical, there is a definite limit to the accuracy obtainable during manoeuvres of the aeroplane. They are, however, very much superior to the simple magnetic compass and their performance is equivalent to that of a directional gyro with the added advantage, of course, that there is no slowly accumulating error due to precession. The small errors which are present during turns—not more than 3 or 4 degrees under extreme conditions—are corrected automatically when the aircraft resumes straight flight. Gyro-magnetic compasses are sufficiently accurate for all normal flying and under no circumstances are they, when functioning correctly, ever likely to confuse the pilot as does the magnetic compass.



Crown Copyright.

Fig. III. 15. Comparative performance of magnetic and gyro-magnetic compasses during turns. In this actual test the aircraft made a turn at constant speed from west to east with a 40° bank.

Most gyro-magnetic compasses are of the distant reading type, that is, they consist of a master unit which transmits its heading to one or more repeaters. Thus, the repeaters are placed in front of the pilot and navigator, etc., and the compass part of the instrument is installed in a part of the aircraft which is relatively free from magnetic disturbance.

A comparison of the heading indications of a gyro-magnetic compass with those of two magnetic compasses A and B of orthodox design is shown in Fig. III. 15. The aircraft actually turned from W through N to E with a 40° bank at a steady rate, and the readings were recorded automatically, at one-second time intervals, by means of a ciné camera. The gyro-magnetic compass shows a practically constant rate of change of heading during half a minute. Compass A tends to indicate a reverse turn while compass B, with less damping, indicates a turn in the direction opposite to the aircraft's actual heading.

It will not be possible to devote any space to a description of the different electrical systems of remote indication used with gyro-magnetic compasses. Examples of the various systems in use are : "Magnesyn," "Autosyn," "Selsyn," Admiralty M type. The latter is a non-self-synchronous step-by-step system in which the transmitter is geared up and a reduction gear is used between the repeater motor and the repeater card. Each system consists of a transmitter, coupled to the instrument of which the reading is to be transmitted, and one or more instruments known as repeaters which, as their name implies, repeat the reading at a distance. All the reader need remember is that a repeater system enables two rotatable parts to turn in synchronism when they are situated on two separate instruments a distance apart. A repeater is not necessarily used to give a visual indication, but may be used to orientate parts of other mechanisms such as air position indicators and bomb-sights.

Crown Copyright

Fig. III. 16. Master unit of R.A.F. gyro-magnetic compass. The suspension from the fixing bolt is pendulous so that the verticality of the compass magnet axis is, during unaccelerated flight, independent of the aircraft's attitude. Swinging of the master unit from its suspension is damped by means of four air dashpots.

R.A.F. gyro-magnetic compass. This compass has been standard equipment on most multi-engined aircraft in the R.A.F. since 1940. An early model using a gyroscope operated by direct current was produced by the Air Ministry in co-operation with S. G. Brown Ltd., in 1934. This instrument was developed by the Automatic Telephone and Electric Co., and at present uses a gyroscope operated by 3-phase alternating current from a small rotary convertor. Advantages gained by the employment of alternating current are more reliable starting and no loss of balance of the gyroscope due to wear af the carbon brushes as used on the D.C. model.

The complete compass system is operated from the 24-volt D.C. supply of the aircraft. The pilot or the navigator is provided with control switches for starting and stopping the master unit and also a device—the variation setting corrector—which enables him to adjust the repeaters to read true instead of magnetic heading. Remote indication is by means of Admiralty M type transmission. The master unit can operate any number of repeaters up to a maximum of six. A complete

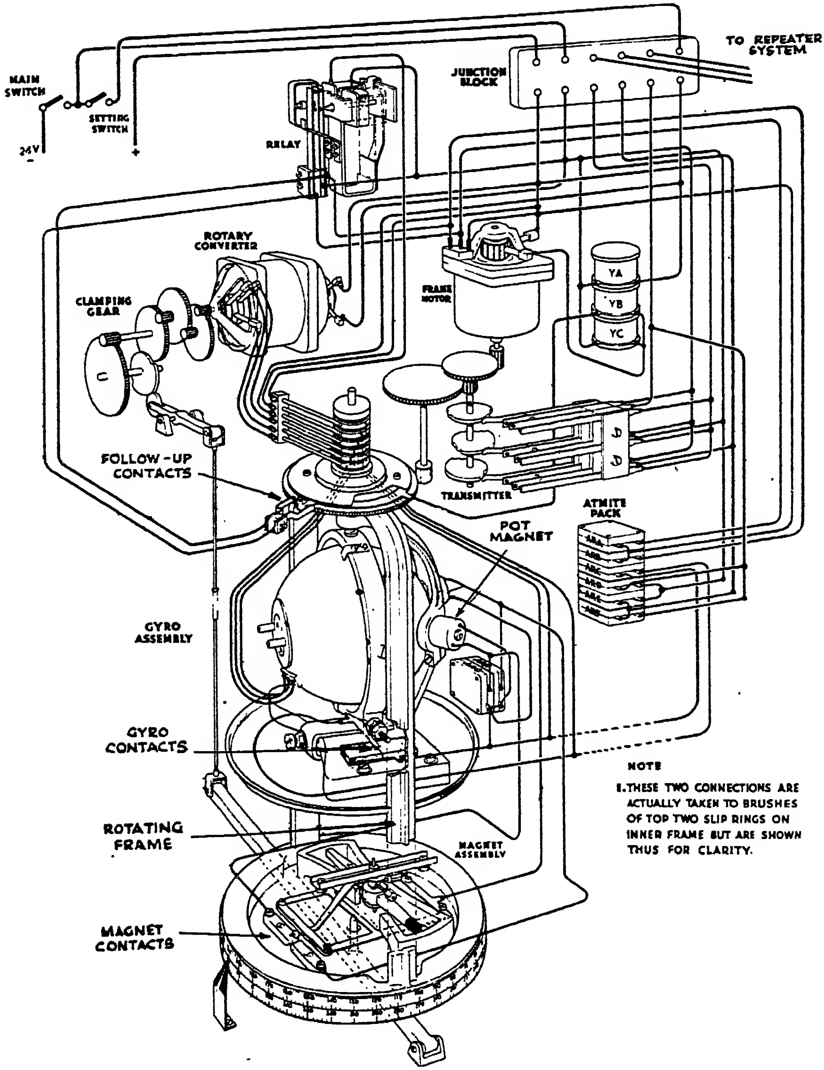


Fig. III. 17. Master unit of R.A.F. gyro-magnetic compass, schematic diagram. The compass magnet controls the gyroscope through two pot magnets which exert an eddy-current drag on the hemispherical copper dome. The gyroscope is thus constrained to remain in a fixed position relative to the magnetic meridian. A rotating frame—similar in principle to the phantom element of the ship's gyroscopic compass—is kept in alignment with the gyroscope by means of a follow-up motor (frame motor). Thus the latter rotates through a number of revolutions proportional to the angle of turn of the aircraft and operates the transmitter of the repeater system.

equipment consists of a master unit, a variation setting corrector, a control switchbox and a number of repeaters.

The master unit combines in a single instrument the compass, the gyroscope, the monitoring and follow-up mechanism and the transmitter for operating the repeaters. The complete assembly is supported on a framework and is totally enclosed by dustproof covers. As shown in Fig. III. 16, it is suspended in gimbals so that in unaccelerated flight it hangs in a vertical position. A small window is provided in the lower cover for reading the heading indication. This is not used by the pilot during flight but is required when adjusting the compass for deviation and also for checking that repeaters are indicating the correct heading before flight. The repeater system is not self-synchronous.

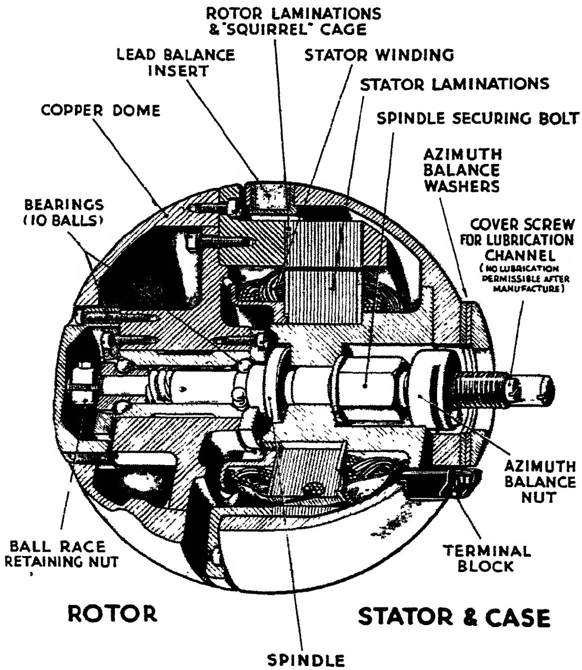
A schematic diagram of the master unit mechanism is shown in Fig. III. 17. The gyroscope and the magnetic compass assemblies are supported on platforms attached to a rectangular frame. This will be referred to as the inner frame. It is rotatable in plain bearings in a main frame which supports the remaining components, the frame itself being omitted in Fig. III. 17.

The magnet assembly comprises a single bar magnet; double pivoted, with $\pm$ 10° freedom in azimuth, and enclosed in a metal box which provides air and eddy-current damping. A ball-shaped platinum contact is carried on an arm fixed to the magnet spindle at right angles to the magnet. The ball contact is free to swing over two flat contacts, separated by a narrow strip of insulation, and under a flat contact strip which, with the compass functioning, is lowered and raised every 5 to 6 seconds, so that it alternately clamps and releases the ball contact.

The gyroscope comprises a 3-phase squirrel-cage motor of special design, as shown in Fig. III. 18. The rotor axis is horizontal and the bearings are offset to enable a hemispherical copper dome to be secured at one end. The motor case, which forms the inner gimbal of the gyroscope, pivots about a horizontal axis with $\pm$75° of freedom in the vertical gimbal which has $\pm$40° freedom about a vertical axis. The support frame for the vertical gimbal carries two small electro-magnets, termed "pot-magnets." These are set to have a small clearance from the rotor dome and when the gimbal system is orthogonal they are symmetrical about the spin axis.

The gyroscope is supplied with 3-phase A.C. through light flexible leads from a rotary converter on the main frame and reaches its nominal speed of 11,000 r.p.m. in about 2 minutes. The rotary converter also operates the clamping contact on the magnet assembly through a gear box, a cam and levers, as shown in Fig. III. 17.

The inner frame is kept aligned with the vertical gimbal by a small continuously energised shunt motor, termed the frame motor, whose direction of rotation can be reversed by completing a circuit to one or the other of its two field windings by means of a relay. The vertical gimbal carries a light spring contact which moves over a quartz and a metal strip secured to the inner frame. When gimbal and inner frame are aligned the contact is just passing from quartz to metal or vice versa. If it rests on the quartz the relay is unenergised and the motor rotates the frame counter-clockwise round the gyro until the gyro contact passes on to the metal. The relay then operates and energises the other field winding which reverses the motor's rotation and the quartz is again driven under the gyro contact. This cycle is repeated about 2 to 3 times per second. Thus when the gyro is on a steady heading the inner frame makes a continuous oscillation or "hunt" about the aligned position. If the gyro moves in azimuth the inner frame follows and afterwards



Crown Copyright

Fig. III. 18. R.A.F. gyro-magnetic compass, section of gyroscope. The special squirrel-cage rotor, with the copper dome attached, rotates round the 3-phase 2-pole stator winding. The domed motor case corresponds to the inner gimbal of the normal gyroscope and is pivoted about an axis perpendicular to the plane of the page.

continues to oscillate in the new aligned position. Similarly, if the aircraft turns, the inner frame tends to move with it but, since the gyro remains stationary, is immediately driven in the reverse direction relative to the aircraft to maintain its previous alignment with the gyro.

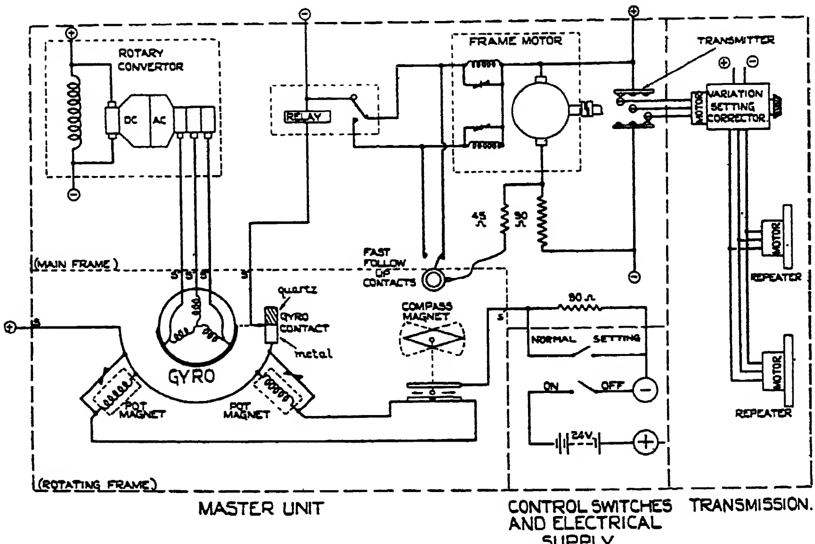
The function of the "pot" magnets is to keep the gyro axle at right angles to the magnetic meridian as follows. The ball contact on the magnet arm is clamped for $2\frac{1}{2}$ seconds in every 5 to 6 seconds clamping cycle and although, if gyro and inner frame are exactly aligned, it is possible for clamping to occur on the insulation a circuit is normally completed between the clamping contact and one of the fixed contacts which are wired to the pot magnets. Thus depending on whether the gyro has precessed to one side or the other of the aligned position, the appropriate pot magnet is energised. Since the gyro dome is rotating at high speed considerable eddy currents are induced in the copper and a drag force is exerted at a tangent to the dome. This force has a component producing a torque about the horizontal gimbal axis and thus precesses the gyro about its vertical axis. The pot magnet connections are arranged so that the direction of precession is towards the magnetic meridian. If the pot magnets are not aligned with a diameter of the gyro dome the eddy current drag is inclined to the vertical gimbal axis and the precessional torque has a component about the vertical gimbal axis. Thus the precessional corrections also keep the gyro-system orthogonal, provided that it is approximately in static balance about the vertical gimbal axis in the first instance. In practice, because of unavoidable free precession in pitch, it will always be inclined at a small angle, i.e., such that the erection torque is sufficient to overcome the free precession in pitch.

From what has been said it will be seen that the gyro controls the frame motor to align the inner frame on the mean heading given by the magnet. The main objects in employing a rotating frame, or follow-up are : (i) to keep the pot magnet aligned with the spin axis, (ii) to eliminate friction in the bearings of the vertical gimbal and (iii) to operate the transmitter and thus transmit the heading indication of the gyro to the repeaters.

The hunt of the inner frame—about $\pm\frac{1}{2}°$—eliminates inaccuracies due to backlash in the gear train from the frame motor. To prevent the hunt from being transmitted to the repeaters a backlash device is incorporated in the mechanical drive to the transmitter. The heading of the master unit can be read against a fixed lubber mark on the main frame from a scale of degrees on the inner frame.

A schematic wiring diagram is shown in Fig. III. 19. In normal operation the pot-magnetic circuit is completed through the 90-ohm resistor YA and the pot magnets then give a precession of about 0·6° to 0·7° each time they are energised, i.e., a mean rate of 5° to 6° per minute over a period. When starting the compass the control switches are moved to ON and SETTING respectively. In the SETTING position, the resistor YA is short-circuited and with the pot-magnets thus fully energised the mean precession rate is increased to about 45° per minute. The object of the increased rate is to reduce the time taken by the master unit in reaching a heading. Thus in the extreme case, when the aircraft is on the reciprocal of the bearing indicated by the master unit, a wait of 4 to 5 minutes is necessary before the compass is ready for use. Afterwards the control switch is restored to normal. Usually the aircraft will be on or near its previous heading and a wait of about 2 minutes only is necessary, that is, the time required to allow the gyro to reach an adequate speed.

When the master unit is on a steady heading the frame motor functions with a 90-ohm resistor YB in its armature circuit. Under these conditions the inner frame oscillates about $\pm\frac{1}{2}°$ about the mean heading. When the aircraft turns the total resistance in the armature circuit is reduced to 30 ohm by automatically shunting YB with the 45-ohm resistor YC. This is done by the "fast follow-up" device fitted near the top of the inner frame (see Fig. III. 17). The two fixed contacts of this device are secured to the main frame and the "change-over" contact is operated by a friction-held ring fitted above the gear wheel on the inner frame. The reduced resistance, 30 ohm, allows the frame motor to drive the inner frame at about 6 to 7 r.p.m. This follow-up rate in conjunction with the ±40° azimuth freedom of the gyro gives an adequate safety margin over the maximum rate of turn of normal aircraft.



Crown Copyright

Fig. III. 19. R.A.F. gyro-magnetic compass, schematic wiring. The normal control rate of the magnet on the gyro is 5° to 6° per min.; the SETTING position of the control switch increases this to 45° per min. for starting purposes. The follow-up rate of the rotating frame during turns is increased to 6 r.p.m. by means of a slipping contact which reduces the effective resistance in the armature circuit of the motor from 90 ohms to 30 ohms.

Sperry "slave" gyro-magnetic compass. In this instrument the magnetic compass and the directional gyro are not combined in a single master unit as with the R.A.F. D.R. compass. A standard Sperry directional gyro is used and this is installed in its normal position on the pilot's flying panel. The directional gyro transmits its heading (a) to a magnetic compass which is installed in a suitable position on the aircraft, and (b) to secondary repeaters which may be provided for the navigator or wherever else they are required.

A schematic diagram of the complete system is shown in Fig. III. 20. The outer gimbal of the directional gyro is geared to an Autosyn transmitter which is built on to the back of the standard directional-gyro case. This transmits the heading of the directional gyro to the compass unit where it is compared with the compass heading by means of a high frequency A.C. bridge circuit as shown in Fig. III. 20. A "slave" magnet carrying a small metal plate is free to turn about a vertical axis directly above the compass magnets. Thus the "slave" magnet always aligns itself with the compass magnets.

The repeater carries two flat segmental plates insulated from each other and free to rotate in close proximity to the compass plate. This arrangement is effectively two variable condensers, and, with two equal inductances, a double-diode rectifier and a trimming resistance, forms an A.C. bridge as shown in Fig. III. 20. The bridge is supplied with current from a high-frequency oscillator, and the coil of a sensitive relay is connected to each side of the bridge as shown.

The action of the compass in monitoring the reading of the directional gyro is as follows. The relative positions of the three condenser plates are arranged so that when gyro and compass readings are similar the compass-operated plate is equidistant from the two plates carried by the repeater. In this position its capacity is the same relative to each plate, and equal pulsating currents are passed by the two anodes of the rectifier; the bridge is balanced and therefore no current flows in the relay coil. If the gyro precesses off heading the repeater operated plates will move, and hence one capacitance is increased while the other is decreased, and the bridge is unbalanced. The rectifier will then pass unequal currents and an out-of-balance current from the bridge circuit passes through the coil of the sensitive relay. If the condenser plates are moved in the opposite direction the out-of-balance current in the relay coil is in the opposite sense. The sensitive relay is used to operate a power relay which controls an electromagnetic precessing device on the directional gyro. This is shown in Fig. III. 20, and consists of two small permanent magnets, fixed to the inner gimbal, and an air-cored solenoid, fixed to the outer gimbal. The magnets are in the shape of an arc, slightly less than 90°, and are attached, one to each side of the inner gimbal, to form a semi-circle about the gimbal axis. The free ends of the magnets lie close together and possess like magnetic poles. The magnets are free to pass through the solenoid and the movement of the inner gimbal is not restricted in any way.

When the gyro reading and the compass reading do not agree the A.C. bridge is unbalanced and the relays are operated to complete a circuit which passes current through the precessing solenoid. The magnetic field thus produced exerts a force on the magnets which results in a torque about the axis of the inner gimbal. This precesses the gyro towards alignment with the compass.

To avoid trouble from vibration the power relay is designed to lock on magnetically, immediately it is energised by the sensitive relay. It does not release until it is energised in the opposite direction. Thus the gyro is continually being precessed first in one direction and then in the other, with the result that the card on the vertical gimbal shows a continuous small oscillation about the true magnetic heading.

The precessing solenoid is designed to operate from a 12-volt D.C. power supply and a series resistor is inserted in the circuit to limit the current to that required for producing a precession rate of about 10° per minute. A small indicator, visible on the face of the directional gyro, is connected in parallel with the precessing solenoid to show whether the compass is functioning and the direction in which the gyro is being precessed.

The complete system consists of the following separate items: directional gyro, compass, power unit, rotary convertor and a number of repeaters for the use of other members of the aircraft's crew. The

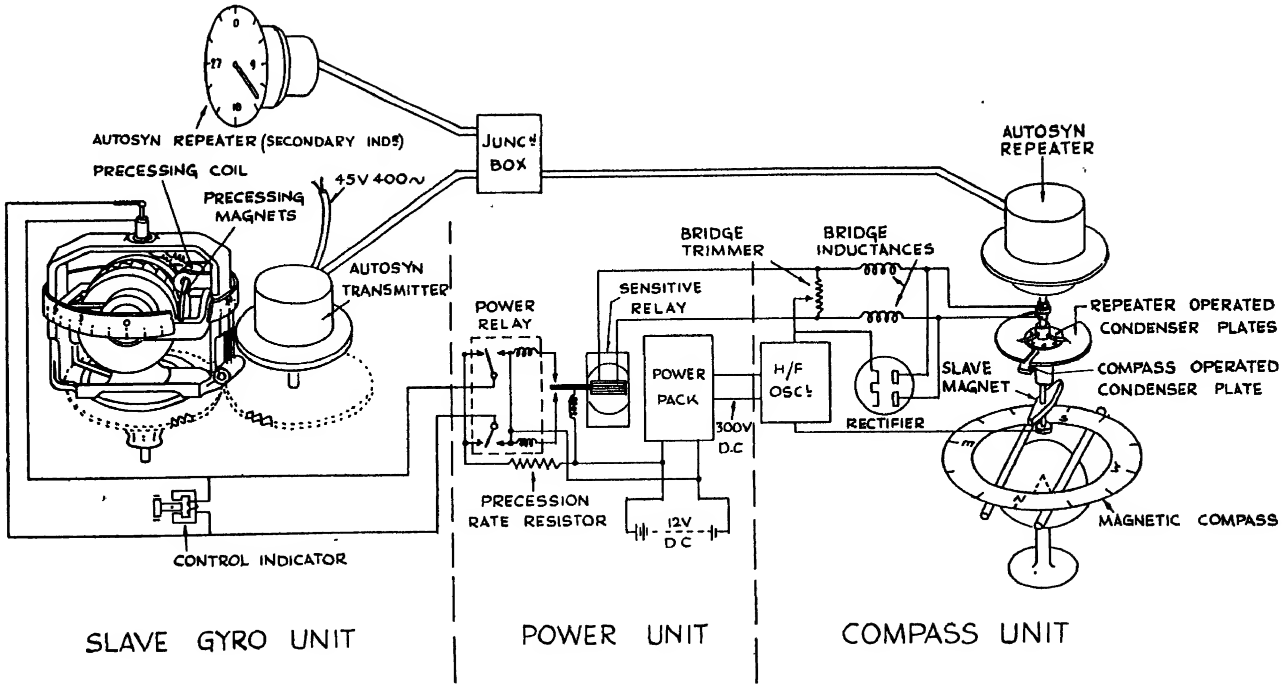


Fig. III. 20. Sperry "slave" gyro-magnetic compass. Relative movement between the compass magnet and the repeater operated by the directional gyro—resulting from gyro precession—is detected by an out of balance current from the high-frequency A.C. bridge. This out of balance current is used to energize the precessing coil on the directional gyro via a sensitive relay and a power relay. The precessing coil applies a couple to the gyro to precess it towards the magnetic meridian.

electrical supply for the power unit is obtained from the 12-volt general services of the aircraft, the "Autosyn" repeater system then being supplied with 45-volt, 400-cycle alternating current from a rotary convertor, and the high frequency oscillator with 300-volt direct current from a power pack forming part of the power unit.

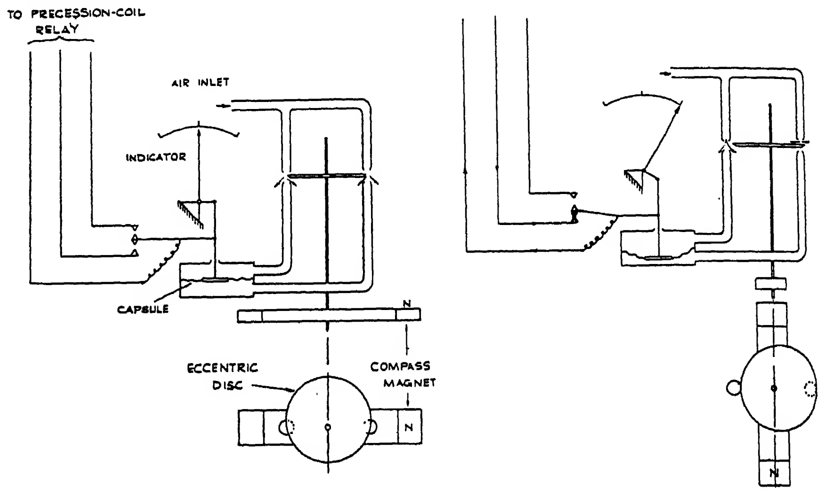


Fig. III. 21. Askania distance course compass, air pick-off and differential pressure capsule. If the aircraft steers off the pre-set course pressure difference on the capsule operates an electrical contact to energise the precession solenoid on the directional gyro. (See Fig. III. 22.)

The compass is a normal liquid-damped type. In a later Sperry gyro-magnetic compass, known as the "Gyrosyn," this is replaced by a compass of the flux-gate or earth-inductor type, and while in this respect the compass is entirely different from the instrument described here, the same electro-magnetic precessing device is used on the directional gyro.

Askania gyro-magnetic compass. This instrument, of German design, has been developed from the Askania "Distance Course Compass." The latter is a distant-reading compass which shows, by means of a small dashboard indicator, whether the aircraft is flying to the left or the right of a pre-set course. It does not use a repeater system to show changes in heading directly. In its gyro-magnetic form the indicator, in addition to giving a visual indication, is also used to monitor a directional gyro.

The compass magnet is double-pivoted in a bowl and the complete compass element is suspended in gimbals, in an outer shock-absorbing case, so that when the aircraft is in unaccelerated flight the magnet spindle is vertical. The magnet spindle carries an eccentric disc arranged to cover or uncover two air ports as shown in Fig. III. 21. If the two ports are covered equally by the disc, as shown on the left, the air pressure transmitted to the two sides of the differential capsule are equal. If the air ports are displaced from this position, as when the aircraft turns, the pressures are unequal and the capsule is deflected as shown on the right in Fig. III. 21.

The heading of the aircraft on which the air ports are covered equally is pre-set by manual rotation of the compass bowl. Thus if this heading is maintained there will be no deflection of the capsule. Movement of the capsule following a turn from the set course is used to close an electrical circuit to a precessing device on the directional gyro.

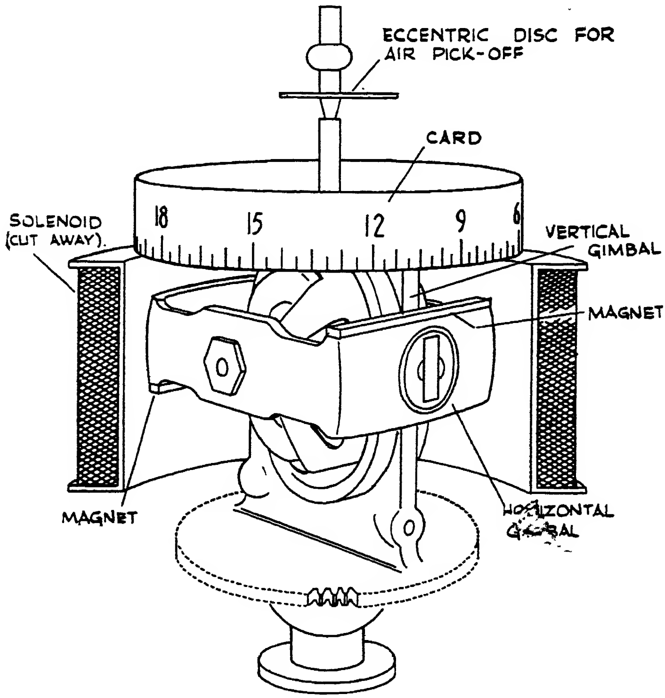


Fig. III. 22. Askania "distance course compass," directional gyro with precession solenoid. When the solenoid is energised the magnets apply a couple about the horizontal gimbal axis to precess the gyro about the vertical axis.

As shown in Fig. III· 22, the directional gyro is enclosed by a large solenoidal coil. The horizontal gimbal supports two small bar magnets, in a horizontal plane and perpendicular to the gimbal axis. Thus when the coil is energised a couple is exerted about the gimbal axis to precess the gyro in azimuth. The magnetic polarity of the coil and the magnets is such that the gyro is precessed towards the correct heading.

The vertical gimbal carries a compass card in the usual way, and an adjustable course-setting scale, not shown in Fig. III. 22, is fixed to the case. This latter scale can be rotated by a cranked handle on the front face of the instrument. The same crank is connected, by means of a flexible drive, to the compass bowl, the latter being installed in the rear of the fuselage.

At the start of a flight the aircraft is flown on the course set on the "fixed" scale of the directional gyro by means of the dashboard steering indicator. The scale on the vertical gimbal of the directional gyro is then set to the same course. (The caging and resetting mechanism is similar to that used on the Sperry instrument previously described.) Thereafter, any desired course may be flown by means of the directional gyro. The cranked handle turns the gyro course-setting scale and the compass bowl by an equal angle. The aircraft is then steered so that similar readings on the two scales of the directional gyro are aligned. If the gyro tends to precess and thus wander off heading, the aircraft will be instinctively turned to follow the gyro. The differential capsule is thereby unbalanced and a circuit is completed to the precessing coil which automatically applies a torque to correct the gyro precession.

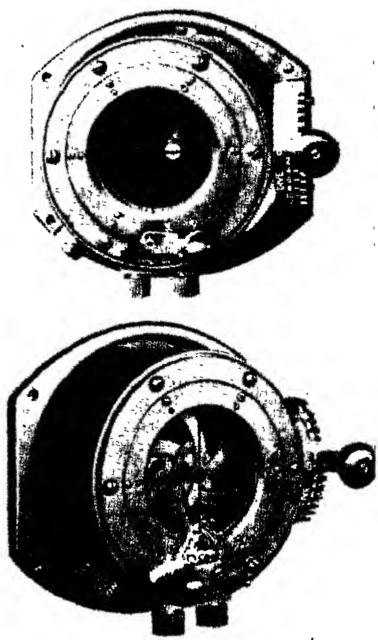


Fig. III, 23. Brown pitch-azimuth indicator. To follow a straight glide path the aircraft is flown so that the black spot on the instrument dial covers the luminous spot on the gyro pointer. The angle of the glide path is pre-set by caging the gyro (see lower photograph) and tilting the complete instrument in its trunnions by means of the setting lever shown on the right.

The rotor is air-driven by a pump which gives a suction of about 2½ lb. per sq. in. After passing through a filter, the incoming air is taken through the "pick-off" jets on the compass. It then passes through the lower bearing of the vertical gimbal of the gyro, and thence through channels in the gimbal to an air nozzle for driving the rotor, opposite the horizontal gimbal pivot, and also via the opposite pivot of the horizontal gimbal to two air nozzles on the latter. The reactions from the air jets on the gimbal are used to keep the gyro axle horizontal, in a manner similar to that described in connection with a directional gyro earlier in the chapter.

The compass also embodies an automatic course control. For this purpose the directional gyro operates a second air pick-off and differential pressure capsule, which is constructed on the same principle as that shown in Fig. III. 21. The vertical gimbal of the gyro carries the eccentric disc and movement of the capsule is used to control servo-motors coupled to the aircraft's rudder controls (see Chapter 5).

The Siemens gyro-magnetic compass, also of German design, although differing in other respects, uses a large solenoidal coil and two small magnets for monitoring the directional gyro.

Brown pitch-azimuth indicator

This instrument was produced in 1930, primarily for use in making fog landings. The object was to indicate to the pilot any divergence of the aircraft from a pre-set glide path. Figs. III. 23 and III. 24 show the appearance and construction of the pitch-azimuth indicator. The gyroscope has three degrees of freedom but the construction of the instrument limits the possible pitch and yaw movement to about $\pm 15^\circ$ only. In the aircraft, the gyro axle lies in a fore-and-aft vertical plane. The instrument case is mounted in trunnions so that its position can be

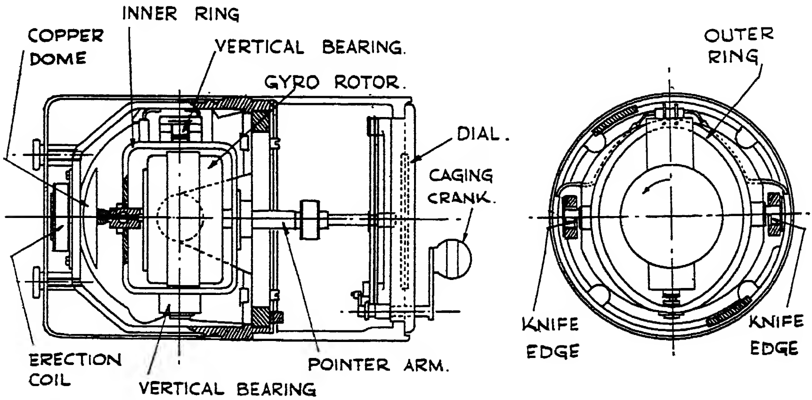


Fig. III. 24. Brown pitch—azimuth indicator, diagram of mechanism removed from trunnions. Eddy current drag on the copper dome keeps the gyro axle parallel to the longitudinal axis of the case.

adjusted about a lateral axis to any position up to an angle of 12° on each side of the horizontal. The gyro rotor is electrically driven from the 12-volt D.C. supply of the aircraft.

A pointer arm on the inner gimbal, aligned with the rotor axis carries a luminized white spot. When the gyro axle is central the white spot is masked by a black datum spot in the centre of the instrum[illegible] glass. The datum spot is intersected by vertical and horizontal li[illegible] dial glass. If the gyro is spinning initially with the pointer spot covered by the datum spot, pitching movement of the aircraft causes the spot to be displaced above or below the horizontal line, while yawing movement results in a displacement to the right or left of the vertical line. A caging mechanism comprising six lever arms, as shown in Fig. III. 23, is actuated by a cranked handle on the front face of the case and enables the gyro to be centralized with the datum spot on the dial glass. A switch for the electrical supply is provided on the left of the case.

To use the instrument it was first necessary for the pilot to ascertain by some other means, such as the natural horizon, that the aircraft was flying straight and level. This would be done with the gyro centralized and with the rotor spinning. After freeing the gyro the aircraft could then be flown straight and level without reference to the natural horizon, that is, by keeping the gyro pointer aligned with the datum spot on the dial glass. A glide or climb path could be followed by tilting the instrument case on its trunnions about a lateral axis, which would displace the datum spot relative to the gyro pointer, and then manoeuvring the aircraft until the gyro pointer was again centralized.

Fig. III. 24 is a sectional diagram of the instrument. The rotor is supported on ball bearings in a vertical gimbal ring which is free to turn about a vertical axis in an outer vertical ring which is supported on knife-edges in a fixed frame attached to the case, and can turn about a lateral axis. As previously mentioned, the pointer is carried by an arm on the inner gimbal. At the opposite end an extension of the rotor axle carries a copper dome which, when the gyro is centralized, is in proximity with and symmetrically disposed in relation to a small electro-magnet carried by the fixed frame. The electro-magnet is continuously energized, after the gyro has been switched on, and as the dome rotates eddy currents are induced in the copper. The interaction between the electro-magnet and the eddy-current magnetic field produces a drag on the copper dome, but this produces no torque about the gimbal axes if the gyro axle is central, but if it is displaced from this position a component of the drag force on the dome precesses the gyro back to the central position. This device is intended to correct any free precession of the gyro, the average erection rate for small displacements being about 2° per min.

It will be seen that the instrument is not monitored in pitch or azimuth, i.e., there is no stable reference datum such as gravity and the earth's magnetic field. It cannot be used to steer a straight path for long periods. Its satisfactory functioning for short intervals is dependent on the aircraft being steered so that the pointer and the datum spot are always in alignment, that is, the intended flight path must always be pre-set by rotating the complete instrument on its trunnions and then changing attitude. Any attempt to steer with the pointer displaced would result in a slow deviation from the intended straight path. Thus the instrument had a limited application for general blind flying purposes, but was satisfactory for blind approach and landing.

CHAPTER 3

RATE-OF-TURN INDICATORS

The first[23] application of the gyroscope in measuring angular velocity was made by H. E. Wimperis who, in 1910, used this device to measure the rate of roll of a ship. The design of the instrument was based on the fundamental principle described in Chapter 1. In the last 25 years a large variety of gyroscopic rate of turn indicators have been produced for use in aircraft. Fundamentally, all these instruments are similar and they differ only in detailed points of design, such as the method of driving the gyro rotor, the form of constraint on the gimbal ring and the indicating mechanism, etc. Spring constraint of the gimbal ring has, however, almost invariably been used.

Design improvements in recent years have been confined to sensitivity, damping and the indicating mechanism. In the past, the methods used to indicate to the pilot that the gyro had moved taxed the ingenuity of inventors and were often more novel than useful. The modern tendency is to keep the instrument indication as simple as possible and the arrays of coloured lights and multi-indicating pointers used on early instruments have disappeared. The modern instrument often uses a pointer and a zero mark on the dial only, and does not require a table of instructions to enable the pilot to interpret its readings.

The axis of spin of the rotor of a turn indicator is usually athwart the aircraft but this is arbitrary and on some instruments it may be fore and aft. The former choice is more convenient in respect of simplification of the indicator mechanism. The spin axis is always in a horizontal plane when the aircraft is in straight and level flight. It is noted that if the gyro axle is athwart the aircraft the instrument indications are unstable during angular movement of the aircraft about its lateral axis, while if the axle is fore and aft the indications are unstable during angular movement about the longitudinal axis. Considering a gyro with its axle athwartships, this is because pitching of the aircraft is unlikely to take place exactly about the spin axis of the gyro, either because the gyro axle is not in exact lateral alignment, or because the aircraft yaws slightly at the same time as it pitches. In either event there will be a component of pitching movement about an axis in the plane of spin which will cause the rotor to precess towards an alignment with the torque. If the sense of spin is in the same direction as the pitching movement, the rotor precesses so that its axle is aligned with the pitch axis, and therefore the false indication of turn is not cumulative. If the rotor spins in the opposite direction, however, the direction of precession is such that the mis-alignment is increased. Thus, with the arrangement shown in Fig. III. 6, the indications are unstable during a loop, that is, large turn indications will be given in either direction depending on whether the aircraft yaws slightly one way or the other during the loop.

The gyro rotor may be either air driven or electrically driven and since 1930 both methods have been in constant use. In the past the air-driven gyro, because of its relative simplicity, gave more reliable service than its electrical brother operating on direct current. This can be largely attributed to the inherent defects of small commutators and brush-gear ; of these faults, uncertainty in starting is perhaps the most common. Air-driven gyros are usually suction operated by either a venturi or an engine-driven pump. Venturis, being continually exposed to the outside air, are liable to failure because of ice-formation and, except on light aircraft, have been replaced by the engine-driven pump.

With any gyroscope it is desirable that the rotor speed should be constant. In a turn indicator variations in the speed affect the sensitivity. The degree of suction for air-driven gyros was kept constant by some form of automatic valve, but because of the increased range of temperature and atmospheric pressure experienced by modern aircraft this has proved inadequate for maintaining a constant rotor speed. If the suction and the temperature are constant the rotor speed increases with altitude, because the reduction in atmospheric pressure results in a decreased air drag on the rotor. For example, a typical air-driven gyro with a nominal speed of 8,000 r.p.m. increases its speed to about 13,800 r.p.m. when the pressure is reduced to a value equal to that obtaining at an altitude of 33,000 ft. However, there is a considerable fall in rotor speed at low temperature. Thus, for the same instrument, the speed falls by 50% at —30°C. and by nearly 90% at —45°C., while at —75°C. the instrument indications cease to be of any value. Irrespective of icing conditions the venturi is of no use above heights of about 28,000 ft. At heights exceeding approximately 36,000 ft. suction-operated gyros are unreliable and it is necessary to use a pressure pump.

The electrically-driven gyro which uses direct current is also subject to speed variation under flight conditions. However, the gyro driven by alternating current (A.C.) is not so adversely affected provided that the frequency of the A.C. supply is constant. That is, while the gyro itself is not subject to appreciable speed variations, it is dependent on the use of a constant speed alternator or rotary convertor. When an A.C. electrical supply is used the gyro rotor is usually the "squirrel-cage" rotor of a small induction motor. The main advantage in using an induction motor is that all electrical contacts are eliminated. Also, provided that the motor design is suitable (correct ratio of resistance and impedance), the slip, that is, the percentage difference between rotor speed and synchronous speed, is not greater than 2% to 3% under all local conditions.

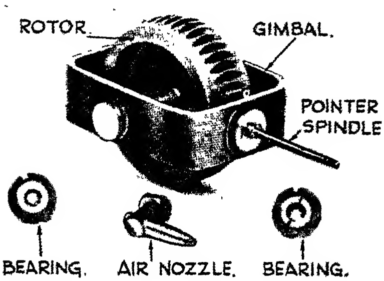


Fig. III. 25. Air-driven rotor, air nozzle and gimbal bearings.

On early aircraft the A.C. supply, usually 3-phase for self-starting purposes, was provided by a small windmill-driven alternator, alternator and windmill being placed in the slip stream of the airscrew. This arrangement was obviously subject to speed variation and suffered to some extent from ice-formation troubles, and, also in common with the venturi, was inoperative until the aircraft was airborne. Because of the added complication of providing a constant-frequency A.C. supply, A.C. turn indicators are not in common use, but other modern gyro instruments are often operated from an A.C. supply, a common arrangement being a rotary convertor which supplies 3-phase A.C. at some frequency between 200 and 500 cycles per second. The rotary convertor is driven from the D.C. electrical supply of the aircraft, and while it is not so susceptible to speed variation as the windmill-driven alternator, its performance in this respect varies considerably with individual designs.

With the general introduction of an independent multi-phase A.C. supply on larger types of aircraft it is probable that all the gyro instruments will be supplied from this common source.

Some D.C. electrical turn indicators have an automatic speed-control device embodied in the gyro rotor. An example, of German design, is described later in the chapter. Typical air-driven and electrically-driven rotors are show in Figs. III. 25 and III. 26. The latter is a squirrel-cage induction motor in which the rotor rotates around a stator attached to one side of the gimbal ring. It should be noted that with each rotor in Figs. III. 25 and III. 26 the mass is concentrated at the periphery to give a maximum moment of inertia for a given weight.

The natural oscillations of the gyro after a disturbance are usually damped by means of either one or two small air dashpots similar to those shown in Fig. III. 27. These consist of pistons, attached to the gimbal, the pistons working with a small clearance in a cylinder attached to the instrument case or to the fixed frame. On some instruments the damping can be varied by adjusting leak orifices in the damping cylinders. A modern instrument made by the Schwien Co., U.S.A., uses a pair of sylphon bellows to give both spring control and damping. The sylphons are filled with a suitable damping fluid and are anchored between gimbal and case on each side of the gimbal axis. They are connected by a passage which has an adjustable restriction. When the gimbal oscillates one sylphon is compressed while the other is extended and the damping fluid is forced from one sylphon into the next. The elasticity of the sylphons provides the necessary spring constraint and the amount of damping can be varied by adjusting the size of the restriction in the interconnecting passage.

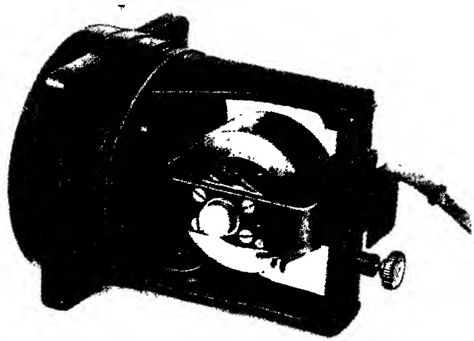


Fig. III. 26. Turn indicator with 3 phase, squirrel cage alternating current gyro rotor.

The turn indicator usually embodies a second instrument which shows sideslip of the aircraft. The sideslip indicator may be a small pendulum, a bubble type of cross level or a small steel ball in a curved glass tube. One modern instrument of German design, described in Chapter 4, consists of an artificial horizon, a turn indicator and a sideslip indicator. An early instrument made by the Pioneer Co., U.S.A., consisted of two angular velocity meters, one of which was used to measure rate of turn in azimuth and the other rate of pitching. A modern "Pioneer" turn indicator of orthodox design is standard equipment on most American aircraft.

Note.—It will be appreciated that some of the foregoing data, e.g., air-driven and electrically-driven gyros, are applicable to gyro instruments in general. Since it has not been possible to devote a separate chapter to this and other simple points of design, the authors-must apologise that such information is distributed in the various chapters.

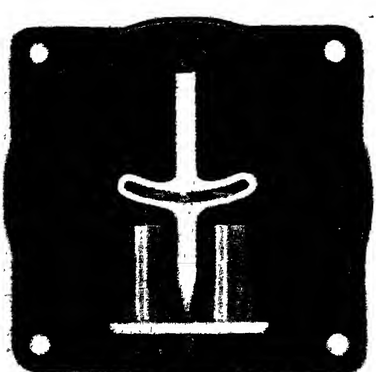


Fig. III. 27. Air dashpots for damping oscillations of gyro. The pistons work with small clearances and the cylinders are sometimes provided with adjustable leaks.

Reid and Sigrist turn indicator

This instrument, which was designed and in use in 1930, is still the standard turn indicator of the Royal Air Force. The basic design has remained unchanged since its inception and the appearance of the instrument, as shown in Fig. III.28, is practically the same as that of its prototypes. Changes have been made in the sensitivity, that is, pointer deflection for a given rate of turn, and the damping has been improved. The rotor is air-driven, the light alloy instrument case being airtight and connected to a source of suction of about 3½ in. mercury. The suction was provided by a venturi with early instruments but is at present provided by an engine-driven pump which also serves the remainder of the air-driven gyro instruments on the aircraft.

Fig. III. 29 shows the mechanism of the instrument. A single air nozzle is attached to the case casting and the jet of air drives the rotor by impinging on buckets cut in its periphery. The brass rotor weighs 12 oz. and runs at 8,500 r.p.m. in ball bearings in a steel gimbal ring. The latter is pivoted in ball bearings between the case and a spider frame bolted to its face. The gimbal can turn, against a spring constraint, about a longitudinal axis only. The spring (sensitivity spring) is anchored in a horizontal position between an adjusting screw on the frame and a gear quadrant attached to the front of the gimbal. The gear quadrant actuates the damping mechanism which comprises a small geared air dashpot attached to the frame as shown in Fig. III. 28.

The rate-of-turn pointer is carried on the front side of the gimbal, as shown diagrammatically in Fig. III. 29. On the actual instrument the pointer protrudes through a hole in the centre of the dial. In Fig. III. 28 the hole is masked by the small circular plate bolted to the front of the dial. This plate supports the sideslip pointer and is not concerned with the gyro mechanism. The sideslip mechanism consists of a small pendulous bar supported in pivots on the rear of the dial plate and its pointer is operated through a pin and slot mechanism, oscillations of the pendulum being damped by a small "piston and cylinder type" air dashpot, also attached to the back of the dial plate.

The dial markings for the rate-of-turn indication, namely 1, 2, 3 and 4, as shown in Fig. III. 28, are related to specific rates of turn about the normal axis of the aircraft as shown by the curves in Fig. III. 30. They are used for adjusting the sensitivity of the instrument, that is, the instrument is mounted in an upright position on a horizontal turntable and the sensitivity spring is adjusted so that the dial indications correspond to the turning rates shown in Fig. III. 30. Under flight conditions in an aircraft the numbers have no quantitative meaning except during a flat turn or a yaw about the normal axis. They do, however, show the relative rates of continuous turns, and familiarity with their use enables the pilot to estimate rates of turn at cruising airspeeds in individual aircraft.

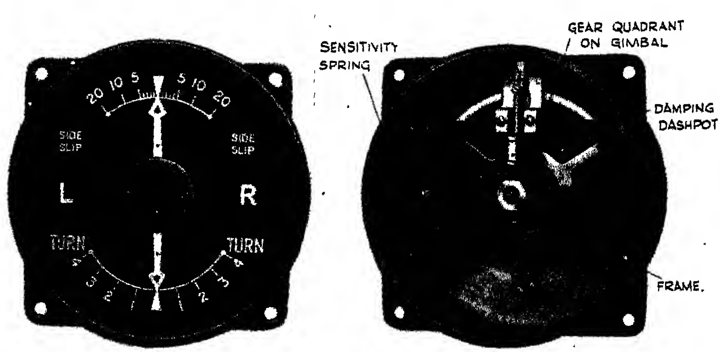


Fig. III. 28. Reid and Sigrist turn indicator. An air dashpot, for damping oscillations of the gyro, is geared to a quadrant attached to the gimbal ring.

This feature is common to all existing rate-of-turn indicators. If the instrument were required to indicate true rate of turn in azimuth it would be necessary to stabilise the instrument case in the horizontal plane so that the axis of spin did not tilt when the aircraft was banked.

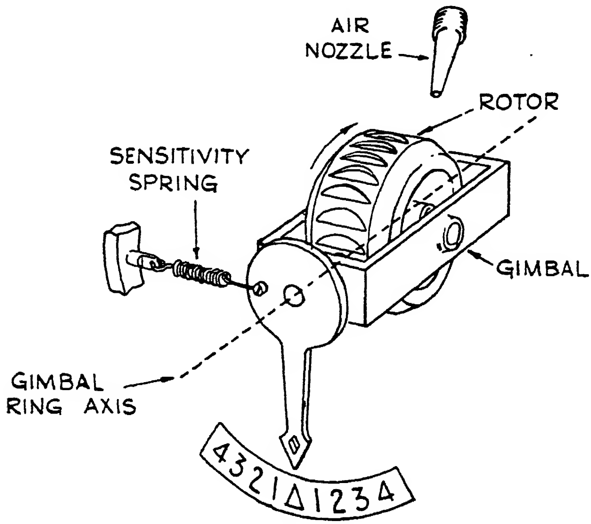


Fig. III. 29. Reid and Sigrist turn indicator, principle of operation and arrangement of sensitivity spring (or control spring).

It is important to note that rate-of-turn indicators were introduced to enable accurate control of yaw disturbances during straight flight, and not as indicators of the rates of continuous turns. However, since the introduction of automatic pilots, with a consequent reduction in manual flying, the tendency is to use these instruments to estimate the rate of continuous banked turns.

It will be seen from Fig. III. 29 that the sensitivity spring is arranged so that the constraint is least for small angles of deflection. Thus for a given increment of rate-of-turn the pointer gives a larger deflection at the beginning of the scale. This is useful in helping the pilot to check disturbances before they reach serious proportions.

The sensitivity is further increased under flight conditions since the direction of spin is such that the rotor turns in the opposite direction to the bank of the aeroplane. Thus in Fig. III, 29, if a right turn is made the aircraft banks to the right, i.e., it turns clockwise about its longitudinal axis while the gimbal turns anti-clockwise. Hence the component of the turn about an axis perpendicular to the spin axis is greater than during a flat turn, and the pointer indication for a given rate of turn in azimuth is more than that shown in Fig. III. 30.

The complete instrument weighs $1\frac{1}{4}$ lb.

Schilovsky-Cooke turn indicator

This instrument, developed in 1929, and now obsolete, is of interest in that it uses gravity control in place of the more usual spring control.

The principle of operation is shown in Fig. III. 32, and the appearance and mechanical details in Figs. III. 31 and III. 33. The rotor is electrically driven from the 12-volt D.C. supply of the aircraft. It runs in ball bearings in a pendulous gimbal ring, the direction of spin being clockwise

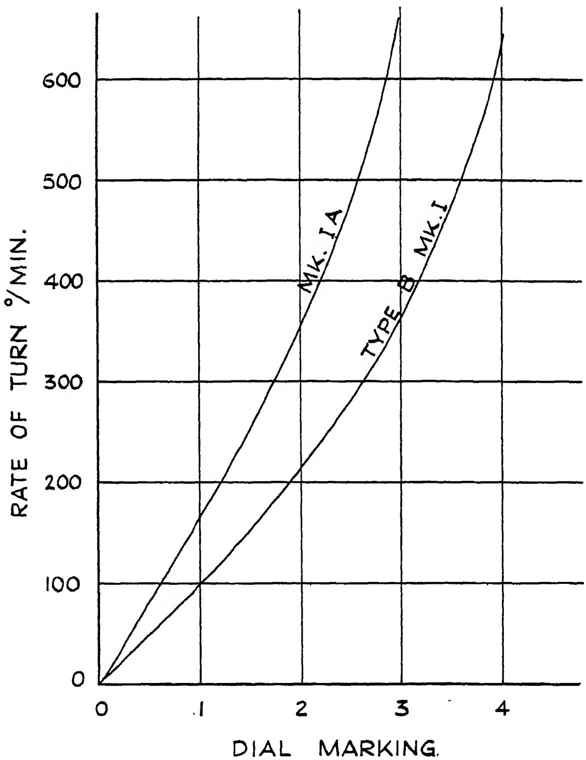


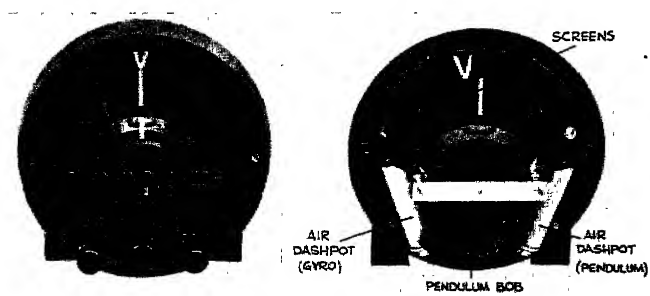
Fig. III. 30. Reid and Sigrist turn indicators, sensitivity curves.

when viewed from the left in Fig. III. 32. The axis of spin is horizontal and athwart the aircraft. The gimbal ring is supported on knife edges and can turn through a limited angle about a fore and aft axis.

Indication of a turn is given in the usual manner by precession of the gyro about the fore and aft gimbal axis, but the actual dial indications are combined with those of a free pendulum supported on a knife edge as shown in Fig. III. 32. The pendulum, while it affects the turn indications given, is not essential for the functioning of the turn-indicator mechanism and for the time being will be ignored. In straight flight the gyro and gimbal assembly act as a free pendulum and the gimbal ring is thus maintained horizontal. When the aircraft turns a couple is applied about a vertical axis and the gyro precesses until the gyroscopic torque is balanced by the couple tending to restore the gimbal to the apparent vertical.

In a correctly banked turn the apparent vertical is normal to the aircraft, that is, in the same direction relative to the aircraft as the true vertical is during level unaccelerated flight. The force acting on the pendulous gimbal, that is, the apparent gravity, is, however, $\frac{1}{\cos\theta}$ times as great as during level flight, where $\theta =$ bank angle of aircraft (*see* Chapter 1). As shown in Fig. III. 34, the torque tending to restore the gimbal ring to the apparent vertical is proportional to $\frac{W}{\cos\theta}\sin\beta$, where $\beta =$ inclination of gyro to the apparent vertical.

As with a spring control, the gyro movement for a given rate of turn in azimuth diminishes as the bank angle of the aircraft is increased, but whereas with the former instrument the sensitivity remains constant, it is dependent on the angle of bank when gravity control is used. It will also be noted that with this instrument the direction of spin is such that during a turn the gyro tilts in the same direction as the bank of the



Crown Copyright

Fig. III. 31. Schilovsky-Cooke turn indicator. Indication of a turn is given by pointers and by the exposure of illuminated screens.

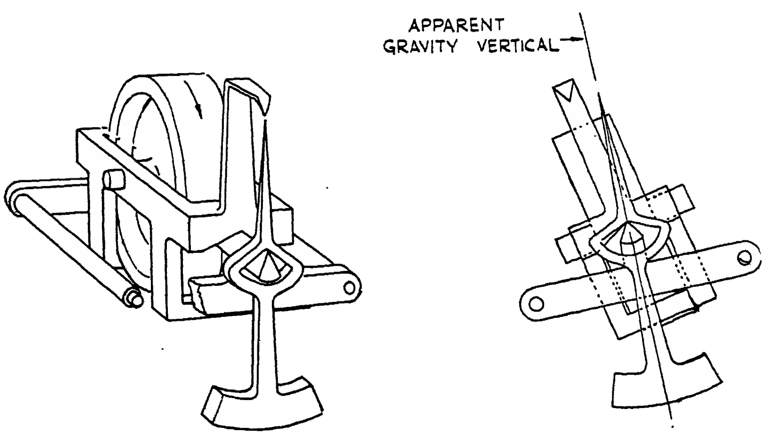
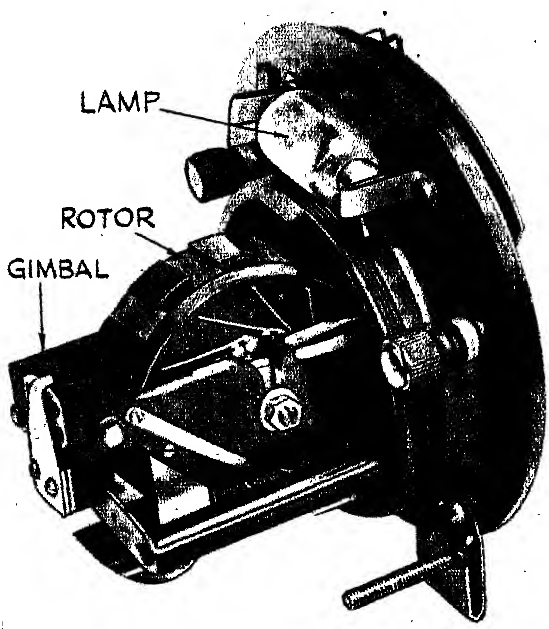


Fig. III. 32. Gravity control is used on the Schilovsky-Cooke turn indicator in place of the more usual spring control. Turns are referred to the apparent gravity vertical defined by a free pendulum.

aircraft. During a turn the inclination of the gyro relative to the aircraft is proportional to $\omega_a \cos \varepsilon$, where ω_a = rate of turn in azimuth and $\varepsilon = (\theta + \beta)$ = inclination of gyro to the vertical. The gyro movement therefore increases rapidly at the start of a turn when the bank angle and the gyro tilt are negligible. Thus during normal straight flight the instrument is very sensitive to small yaw disturbances. The sensitivity is such that when the instrument is turned on a horizontal platform the minimum indication is given by a rate of 18° per minute, while the



Crown Copyright

Fig. III. 33. Schilovsky-Cooke turn indicator. The gyro rotor is externally wound. Modern practice with electrically driven gyroscopes is to wind the rotor internally. (See Fig. III. 36.)

maximum indication is produced by a rate of only 90° per minute. The instrument is therefore essentially for use in steering a straight course and is of no value in estimating the rate of continuous banked turns.

Indication of turning is given by a pointer and also by the exposure of one or the other of two illuminated screens, coloured red for port turns and green for starboard turns. The datum for zero turn is provided by the free pendulum shown in Figs. III. 31 and III. 32. In a correctly banked turn the pendulum is central, that is, aligned with the fixed datum line on the instrument face. However, if sideslip is present during a turn both the turn pointer and the pendulum datum are displaced. A coloured screen is carried on the pendulum each side of the apparent vertical datum mark. Behind each screen is a metal sector, integral with the pendulum and free to turn, relative to the pendulum, about the pendulum axis. The sectors are held in towards the datum mark between the two screens by a light spring control so that normally they mask the screens. The gimbal ring of the gyro has a perpendicular arm which rests between two pins, one on each of the metal sectors. The gimbal carries the turn pointer which is formed to pass over the front of the screens as shown in Fig. III. 31. A small 12-volt lamp is placed behind the screen and mask assembly. Relative movement between the pendulum and the gimbal ring can be observed from the

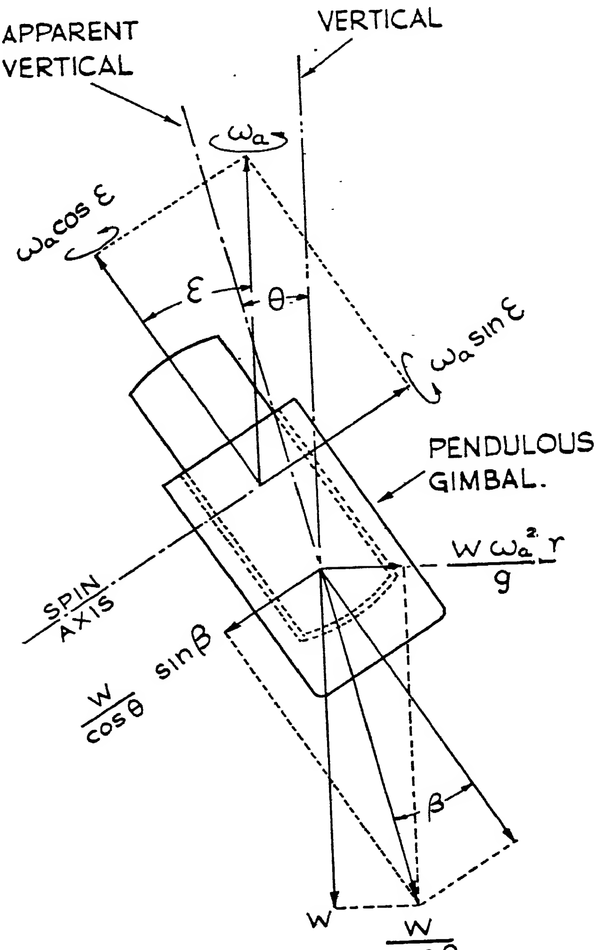


Fig. III. 34. Schilovsky-Cooke turn indicator. Since turns of the aircraft do not take place about the centre of suspension of the gyro the control force on the inner gimbal during continuous turns is a function of apparent gravity, that is, the resultant of gravity and centripetal force on the pendulous gimbal.

pointer. In addition, one or the other of the metal sectors is displaced to expose a band of light from the appropriate coloured screen. If, in addition to turning, sideslip takes place, the inside edge of the band of light, which would otherwise coincide with the fixed datum mark, is displaced to port or to starboard depending on the direction of the sideslip. A bubble-type cross-level is embodied in the instrument as an alternative sideslip indicator.

Oscillations of the gyro and of the free pendulum are damped by piston and cylinder type air dashpots, the amount of damping being adjustable by varying the aperture of small holes in the damping cylinders by turning two small knobs at the base of the instrument face. It should be noted that the damping does not affect the sensitivity of the instrument. But, if overdamped, the indication lags and if underdamped it is unstable. In practice, care was necessary in adjusting the damping to suit individual pilots and aircraft. Also it was important to obtain the correct ratio between gyro damping and pendulum damping as otherwise the instrument tended to indicate that a turn was taking place for angular movement about the longitudinal axis.

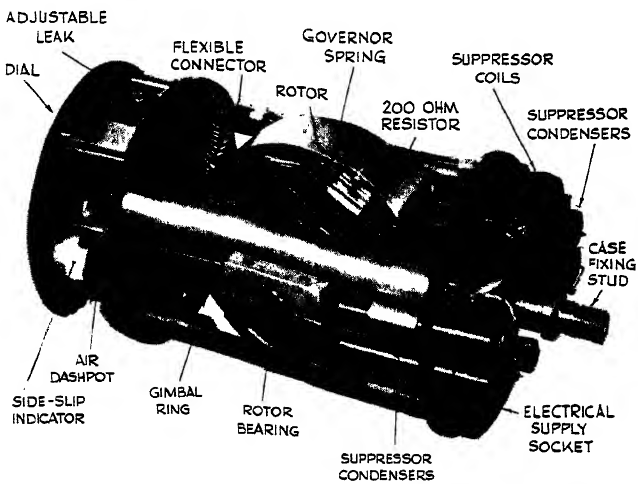
The complete instrument weighs about 2 lb. and the current consumption is $\frac{3}{4}$ ampere.

Horn electrical turn indicator

This instrument, of German design, is operated from the 24-volt D.C. supply of the aircraft. The mechanism is shown in Fig. III. 35 and is normally enclosed by a cylindrical case secured by a nut on the fixing stud at one end. The gyro rotor comprises a small permanent-magnet-field electric motor fitted with a flanged steel disc to increase its moment of inertia. The arrangement of the gyro axes is conventional and a spring constraint is used on the gimbal ring. Ball bearings are used for both the rotor and the gimbal ring which is supported between the two circular end plates of the frame assembly. The motor armature is the innermost member of the rotor and the flange of the steel disc is the outermost. A small two-pole permanent magnet of cylindrical form is secured to one side of the gimbal so that it projects into the annular space between the armature and the flange of the disc. The complete rotor assembly weighs $\frac{1}{2}$ lb.

The rotor spins at a pre-set constant speed of about 6,000 r.p.m., which is controlled by a centrifugal governor. The latter consists of two spring-loaded arms secured to the rotor disc on each side of the spin axis. Each arm carries an electrical contact which makes with a corresponding contact fixed to and suitably insulated from the disc. Resistors of 200 ohms are secured to the disc, and wired in series with the armature brushes and in parallel with the governor contacts. Thus when the rotor is stationary the two resistors are short-circuited. The spring tension of the governor arms is adjusted so that the contacts remain closed at all speeds up to 6,000 r.p.m., that is, the nominal speed of the rotor. Above this speed centrifugal force is sufficient to open the contacts against the spring tension.

Hence the motor normally runs with no series resistance but if the speed tends to rise above 6,000 r.p.m., because of increased supply voltage or reduced atmospheric pressure, etc., one or both pairs of contacts are opened. This introduces a 200-ohm or a 400-ohm series resistance into the armature circuit. The rotor speed falls and the contacts close again and the process is repeated so long as an excess driving torque exists. The governor keeps the rotor speed constant over a range of 18 to 30 volts and its functioning is not affected by temper-



Crown Copyright

Fig. III. 35. Horn electrical turn indicator, view showing gyro and radio interference suppressor components. The D.C. motor comprising the gyro is controlled at a constant speed by a centrifugal governor which varies the resistance of the armature circuit inversely as the speed.

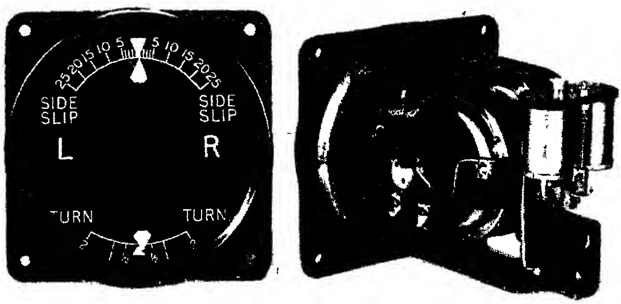
ature down to —45°C. It will be appreciated that the governor contacts are continually making and breaking, at a frequency proportional to the excess driving torque, so that the mean driving torque is just sufficient to maintain the correct rotor speed. To prevent sparking at the contacts from causing interference with the aircraft's radio receiver, a suppressor circuit, comprising two inductance coils and four condensers, is embodied in the instrument.

Electrical connection to the gimbal is made by 0·001-in. metal strips folded "concertina fashion" so that they exert negligible constraint on the gimbal ring. The motor commutator employs the usual copper-carbon brushes.

Damping of the gyro oscillations is provided by an adjustable air dashpot. The turn pointer is slotted and supported on the rear of the dial. It is operated by a pin, carried on the gimbal, which works in the slot. A black ball carried inside a curved, liquid-filled glass tube is visible through a slot in the dial, and provides an indication of sideslip. The complete instrument weighs 2 lb. 6 oz. and consumes 0·075 amperes on a 24-volt supply.

Pullen electrical turn indicator

This is a modern instrument of simple construction, designed to operate from a 9-volt D.C. supply on glider aircraft. Its appearance and construction are shown in Fig. III. 36.



Crown Copyright

Fig. III. 36. Pullen turn indicator. A simple modern type designed to operate on the 9-volt D.C. supply of glider aircraft.

The stator of the small electric motor is cylindrical in shape and is secured to one side of the gimbal ring. The armature comprises the rotor gyro. It is internally wound and rotates around the stator on ball bearings in the gimbal ring which is supported in ball bearings in the frame. Lubrication of the bearings is by felt oil pads.

Each gimbal pivot has an extension which projects through the main frame ; at one end to operate the turn pointer and at the other end the damping dashpots, the pistons of which are linked to a small cross-arm carried on the pivot extension. An adjustable sensitivity spring is anchored between the centre of the cross-arm and the support bracket for the dashpot cylinders.

Electrical connection from the 2-pin supply socket on the frame to the stator winding and the carbon brushes serving the rotor is made by means of two hairsprings, one at each end of the gimbal axis.

The numbers ½, 1 and 2 on the dial correspond to turn rates on a horizontal platform of 75°, 160° and 410° per minute respectively. At reduced temperature these values are lower. The motor consumes about 0·3 amperes on a 9-volt supply. The weight is 1 lb. 10½ oz. and the dimensions 3½ in. dia × 5¼ in. long.

CHAPTER 4

GYRO VERTICALS

The first attempts to use the gyroscope as an aircraft flight attitude indicator centred rather naturally on the simple spinning top type of gyro. The need was for a sure indication of the vertical about pitch and roll axes, in order that the pilot could maintain the aircraft's equilibrium without external visual references, as explained in Chapter 1 dealing with the problems of blind flying.

Griffin gyro indicator

Fig. III. 37 shows a gyro attitude indicator made by Griffin before the First World War. This instrument, typical of early gyro flight instruments, gave the pilot indication to enable him to determine his

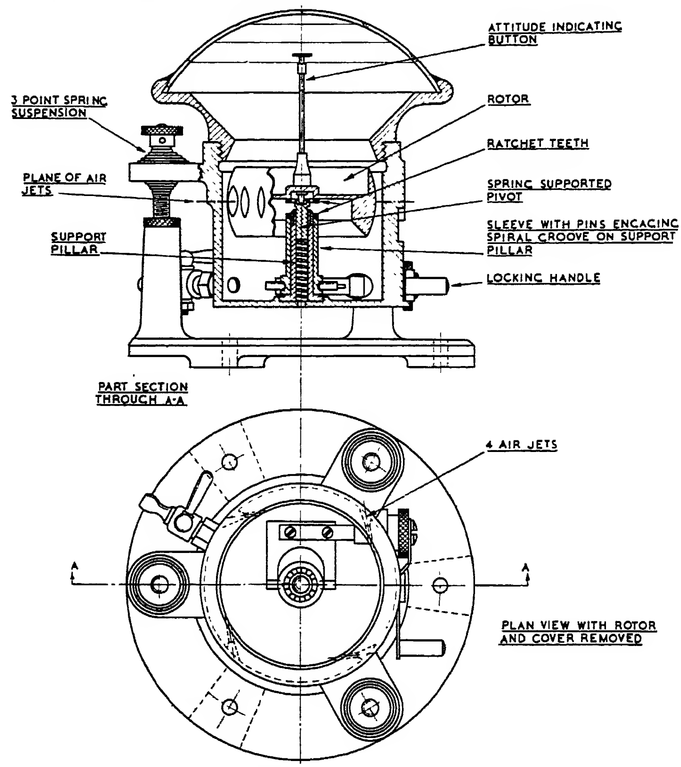


Fig. III. 37. Griffin gyro indicator, sectional elevation and plan views showing construction. The air driven top-form gyro has an extension of the shaft ending in a button which indicates the aircraft attitude against concentric graticule lines on the domed glass cover.

pitch and bank attitude, but without the natural presentation of the later artificial horizon.

The instrument consists essentially of a top-like gyro spinning with its point supported on a cup bearing on top of a pedestal rising from the bottom of a cylindrical case. The gyro wheel has a long "stalk" projecting upwards, terminating in a button just below a part-spherical glass dome, which is marked with concentric rings representing angular tilt of the aircraft in bank or pitch, relative to the gyro stabilised button. The case being evacuated, by venturi or air pump, atmospheric air enters four semi-tangential jets quadrantally placed round the instrument casing in the plane of the rotor rim, which has buckets milled in it.

A lever on the side of the case, actuates a shaft and forked lever engaging a groove in a sleeve surrounding the round pillar carrying the cup bearing. The sleeve has two pins which engage in spiral grooves in the pillar.

The upper edge of the sleeve has ratchet teeth corresponding with similar teeth surrounding the gyro pivot. When the sleeve is raised by the lever it engages the teeth on the gyro and lifts it up off its bearing. The ratchet teeth slip as the sleeve rotates. As the sleeve is lowered again it rotates on its spiral in the opposite direction and the ratchet teeth engage and spin the rotor in the proper direction. To protect the gyro pivot and bearing from shock as the rotor descends, the cup is mounted on a small spindle sliding in the pedestal and supported underneath by a spring.

The gyro rotor has a skirt projecting below the level of the pivot, so that it is slightly pendulous and thus remains upright even when stationary.

The purpose of the lever on the side of the case is to help the rotor to start spinning when the vacuum is first turned on, and also to act as a caging or centralising lever, so that in the event of the gyro being accidentally toppled, it can quickly be righted and started spinning again.

Erection. The rotor will erect itself to the vertical in a slow spiral when spinning with the air turned off. The action of the four air jets has a further direct erecting action, which is analogous to the erection system of the Sperry direction indicator, described previously.

Operation. The instrument, with its self-contained spiral spring anti-vibration mounting, had of course to be mounted where it could be viewed from above, presumably between the pilot's legs. One can imagine the pilot of those days peering through the glass dome and seeing the button on the gyro stalk apparently move forward and to the left, say, from the centre of the circles. He had to interpret this as nose up and right wing low, and, if he wished to fly straight and level, apply down elevator and left bank control to bring the button back to the centre.

In the 1920's, a number of similar gyro indicators were made in France, for example, the Bodin indicator and the gyro clinometre of Le Prieur Bonneau. In the latter instrument the rotor, instead of carrying a stalk and button like the Griffin type, had a polished upper surface which reflected a ray of light from a small lamp embodied in the instrument, on to an inclined ground glass cover. This had the advantage that the pilot did not have to view it from above.

Most of these top-like gyro attitude indicators relied primarily on pivot friction for erection in a damped spiral. Apart from the presentation, which required interpretation, they had other limitations such as a very limited angle of freedom about the pitch and roll axes, and an obvious inability to stand negative gravity as in a downward air gust, without the rotor leaving the supporting pivot and fouling some part of the case.

Although included in this chapter, the foregoing instruments are not gyro verticals in the sense of the term as it has now become applied to gyros mounted in gimbal rings.

Sperry artifical horizon

As we have already seen, the earliest gyro aids to help the pilot maintain stability about the horizontal axes, were the rate of turn gyro and certain types of gyro verticals. From the indications of these instruments the pilot could for the first time fly with certainty and confidence without any visual reference external to the aircraft. The pilot was, however, forced to interpret more or less arbitrary indications on the dial of the instruments and translate these into appropriate control corrections. The type of instrument now known generally as the artificial

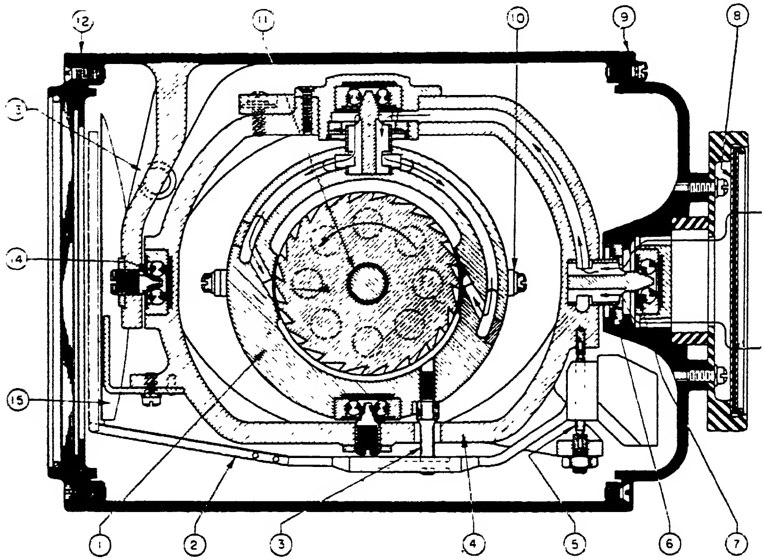


Fig. III. 38. Sperry artificial horizon, sectional plan view.

1. Rotor case
2. Horizon actuating arm
3. Guide pin
4. Gimbal ring
5. Horizon arm pivot
6. Air Seal assembly
7. Air pivot bearing
8. Air filter
9. Rear cover
10. Balance weight
11. Rotor shaft
12. Bezel
13. Front bearing support
14. Front gimbal bearing
15. Dial

horizon, and introduced by the Sperry Gyroscope Co. in 1929, gave the pilot, for the first time, a visual picture of the flight attitude of the aircraft. By enabling him to make use of his natural reactions from clear weather flying experience, the artificial horizon avoided the fatigue produced by an unnatural presentation, and so permitted instrument flying for long periods with greater accuracy.

The standard Sperry artificial horizon provides, in effect, a miniature horizon represented by a horizontal bar on the dial of the instrument, controlled in pitch and stabilised in roll by a gyro vertical. The aircraft is represented on the dial by a miniature silhouette fixed relatively to the instrument case. In normal flight the miniature aircraft is aligned with the horizon bar. Any manoeuvre of the aircraft with respect to the real horizon, about the two horizontal axes, produces a corresponding relative movement of the miniature aircraft and the horizon bar. Thus the pilot can fly level or make banked turns, climb or glide in fog or heavy cloud, and see his flight attitude at all times as easily and certainly as if he could see the real horizon. Figs. III. 38-III. 41 in conjunction with a brief explanation, will enable the reader to understand the construction and operation of the artificial horizon, that has for many years been standard equipment in British and American military and civil aircraft.

As mentioned in a previous chapter, a gyro vertical has two gimbal rings, one in a vertical plane and one in a horizontal plane. In this artificial horizon, the first ring, in which the rotor is pivoted for rotation, takes the form of a case totally enclosing the rotor, which has its axle vertical. The rotor case is itself pivoted with an axis athwartships in the second ring called the gimbal ring. The gimbal ring, lying in the horizontal plane, has bearings in the fore and aft axis of the aircraft in the instrument case. Attached underneath the rotor case is the erection system, consisting of a pendulum assembly, which maintains the rotor vertical under normal level flight conditions, as described later.

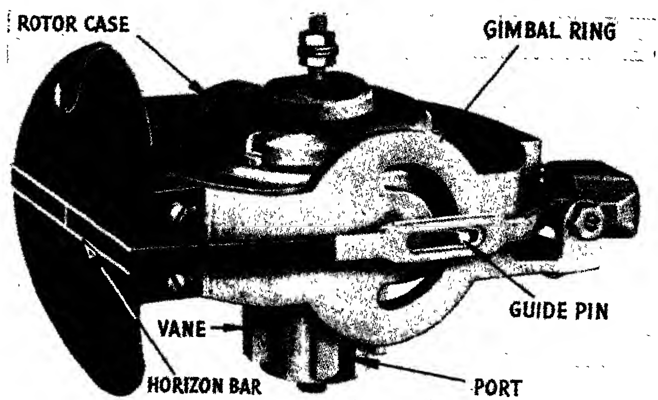


Fig. III. 39. Mark I. Sperry artificial horizon, rotor and gimbal assembly. The horizon bar is stabilised in pitch and roll by the gyro, which is erected to the vertical by the pendulum assembly carrying the gravity controlled vanes.

The case of the instrument is a horizontal light alloy cylinder with a glass-fronted dial, mounted flush with the instrument panel. The dial end of the instrument is of course the rear end with respect to the direction of flight, but for convenience of description, the dial end will here be referred to as the front of the instrument and the other end as the back.

The gimbal ring is supported at the front end by a bearing and pivot on a bracket projecting from the side of the case, and at the rear in a bearing in the rear cover.

Fixed in one side of the rotor case, behind the athwartship pivot axis, is an actuating or guide pin engaging in a slot in the horizon bar arm. The latter is pivoted near its rear end in the gimbal ring and extends along the outside of the gimbal ring to the front end, where it carries the horizon bar proper, lying close across the curved dial, which is attached rigidly to the gimbal ring. Thus pitch movement of the rotor case moves the horizon bar up and down on the dial, and bank movement of the gimbal ring tilts the horizon bar.

Air is caused to flow through a filter on the rear cover, round the bearing and through holes in a special air pivot into a duct round one side of the gimbal ring. It passes through a second air pivot into ducts in the walls of the rotor case and thence through two jets, impinging on

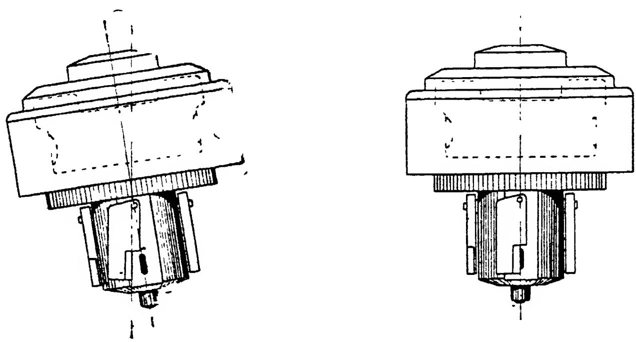


Fig. III, 40. Sperry artificial horizon, erection system. (Right) When the gyro is vertical, all four ports have equal reaction. (Left) When the gyro tilts the open port applies jet reaction to precess the gyro back to the vertical.

buckets milled in the periphery of the rotor, which is caused to spin at about 13,000 revolutions per minute. The air leaves the rotor case through holes in the bottom and passes into the pendulum assembly, from which it escapes through four horizontal ports into the instrument casing. The flow of air is maintained by a vacuum pump and pressure regulator, which are connected by tubing to the case and keep the pressure in the case at 4 inches of mercury—approximately $1\frac{3}{4}$ lb./sq.in.—below atmospheric pressure. In small aircraft, venturis in the air stream are still sometimes used as a vacuum source.

Erection System. The four ports at the bottom of the pendulum assembly are normally each half covered by knife-edged pendulous vanes. These are arranged in pairs, one pair rigidly attached to each end of a

Fig. III. 41. Pre-war civil type. Sperry artificial horizon, dial indication. (Left) Climbing. (Right) Left bank. The latest type has a single line horizon with bank scale at the bottom of the dial.

shaft fore and aft, and the other pair to a shaft athwartships, in the pendulum body. Fig. III. 40 (right) shows the position of all four vanes and ports with the gyro erected to the vertical. As the area of the four half-opened ports is equal, four equal streams of air escape from the pendulum assembly into the instrument case. The accelerated air in these jets causes reactions on the pendulum assembly, which balance each other. If now the rotor case tilts for any reason, as for instance in Fig. III. 40 (left), one port is uncovered fully by its pendulous vane, while the port on the opposite side is closed. The jet from the fully-open port causes a reaction which has no counter reaction from the closed port, and torque is thus created about the horizontal axis lying in the plane of the page. As the rotor is arranged to spin anti-clockwise viewed from above, and as the precession due to the jet reaction torque takes place at 90° in the direction of spin, i.e., clockwise in the plane of the paper, this restores the gyro axis to the vertical.

The erection action about the other axis is similar. In the case of simultaneous tilt in roll and pitch axes, each pair of jets operates to produce a resultant torque, the plane of which is displaced 90° to the plane of tilt and in the sense to counteract the tilt. For very small tilts, the erection torque increases as a function of the tilt angle, but once the port is fully opened or closed, the erection torque becomes constant at the rate of between 5° and 10° per minute.

The erection rate is a compromise, being made only strong enough to overcome, by a safe margin, parasitic friction and out-of-balance torques, so that when the vanes are disturbed from the vertical by acceleration forces, the resulting control precession rate away from the vertical shall be as low as possible. This error, caused by the vanes erecting to the apparent vertical, will be discussed later. The erection torque of the ports to produce this precession rate is very small, about 5 gramme cms., so that it is of the utmost importance that out-of-balance torques and friction effects shall be reduced to the minimum. For this reason the greatest accuracy of manufacture is essential.

The bearings are of a special low friction type with conical pivots in 5-ball races. Only sufficient oil is used in assembly to moisten the bearings and oil soak pads, and no further lubrication is supplied until the instrument requires overhaul. The oil serves mainly as a rust preventative. Balance about the two gimbal axes must be as nearly perfect as possible. Balance weights at various points enable the rotor case to be balanced neutrally in any attitude in the gimbal ring, after which the gimbal ring assembly is balanced to be exactly neutral in any attitude in the case. In the final balance the rotor case assembly is made slightly bottom heavy so that it remains approximately upright when the rotor is at rest. This ensures that the instrument erects quickly to the vertical when starting up.

Temperature Compensation. As the case, gimbal ring, and rotor case are all of aluminium alloy, no relative expansion and contraction of these parts affect the adjustment of the gimbal axes bearings. The steel shaft carrying the brass rotor has a different coefficient of expansion from the aluminium rotor case, so that temperature changes cause a differential expansion which alters the axial adjustment of the rotor bearings. To compensate for this, the top rotor bearing is mounted in a circular housing, which is a sliding fit in the cover of the rotor case. A pin engaging a groove in the housing prevents the latter from rotating. Between the housing and the cover is a slightly dished flat spring washer and the rotor is assembled in the rotor case so that this washer is lightly compressed at room temperature. The right tension is gauged by the free coast time of the rotor, which is adjusted to be not less than 8 minutes from full speed to rest after the air is shut off. If the temperature drops (and the instruments are tested to —40°C.) the case contracts more than the rotor shaft, compressing the spring washer. Conversely, if the temperature is raised to the upper test limit of 60°C., the spring washer takes up any slackness that might develop.

Operation. The instrument will usually erect to the vertical within a minute of applying the vacuum to the case. In flight, if the artificial horizon is mounted on the panel with its face in correct vertical alignment, with the aircraft also in normal flight position, the horizon bar will be parallel to the real horizon. It will also be parallel and on a level with the miniature aircraft on the instrument dial.

If the aircraft banks to the right, the horizon bar, being stabilised by the gyro, remains parallel to the real horizon, and the miniature aircraft, fixed to the case, makes the same angle with the horizon bar as the aircraft's athwartships axis makes with the real horizon. If the aircraft's nose is raised above the horizon in a pitch movement, a consideration of the linkage of the horizon bar, instrument case, and rotor case, will show that the horizon bar will move down. Relatively, the miniature aircraft on the dial appears to rise above the horizon bar. In a banked gliding turn to the left, for instance, the miniature aircraft appears below the horizon bar and banked to the left. A pointer on the dial indicates the angle of bank against a scale.

In the standard artificial horizon, the angular freedom of movement is limited in pitch to 60° climb or dive and 110° roll either way. If these limits are exceeded about one axis, stops on the case strike the gyro element and cause violent displacement or "toppling" of the gyro about the other axis. The vertical reference is then lost and it may take several minutes before the erection system can precess the gyro back to the vertical. During this time, of course, the artificial horizon cannot be used by the pilot. The freedom limits are usually adequate for all normal flying attitudes, to prevent toppling of the gyro. It is only aircraft which indulge in the extreme attitudes of aerobatics that are liable to render the artificial horizon temporarily useless. For fighter aircraft particularly, certain types of artificial horizons are fitted with caging devices, by which the pilot, by turning a knob, can instantly constrain the gyro mechanism back to the normal vertical alignment in the case and release it again. This is only of use if the pilot can be sure that the aircraft is approximately level at the moment of uncaging.

Limitless artificial horizons

It has been recognized that the only satisfactory solution to allow complete tactical freedom of the aircraft is to design a flight attitude indicator to have complete limitless freedom about both axes. Several designs of limitless horizon are already in existence. One of these, the O.M.I., is described later. So far, though, it has not been possible to produce an instrument that is completely immune from disturbance of the gyro under any evolution, even with unlimited freedom about both gimbal axes. Disturbance of the gyro in a limitless movement is due to "gimbal lock" or the temporary loss of one degree of freedom during the momentary alignment of two of the gimbal axes in certain attitudes. If the standard Sperry artificial horizon, for instance, had limitless movement, gimbal lock could occur with the aircraft nose pointing vertically up or downwards, as during a loop. The addition of a third gimbal ring in the design of a limitless instrument helps to prevent gimbal lock, but is not absolutely proof against some disturbance under all circumstances. However, a maximum of few degrees of error in the vertical

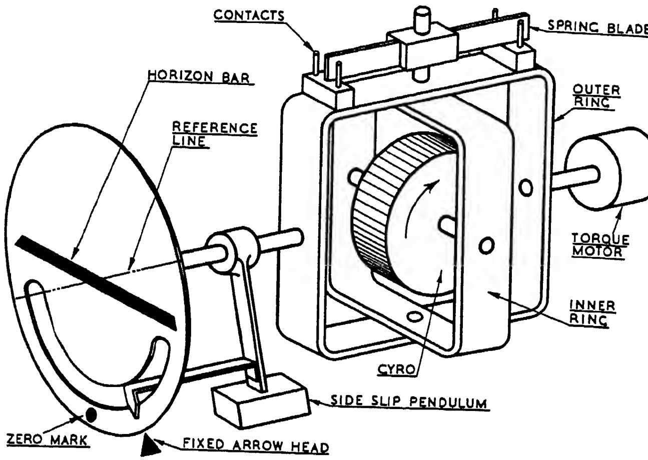


Fig. III. 42. Gyrorector, principle of construction. The horizon bar is carried on the outer gimbal ring horizontal axis. Any tilt of the pendulous gyro assembly causes a gravity torque about this axis and the resulting precession of the vertical axis ring closes contacts which cause the torque motor to oppose the gravity torque while the reaction of the contacts on the spring blades precesses the gyro axle back to the horizontal.

probably lasting not more than a minute can be much better tolerated than complete loss of the vertical reference after aerobatic manoeuvres. There is no doubt that limitless artificial horizons have come to stay, as far as fighter aircraft are concerned.

The Gyrorector

Although not actually a gyro vertical, this German design is a form of artificial horizon with the addition of a side-slip indicator. The instrument is electrically operated and the main interest lies in the method of stabilising the horizon bar about the roll axis. The pitch indication is a fore-and-aft inclinometer of the spirit-level type. Fig. III. 42 shows the schematic form of the gyrorector.

The rotor is mounted with its axle horizontal and athwartships, and is driven by three-phase alternating current at about 18,000 r.p.m. The inner gimbal ring carrying the rotor has its axis vertically mounted in the outer gimbal ring, the axis of which is fore-and-aft in the instrument case. An extension at the top of the inner ring carries two insulated contact blades, which form the reversing switch for controlling the torque motor on the outer gimbal axis. The outer ring is pendulous and carries a dial on an extension of its axis at the front. This dial is a disc with an artificial horizon marking and a zero mark at the bottom. Co-axial with the disc is a simple damped pendulum carrying a pointer which indicates against the dial.

The instrument case itself has two reference marks on the cover glass, one a line across the face parallel to the aircraft's transverse axis, and an arrowhead at the bottom of the glass.

Operation. In straight flight, if the gyro axis tilts from the horizontal, the bottom-heavy outer ring applies a torque to the rotor axle. The precession due to this torque occurs about the vertical axis carrying the contact blades, which close the reversing switch in one direction. The connections to the torque motor are arranged to cause the motor to apply a torque about the fore-and-aft axis which opposes the torque due to the pendulous moment of the outer ring, and the result is an azimuth oscillation of the vertical ring making and breaking the contacts. The reaction of the contacts against the spring blades precesses the outer ring back to the vertical plane, bringing the gyro axis to the horizontal. As long as the outer gimbal is vertical, the contact blades float between the contacts.

During a turn, centrifugal force acting on the pendulous outer ring produces a torque about its axis. As we have seen, the effect is to cause an azimuth precession of the inner gimbal.

If now we arrange that the azimuth rate of turn of the aircraft is equal to the azimuth precession rate of the inner gimbal, the contacts will keep pace with the blades and prevent their closing. Under these conditions, the gyro system will remain erected to the vertical, so that the angle between the reference line on the cover glass and the horizon mark shows the bank attitude of the aircraft. Actually, the precession rate of the inner ring is made to be the same as the aircraft turn rate by the choice of a suitable degree of pendulous moment for the outer gimbal.

It can be proved that for the two rates to be equal, the pendulous moment can be fixed independently of the radius of turn, provided a certain ratio between airspeed and gyro speed is maintained.

Let Ω = rate of turn of aircraft = precession rate of inner ring
ω = speed of gyro wheel
I = moment of inertia of gyro wheel
K = torque causing azimuth precession of inner ring
P = pendulous moment of outer ring
v = airspeed

$$K \text{ due to centrifugal force} = \frac{Pv\Omega}{g} \text{ or } P = \frac{Kg}{v\Omega}$$

But $K = I\Omega\omega$

$$\therefore P = \frac{I\Omega\omega g}{v\Omega} = \text{constant} \times \frac{\omega}{v}$$

Showing that the pendulous moment depends only on the ratio of rotor speed to airspeed.

By driving the rotor from a wind-driven generator, the ratio between airspeed and rotor speed can be kept approximately constant. Any discrepancy results in a negligible tilt of the horizon bar.

In a correctly banked turn the sideslip pointer remains opposite the fixed arrowhead and both are displaced from the zero mark by the bank angle.

O.M.I. artifical horizon

An interesting design of artificial horizon with several novel features is illustrated in Figs. III. 43 and III. 44. It is an Italian instrument made by the O.M.I. company.

Like the Sperry artificial horizon it is designed to be suction operated, but can also work on positive air pressure. As in an early Sperry proposal, the dial presentation, although indicating bank and pitch by the relative movements of a miniature aeroplane and horizon bar, is different from the standard Sperry arrangement. In the O.M.I. the horizon bar is fixed to the case of the instrument, and the minature aeroplane, mounted on the gyro element, is caused by gearing to roll with respect to the case in the same direction as the aircraft itself rolls about its fore-and-aft axis. Instead of the miniature aeroplane being displaced above and below the stabilised horizon bar, the horizon bar is displaced below or above the stabilised miniature aeroplane during climb and dive respectively. The relative movement and indication is the same in either case, however.

The instrument has full 360° freedom about both horizontal axes, with bank angle markings up to 45° and dive angles marked from 40° to 90°. A knob centrally below the dial adjusts the pitch datum of the horizon bar plus or minus 10°, for different trim angles in level flight. The larger knob operates a centralising or caging mechanism.

Construction. The outer gimbal ring is pivoted athwartships in the case in ball bearings, the pivots of which are fixed in the case and form the jets which drive the rotor. The inner gimbal ring, corresponding to the rotor case of the Sperry instrument, is pivoted in ball bearings fore and aft in the outer gimbal ring. The inner ring is made in two halves held together by screws, the upper half housing the erection system.

The brass rotor has a part spherical periphery with wide buckets. The rotor of course has its axle vertical, and the lower half of the hub has five symmetrically placed holes sloping slightly inwards from top to bottom. Each hole contains a steel ball. When the rotor is stationary, the balls rest at the bottom of the holes, in which position the rotor assembly is balanced slightly bottom heavy. This keeps it approximately vertical before starting up, so that initial erection time is short.

When a certain rotor speed is reached, centrifugal force causes the balls to climb up the inclined holes, until they are restrained by a blanking ring. In this position the centre of gravity is raised so that the rotor assembly is neutrally balanced at normal running speed. This prevents that part of turn error due to pendulosity, as later explained. No provision is made for temperature compensation.

Erection System. Mounted under the top half of the split inner gimbal coaxial with the rotor is a shallow cylinder driven through 300 to 1 reduction gearing from the rotor by worm, bevel and pinion. Projecting from the inner wall of the cylinder are ten hooks, facing and rotating in the same direction as the rotor.

The cylindrical chamber contains four steel balls. If the rotor axis is not vertical, the steel balls roll to the low side and are caught in the hooks which carry them to the high side. The hooks are shaped so that the balls disengage at the highest point and roll to the lower side. This process is repeated continuously, with the result that the mean centre of gravity of the balls is halfway up the side of the slope in the direction of rotation.

By the rule of precession, the torque due to the weight of the balls takes effect 90° in the direction of rotation, which is in the right sense to reduce the tilt and bring the gyro axis to the vertical. This system of erection originated with Professors J. and J. G. Gray. Another version of it is used in the Fluxgate vertical gyro, described later.

Dial Mechanism. The front inner gimbal pivot has an extension passing through the outer gimbal ring and carrying a pinion meshing with a second pinion pivoted on the outer gimbal. The miniature aeroplane is mounted on the shaft of the second pinion, which pinion is in effect a planet wheel revolving round the sun pinion stabilised on the inner gimbal axis. Thus, when the outer gimbal is carried round with the case when the aircraft banks, the planet wheel carrying the miniature aeroplane turns in space through twice the bank angle in the same direction, that is, from the pilot's point of view, by the amount of the bank angle relative to the horizon bar.

Crown Copyright

Fig. III. 43. O.M.I. artificial horizon external view showing dial presentation. The lever at the bottom right corner is for caging the movement. The small knob adjusts the horizon bar pitch datum plus or minus 10° to suit aircraft trim.

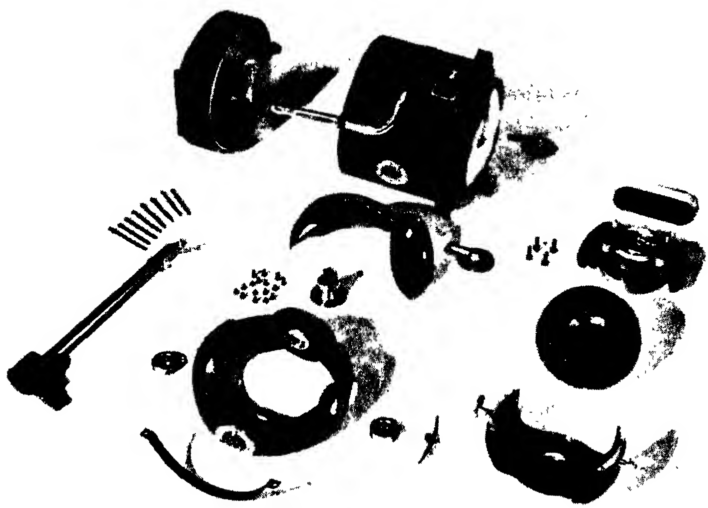
Caging Mechanism. An extension of the rear inner gimbal pivot carries a heart-shaped cam, and a similar cam is fastened about one of the outer gimbal pivots.

The caging knob at the front of the instrument turns a shaft actuating two levers pivoted on the back cover of the instrument. Initial movement of the knob raises one of the levers which presses a roller against the heart-shaped cam on the outer gimbal and causes it to centralise. Further rotation raises the second lever which centralises the inner gimbal in a similar manner.

Operation. Suction is applied to the instrument through a pipe leading into the top of the case, which is maintained at four inches of mercury below atmospheric pressure. Air enters at both sides of the case through the outer gimbal pivots and through the nozzles formed on their inner ends. As the jets are fixed to the case, they drive the rotor only up to 35° bank angles, beyond which they miss the buckets. If the aircraft is inverted the jets oppose the direction of spin. Gimbal lock, or loss of one degree of freedom occurs when the outer gimbal axis aligns with the rotor axis in a 90° bank. After a roll, for instance, the gyro may be tilted as much as 20° from the vertical.

If the aircraft performs a half-loop and half-roll, the back of the gyro system appears at the front and consequently the miniature aeroplane is lost to view.

Earlier models carried an indicating mechanism at both ends of the



Crown Copyright

Fig. III. 44. O.M.I. artificial horizon, dismantled. The outer gimbal axis is arranged athwartships in the case and the model aeroplane indicator driven by gearing from an extension of the inner gimbal pivot.

inner gimbal which overcame this objection and also prevented the indication from being lost if the outer gimbal somersaulted, as it may do during gimbal lock, during a full roll for instance.

If the indication is lost in this way with the present instrument, the movement can be centralised again by the caging knob. This of course presupposes that the pilot is able to determine by external reference that the aircraft is approximately on an even keel before caging. The caging knob is spring-loaded to free the gyro when the knob is released.

Acceleration errors

Gyro verticals, being erected to the vertical by gravity control, are subject to errors due to the susceptibility of all gravity detectors, such as pendulums, to acceleration forces. The latter, if not themselves vertical, combine vectorially with the gravitational force to form a resultant false vertical. Any gravitational control exerted on the gyro then tends to bring the gyro axis, not to the true vertical, but to this apparent vertical. Additionally, if the gyro is not neutrally balanced, but pendulous for instance, the acceleration forces acting directly on the centre of gravity of the gyro system exert a disturbing precessing torque.

Both these effects may be produced by continuous straight line accelerstion in one direction, as for instance during take-off, when the false gravity erection, due to forward acceleration, tends to pitch the top of the gyro forward, and any bottom heaviness of the gyro system is acted

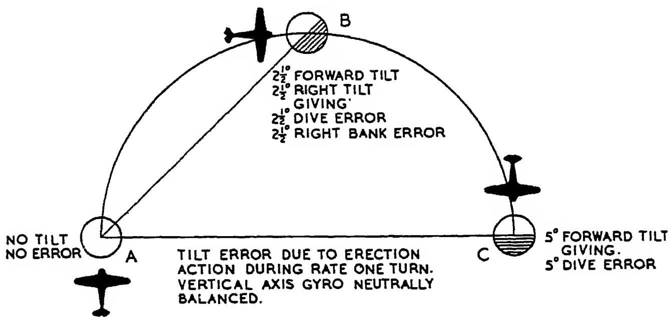


Fig. III. 45. Artificial horizon, centrifugal force during turn, causes gyro to erect to the apparent vertical, i.e., the natural bank angle. The instantaneous tilt is in roll about the mean line of flight.

on by the acceleration to precess the gyro in roll to right or left, depending on the direction of rotation of the rotor.

The other main acceleration error is due to centrifugal force during turns, and again has two distinct effects, one due to "erection" action, and one due to non-neutral balance (if any) of the gyro assembly.

The turn errors are usually considered to be the more important, so we will examine them in detail, for convenience calling them erection and pendulous error respectively.

Erection Turn Error. In the case of the pendulous vane erection system, the effect of a right-hand turn is to cause the bank erecting vanes to swing outwards to the natural bank angle. The erection action of the open port tends to precess the gyro to follow the vanes, i.e., to tilt the top of the gyro axis to the right. Provided the centrifugal force is sufficient to open the port fully, the precessional tilt rate to the right will be constant. It should be noted that the direction of the precession is at right angles to the roll axis of the aircraft and turns in azimuth with the aircraft.

Consider first the case of a hypothetical turn of infinite rate. The time taken to complete a 360° turn would be zero. Hence, with a constant limited rate of precessional tilt due to centrifugal force, the tilt error at any point in the turn occupying no time, must be zero. Again it is obvious that in an infinitely slow turn, i.e., straight flight, there can be no centrifugal tilt effect. The condition for maximum tilt to develop for a given airspeed is the slowest rate of turn, which will just cause the bank erecting port to open fully, i.e., maximum erection rate, and allow the maximum time for the tilt to develop. Provided the port is fully open, the error is a function of rate of turn only. The effect of tilt error due to action of the erection system alone in a turn, can be studied by reference to Fig. III. 45, in which a neutral vertical balance of the gyro is assumed.

In Fig. III. 45 the aircraft is assumed to start from A with the gyro axis vertical. At any instant during the right-hand turn, the precessional tilt of the top of the gyro axis, due to displacement of the vanes is to the right in relation to the aircraft's heading. After 90° turn at B, the tilt error will be the integral of the tilt rate, i.e., erection rate, during the time interval from A to B, and to the right of the mean heading, that is, the line joining A to B. If the rate of turn is 180° per minute (rate one) and the erection rate 5° per minute, the aircraft attitude error after ½ minute at B will be 2½° right bank and 2½° nose down or dive. Similarly after 180° turn at C along a mean heading AC, the tilt error will be 5° dive. After 180° the direction of the erection tilt starts to oppose the tilt error already produced, so that at 270° the error would be 2½° left bank and 2½° climb. Finally, after one complete turn back to A, the mean change of heading is zero and the tilt error is also zero. This shows firstly, that this tilt error is not cumulative for a number of consecutive turns, and secondly, that for a given rate of turn, the slower the erection rate, the less will be the maximum tilt error.

Pendulous Turn Error. Consider now the case of a rotor assembly balanced bottom heavy, or pendulously. In a right-hand turn, centrifugal force produces a clockwise torque on the rotor axle looking forward, about the roll axis. With the counter-clockwise spinning rotor, the resultant precession of the gyro axis will be in a direction which tilts the top of the rotor axle forward. The centrifugal torque in this case will depend on both rate of turn and airspeed, and the pendulous moment of the gyro element. Let us assume that the pendulous moment is such that with a rate of turn of 180° per minute at 220 m.p.h. airspeed our formula of a previous chapter $\omega = \frac{K}{I\Omega}$ gives us a forward precession tilt rate of 3½° per minute. Referring to Fig. III. 46 representing a right-hand turn of 180° per minute at 220 m.p.h., we start as before at A with the gyro vertical. After ½ minute at B, the top of the rotor axis will be tilted forward in the mean heading as shown, giving a nose down error and left bank error of 1¾°. The maximum error will again occur at 180°, being 3½° to the left. At 270° the tilt could be shown to be 1¾° nose up and right bank. Finally at A, after a complete turn, the tilt error, due to pendulosity of the gyro, will again be zero. In practice of course, friction effects modify the tilt errors.

Turn error correction

As turn error occurs in all gyro verticals, whether in flight instruments such as the artificial horizon, or in vertical gyros used in automatic pilots, or for stabilising other instruments, much time and thought has been given to methods of reducing or eliminating its effects.

The second cause which we have considered, pendulosity of the gyro element, can be eliminated by making the vertical balance of the gyro neutral. This can be done where initial time of erection is not important, or some means of caging the gyro to the vertical is provided. Another method is the automatic change of balance, used by O.M.I. The error due to false gravity erection is most commonly countered by reducing or cutting out the erection torque during a turn. This is comparatively simple to achieve on electric gyros where the electric erection system can

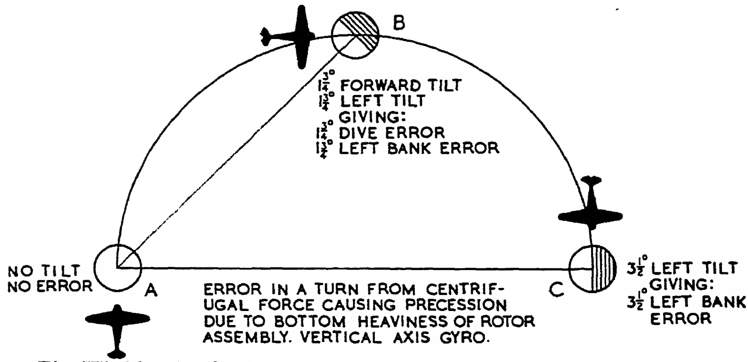


Fig. III. 46. Artificial horizon, centrifugal force during turn causes precession error due to pendulous gyro system, forward in the mean line of flight in a right-hand turn, with rotor turning anti-clockwise.

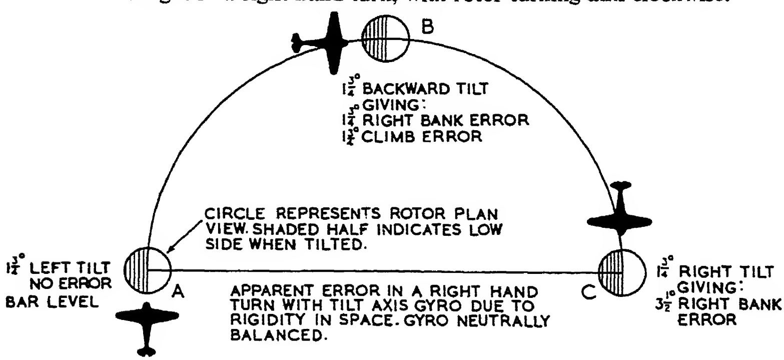
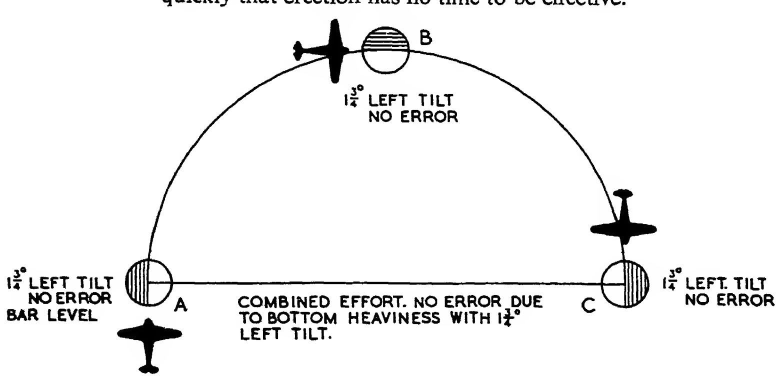


Fig. III. 47. Artificial horizon, gimballing effect with initial tilt. It is here assumed that the gyro is freee, or that the turn is made so quickly that erection has no time to be effective.



NOTE: ERRORS SHOWN ARE AIRCRAFT ATTITUDE ERRORS WHEN LEVELLED OUT BY ARTIFICIAL HORIZON INDICATIONS.

Fig. III. 48. Artificial horizon neutralising of turn errors by combination of tilted gyro and gimballing effect. The result of combining the effects shown in Fig. III. 46 and Fig. III. 47.

be controlled independently of the electric drive for the gyro. In this case, during a turn, the erection can be reduced by putting a resistance in the electric circuit of the erecting device for instance, or switching off the erection altogether. One method of automatic turn error correction is to use a rate gyro to detect the turn and operate a switch or other means of "spoiling" the erection torque.

In an automatic pilot gyro vertical, the spoiling of the erection during a turn may be achieved by the act of operating the control which causes the aircraft to turn. During the time erection is totally cut off, the gyro relies on rigidity alone to resist any frictional or other disturbing torques. The turning of the earth, at any latitude but the poles, produces an apparent tilt of the free gyro-vertical.

On air-driven instruments, particularly flight instruments, it is difficult to arrange an erection system that can be controlled independently of the pneumatic rotor drive. It would not be practicable to shut off the air to the pneumatic erection system, as the rotor speed would be affected in a prolonged turn, and errors due to the fore-mentioned causes would develop. An ingenious method of reducing erection turn error to small proportions was introduced by Sperry on the latest type artificial horizons. It relies on a combination of gimballing effect and a permanent initial tilt of the gyro axis. In these artificial horizons, the gyro axis, instead of being truly vertical when erected, is inclined top forward at $2\frac{1}{2}°$. This is done by counterbalancing the erecting vanes to hang off the vertical by those angles. The horizon bar is arranged to be in correct alignment with the miniature aircraft when the instrument is level and the rotor case tilted as described. The $2\frac{1}{2}°$ forward tilt is designed to eliminate erection torque tilt for a turn rate of 180° per min. British artificial horizons now also incorporate a Royal Aircraft Establishment development a $1\frac{3}{4}°$ left tilt, to eliminate pendulous error for the same rate of turn at 220 m.p.h. Some error, but greatly reduced, will be left at other rates and airspeeds.

The principle involved can be understood for both cases by consideration of one, for example, the pendulosity error. Turning to Fig. III. 47, we will consider the effect of the $1\frac{3}{4}°$ left tilt of the gyro without centrifugal force present. At position A there is no error. At position B the gyro has not been acted on by any external force and maintains its original attitude in space. The whole instrument, including gimbal ring and rotor case, has been turned 90° round the vertical axis, so that the original tilt of $1\frac{3}{4}°$ left has been converted by gimballing effect to $1\frac{3}{4}°$ backward tilt. As it required $1\frac{3}{4}°$ left tilt to maintain the bar level originally, no tilt about the fore-and-aft axis produces a $1\frac{3}{4}°$ right tilt of the horizon bar or right bank error. Simultaneously, the backward tilt gives a pitch error of $1\frac{3}{4}°$ climb. At C the tilt has become $1\frac{3}{4}°$ right instead of $1\frac{3}{4}°$ left corresponding to horizon bar level. The right bank error is thus $3\frac{1}{2}°$.

If we now combine the tilts of Fig. III. 47 with the tilts we found in Fig. III. 46 due to pendulosity, we get a combined tilt as shown in Fig. III. 48. It will be seen that the effect of the permanent $1\frac{3}{4}°$ left tilt of the gyro axis when added to the pendulosity error is to cancel out all tilt except $1\frac{3}{4}°$ left in any position, which was the original condition for no error.

Similarly it could be shown that if the rotor is normally erected to a $2\frac{1}{2}^\circ$ forward tilt with the horizon bar level, this initial tilt will combine with the erection tilt errors of Fig. III. 45 and neutralise them at all stages of the turn.

Comparison of pneumatic and electric operation

Although air-operated instruments have the advantage of relatively simple construction, they also have drawbacks compared with electric drive, especially in the case of artificial horizons.

To spin the rotor on air-driven instruments, air has to traverse bearings in order to pass from the external atmosphere to the rotor jets. The atmosphere carries a certain amount of moisture at all times and it is extremely difficult to protect the gimbal pivots in particular from the effects of damp air passing close to the bearing surfaces, which are very susceptible to corrosion.

The most serious disability of pneumatic drive is for high altitude operation. Owing to the decrease of air density with increase in altitude, the working of vacuum pumps becomes less efficient until any surplus capacity is absorbed, at which time the pump is working at full delivery to maintain the necessary depression at the instrument case. Any further increase in height causes a progressive falling-off in vacuum which the vacuum regulator valve is unable to check. Unless special vacuum systems are installed, involving the extra weight and bulk of abnormally large pumps, vacuum operation at present is not very satisfactory for instrument operation above about 25,000 feet.

This last trouble will be neutralised by the introduction of pressure cabins in aircraft. In this system compressors maintain the interior of the sealed cabin above the pressure of the outside air at high altitude, for the benefit of passengers and crew. The air in the cabin might be stabilised at the equivalent atmospheric pressure at 10,000 ft. for example, no matter at what altitude the aircraft flew above that level. A pressure gradient is thus created between the air at the instrument filters and the vacuum pump, to assist the latter, so that the compressors tend to replace the function of the vacuum pump.

Closed air systems, in which the air is circulated in a closed path from pump to instrument and back, largely overcome both the foregoing difficulties, and may also come into favour.

In electric instruments, the case can be virtually sealed from the external atmosphere, which greatly reduces the chance of rust attacking bearings. Electric operation is also unaffected by low air density at high altitude.

Another advantage of electric operation is the increased efficiency of rotors that can be achieved with induction drive. Electric gyros are almost universally driven by alternating current, more usually by three-phase supply. In A.C. gyros, the rotor is, in effect, a squirrel-cage induction motor, with the windings carried on a stationary armature, and the rotor a cylindrical shell surrounding it. A rotating magnetic field is set up by the armature windings and the induced currents in the rotor cause it to be dragged round at nearly the same speed as the rotating field. The gyroscopic momentum of a cylindrical rotor is proportional to its speed and the fourth power of the diameter. High speed is easily attained by electric drive and the external cylindrical rotor is of maximum efficiency from the point of view of the ratio of moment of momentum to weight.

A further asset to be claimed for electric operation is the ease of installation and the saving in weight of wiring compared with vacuum pipe-lines and fittings.

Sperry electrical artificial horizon

Typical of the latest practice in electrical design is the Sperry artificial horizon shown in Fig. III. 49. The whole mechanism is carried in a dummy case or open frame attached to the front of the instrument. A light pressed sheet cover, secured by screws at the back, seats on a gasket round the back of the front casting. The edges of an opening in the back of the cover seat on a gasket surrounding the electrical socket to which the supply cable connects. The case is normally practically airtight, but by removing the screws at the back, the outer cover can be drawn off leaving the movement in working order and fully accessible.

Three-phase current at 115 volts and 400 cycles is supplied to the multi-pin socket at the back, and thence to three contact blades mounted on the frame. Three similar blades mounted on an extension of the outer gimbal ring make point contact with the first three interleaved blades, on the fore-and-aft axis. A similar arrangement transfers the three-phase supply to the rotor case, which acts as inner gimbal ring.

The thin die-cast rotor housing and cover contains an induction type rotor of the type already described. Rotor and other bearings are all journal type ball races. The 400 cycle per second current produces a magnetic field rotating at 24,000 r.p.m. and the rotor turns at approximately 23,000 r.p.m. Carried on the die-cast gimbal ring and on the

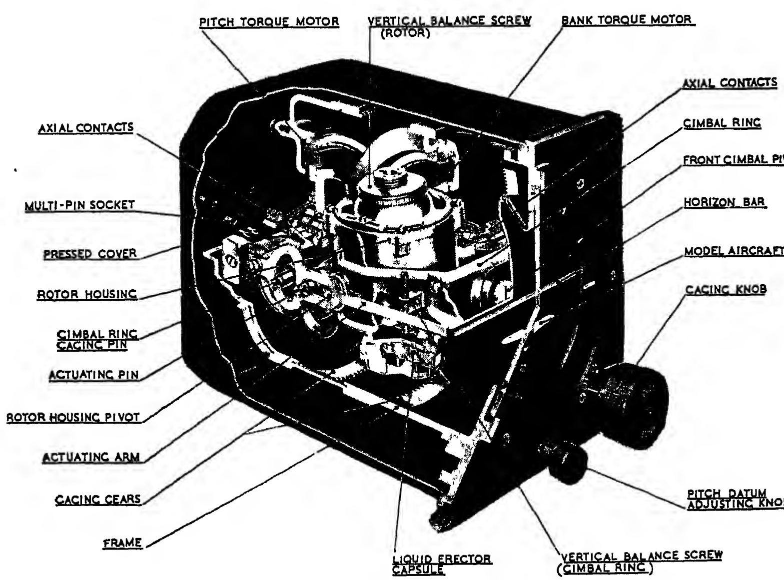
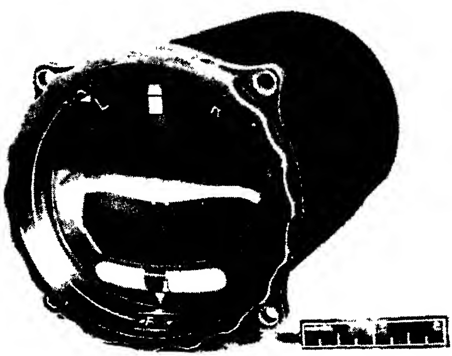


Fig. III. 49. Sperry Type E—1 electric artificial horizon, cut-away view of mechanism. The gyro is driven at 23000 r.p.m. by three phase A-C supply at 115 volts 400 cycles°sec.

rotor housing are the wound rotors of two torque motors, the stators of which are mounted on the frame and gimbal ring respectively.

Fastened to the bottom of the rotor housing is the erector capsule, a small circular sealed chamber with four contact studs in the slightly domed roof and nearly full of semi-conducting liquid. The studs are arranged in pairs fore-and-aft and transversely, and are connected as a reversing switch between one of the supply phases and one winding of their respective two-phase torque motors. The other torque motor phase is connected permanently to another supply phase. When the gyro is erected to the vertical the contact of the liquid on all four studs is equal. If a tilt develops, the contact and resistance between pairs of opposite studs alters differentially, and the reversing winding on the torque motor becomes energised to apply the appropriate erecting torque.



Crown Copyright

Fig. III. 50. Horn artificial horizon, view of dial. This German instrument has a horizon bar indication and in addition a rate-of-turn gyro at the back of the case operating the pointer at the top of the dial, underneath which is a ball bank indicator.

The caging knob rotates two gear rings in the frame, which have an axial finger each. Turning the knob to the caged position causes the rings to rotate in opposite directions. The two parallel fingers finally trap the gimbal ring caging arm and actuating pin and centralise the movement from any position.

Horn artificial horizon

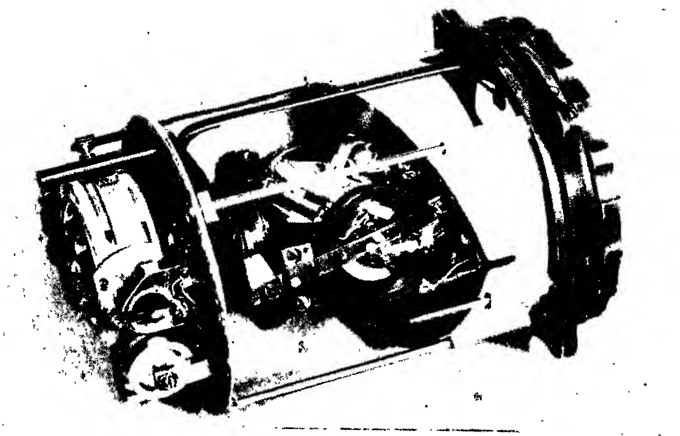
The German instrument shown in Fig. III. 50 is an unusual combination of artificial horizon and turn indicator, with a ball type sideslip indicator. This horizon dial presentation is similar in principle to that of the Sperry artificial horizon, a fixed miniature aeroplane and a horizon bar being stabilised by the vertical gyro system. At the top of the dial is the turn pointer, showing rate of turn to right or left, though no scale is provided for this, or for the horizon back indication.

The sideslip indicator at the bottom of the dial is of the conventional type with a ball in a curved liquid-filled glass tube, and acts like a simple damped pendulum to show whether the aircraft is side slipping. Surrounding the dial is a large scalloped ring, rotational movement of which operates the caging mechanism of the artificial horizon, the markings "Los" and "Fest" corresponding to "Free" and "Caged" respectively.

Construction. The instrument is electrically driven by 36-volt 500-cycle 3-phase supply. The horizon movement is pivoted fore-and-aft in a rigid open framework, the back of which carries the turn indicator gyro.

A detachable cylindrical cover which encloses the whole mechanism is shown removed in Fig. III. 51.

The steel gyro rotor and shaft are integral, and a recess at one end has an aluminium ring with cast-in laminations of high magnetic per-



Crown Copyright

Fig. III. 51. Horn artificial horizon, cover removed showing vertical gyro, turn indicator gyro and caging mechanism.

meability, which act as the "squirrel cage" of the induction driving motor. The three-phase wound stator is attached to the top cover of the rotor case and projects into the recess in the rotor. A screwed ring holds the aluminium alloy top to the rotor housing, also of light alloy.

Although the rotor only weighs 141 grammes, and has a moment of inertia of less than two-thirds of the British air-driven horizon rotors, the higher speed of 26,000 r.p.m., possible with the induction-driven rotor, gives it a comparable angular momentum. Deep groove journal ball races, 3 m.m. inside and 10 m.m. outside diameter are used for the rotor bearings, which are of the caged type with seven balls.

Erection System This is very similar to that used in the electrical horizon which has already been described. Induction torque motors are mounted on the two gimbal axes. Axial point contact blades between case and gimbal ring and also between gimbal ring and rotor housing carry the 3-phase supply from the 6-pin plug at the back of the case to the rotor, as well as the current to the torque motors from the erector mechanism.

The latter is a double two-way mercury switch carried on the underside of the rotor housing. Fig. III. 52 shows the connections from the erector to the torque motor windings, each of which consists of four star connected windings. Two of the windings are permanently connected to two of the supply phases. One or other of the remaining torque motor windings is connected by the erector switch to the third supply phase to produce a rotating field in the appropriate direction when either of the mercury contacts closes due to tilt of the gyro axle from the vertical. The resistances connecting the two control windings to one of the permanently connected phases are intended to improve the balance of the rotating field, which is uneven on account of the asymmetrical arrangement of the windings.

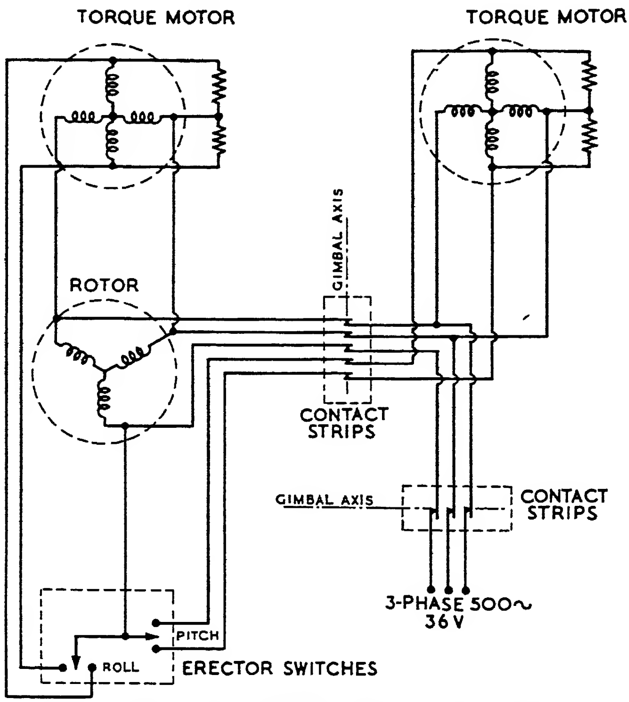


Fig. III. 52. Horn artificial horizon, wiring diagram.

Caging Mechanism. The caging ring on the dial rotates a quick-thread screw engaging a cam-edged sleeve sliding on axial guide rods. This mechanism is clearly shown in Fig. III. 51. As the ring is turned towards the caged position, the cam sleeve is forced along the guide rods until the edge of the cam bears against a lever on the horizon bar actuating pin. The free end of this lever projects towards the athwartships gimbal axis, but stops short of it. The result is that not only is the gimbal ring forced to turn so that the actuating pin lever rides down the cam from either side, but the pressure on the lever also causes it to align itself longitudinally, so that it finally slides into the slot at the bottom of the cam contour, where it is caged about both axes.

Turn Indicator. The construction of the rate of turn gyro is similar to the horizon gyro. It has of course only two degrees of freedom, and is mounted with the gyro axle fore-and-aft, the rotor housing being pivoted athwartships, with a conventional centralising spring and piston dash-pot control about the pitch axis. A slot on the rotor housing engages a pin on the indicator arm, which is pivoted on the instrument roll-axis and passes over the top of the horizon movement to the front of the dial. A pointer movement of approximately .3 inches represents a turn rate of 180° per minute. Below the turn gyro in Fig. III, 51 can be seen a small wheel. This is actually a flywheel geared to the rotor housing by quadrant and pinion, and is intended to be a compensator for pitch accelerations.

Theoretically, any angular acceleration of the aircraft about the pitch axis would tend to cause a lag of the rotor housing, which would appear as a false turn indication.

By designing the flywheel with a suitable moment of inertia and gear ratio, and gearing it to rotate in the opposite direction, the device is made to neutralise the inertia lag of the rotor housing, though in practice this effect is almost negligible.

British turn indicators are designed with the gyro axle athwartships and the top of the rotor moving forwards. Gimbal lock instability therefore shows itself when the outer ring, represented by the aircraft itself, is rotating in the opposite direction to the rotor, i.e., during a loop.

As the Horn gyro has its axle fore-and-aft and rotates clockwise looking forward, in this case a tendency to instability is noticeable during a left-hand roll of the aircraft.

Pioneer Bendix Flux-gate gyro

This is an example of direct gyro stabilisation other than for direct visual reference.

The gyro used to stabilise the Flux-gate compass unit in this system is illustrated in the cut-away view of Fig. III. 53 and consists of a capacitor type split-phase four-pole induction motor. The usual gimbal system is employed to mount the gyro freely in the main casing with its axis vertical.

Instead of the more usual three-phase winding, the stator carries a two-phase winding and is surrounded by the rotor itself which has the normal squirrel-cage laminations on its inner periphery.

The power supply is 115-volt 400-cycle single-phase current which is led into the stator windings via hair-spring type connections on the gimbal axes. One of the stator windings has in series with it two parallel-connected condensers, the whole being in parallel with the other stator winding. The effect of the condensers is to advance the phase of the capacitor winding with respect to the other winding so that the two windings, supplied by the same single-phase current, become equivalent to a two-phase system.

Eddy currents in the rotor "squirrel cage" caused by the rotating two-phase field drag the rotor round at a speed of 10,500 r.p.m.

Cone bearings on each end of the rotor shaft revolve in ball bearings carried in the gyro frame or housing.

A triangular Flux-gate compass unit is mounted below the gyro housing. The whole gimbal system is mounted in spherical housing with three shock mounts for supporting it in the aircraft.

We are not concerned here with the compass system as such, and it will suffice to say that the Flux-gate (as it is named by the Bendix Co.) consists of an inductive device responsive to the earth's magnetic field for providing remote magnetic compass readings on a repeater system. Like the ordinary magnetic compass, the Flux-gate is susceptible to banking and acceleration effects, and the purpose of stabilising the

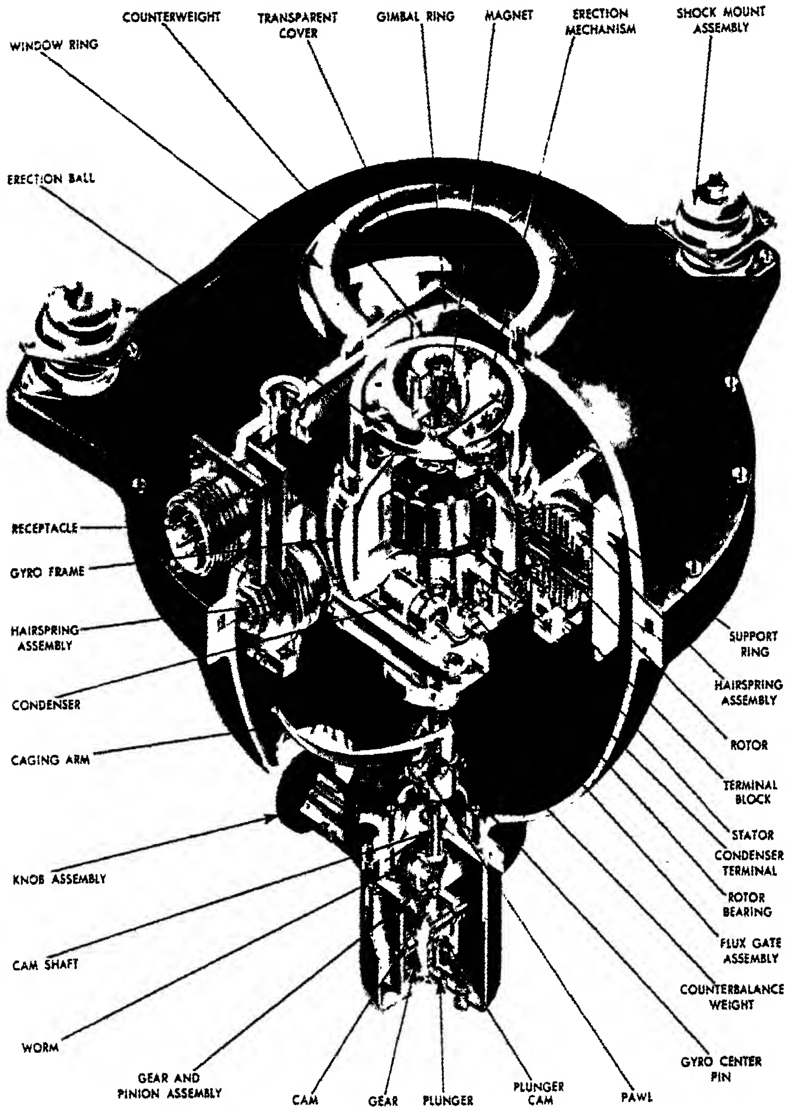


Fig. III. 53. Pioneer Bendix Flux-gate gyro, cut away view showing rotor, erector and caging mechanism. The rotor is driven at 23000 r.p.m. by single phase 115 volt 400 cycle supply. Split-phase capacitor winding is used for starting up.

element on a vertical gyro is to eliminate, or at least reduce, errors from these causes.

Caging Mechanism. Mounted at the bottom of the spherical housing, the caging mechanism consists of a curved caging arm carried at the top of a vertical shaft, which rests on a cam. Operation of the caging knob causes a worm gear to rotate the vertical shaft, while another gear train turns the cam and raises the shaft. The caging arm thus rises and rotates with a sweeping movement, coming into contact with the gyro centre pin which projects down from the gyro assembly. If the latter is lying at an angle to the vertical, the force of the caging arm against the centre pin causes the latter to precess downwards along the arm till it passes over a latch into a slot in line with the vertical shaft.

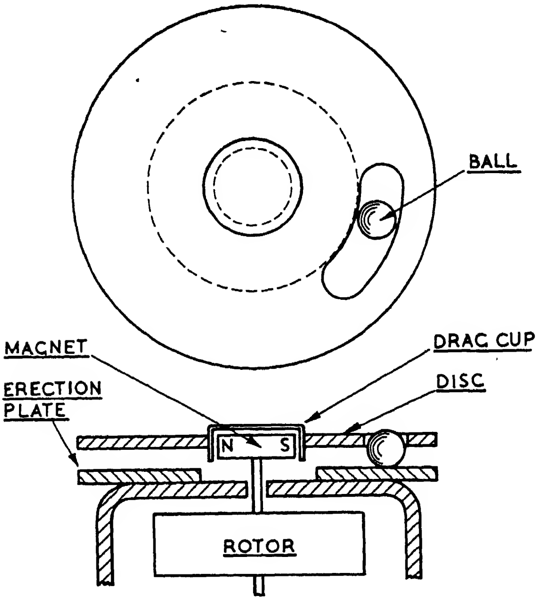


Fig. III. 54. Pioneer Bendix Flux-gate erection system. The slotted disc is carried round by the induction between the drag-cup and the magnet on the rotor shaft.

To uncage, the knob is turned in the same direction until the vertical shaft falls off the peak of the cam and releases the centre pin from the caging slot.

A small spring-loaded plunger, operated by a second cam on the same shaft, protrudes through the bottom of the caging head, to indicate whether the gyro is caged or not. In the caged position, the end of the plunger protrudes about 3/32 of an inch, and is flush in the uncaged position.

Since the caging operation depends on precessional movement, the gyro can only be caged when it is running.

Erection System. The erector in this case is mounted on top of the gyro, and Fig. III. 54 represents diagrammatically the rotor with an upward extension of the axle, carrying on its end a circular magnet with the poles across the diameter. Closely surrounding the magnets is an aluminium drag cup which rotates in bearings co-axial with the rotor shaft. The drag cup is integral with a circular plate in which is cut an arcuate slot, and the latter locates a .4-inch diameter steel ball resting on another circular plate carried on the top of the rotor case and normal to the rotor axis.

When the gyro is rotating at the normal running speed of 10,500 r.p.m., the rotating magnets induce eddy currents in the drag cup and the induction effect causes the drag cup and slotted plate to turn with the rotor. A form of escapement governs the speed of the drag cup and plate to 30 r.p.m.

When the gyro axle is off the vertical, the plane of the plate on which the ball rests is not horizontal, represented diagrammatically in Fig. III. 55 as tilted towards the reader.

As in the case of the O.M.I. hooked cylinder, the steel ball tends to roll to the low side and is carried up the slope of the inclined plate, resting at the lower end of the arcuate slot. At the upper dead-centre it rolls down to the other end of the slot, travelling faster than the slotted plate during this part of the descent.

As the ball, therefore, spends a longer time on the ascending side, there is a torque, due to the weight of the ball, applied to the gyro system for a longer time clockwise in the plane of the paper than anti-clockwise. This precessional torque erects the gyro for small tilts at about 1° per minute.

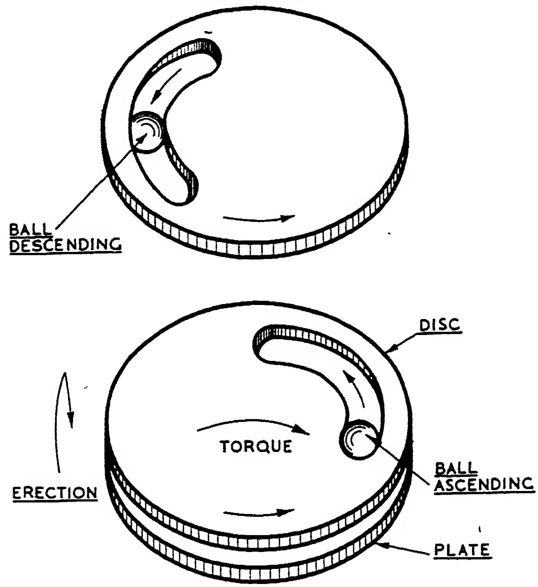


Fig. III. 55. Pioneer Bendix-gate Flux-gate erector, ball ascending (bottom) spends more time on one side of gyro axis than on the other side (top) descending. Difference of torque integrals due to the weight of the ball causes erection.

If the gyro is tilted at a large angle, the weight of the ball is sufficient to prevent the slotted disc from rotating. In this event the drag cup turns the ball to a point somewhere on the upward slope. If this is not halfway up, the erection precession will not be directly towards the vertical until the tilt has been sufficiently reduced to allow the drag cup to set up rotation of the slotted disc.

Gun sights and bomb sights, etc.

Gyros are widely used in modern gun and bomb sights. A free gyro of the type used in the artificial horizon is commonly used in bomb sights to stabilise the bomb-aimer's line of sight to the target to render the sighting mechanism immune from movements of the aircraft in pitch and roll. Even where the aircraft itself is stabilised by an automatic pilot, some small movements cannot be prevented, and these would otherwise disturb the precise alignment of the sight on the target. Similarly, horizontal-axis free gyroscopes of the directional gyro type serve to stabilise the line of sight in azimuth against inadvertent yawing.

Gun sights may also use free gyroscopes but more often employ rate-of-turn gyros to measure angular rate of the gun or sighting system when following or "tracking" a target.

In conjunction with range-finding devices, the angular rate indicated by the gyro can be made to compute automatically the targets' transverse speed, and from this information and the time of flight of the projectile, the requisite lead or "aim ahead" can be applied automatically to the gun.

In gyro-stabilised bomb sights, the azimuth gyro provides a stabilised drift reference, so that the sight can be conveniently used as a navigational instrument for accurately determining wind drift. The Bendix Corporation make a gyro-stabilised drift sight, as such.

Reasons of security prevent any fuller description of gyro sights in these pages.

Other applications of the gyroscope are the stabilisation of the line of sight in aircraft sextants, a development by the Sperry Gyroscope Company, and flight recorders. In the latter a free gyroscope stabilises a stylus tracing on a moving chart in a manner similar to a barograph.

Flight recorders are used for recording angular movements of an aircraft in flight. For instance, an accurate comparison and analysis can be made of the behaviour of an aircraft under automatic and manual control. By mounting the flight recorder with the gyro axle in the appropriate direction, successive recordings are obtained about all three axes of reference.

The stabilisation of cameras for aerial survey work is another coming application of the gyro in aircraft. In fact, wherever there is a requirement for a stable absolute reference, the gyro is the only means known that approaches this ideal.

The foregoing chapter has no pretensions to being a complete catalogue of gyro-vertical applications, and the few instruments described have been chosen as representative of their type or as being of particular interest to the reader who wishes to gain a general idea of the subject in the space available in this chapter.

The same may be said of the following Chapter 5.

CHAPTER 5

AUTOMATIC PILOTS

Probably most people would be slightly surprised to learn that an aircraft was flown by a gyroscopic automatic pilot before the first World War, when aircraft themselves were in a primitive state of development. Yet it was in 1909 that the first gyroscopic stabiliser was built and successfully installed in an aircraft by the Sperry Gyroscope Company of New York. In 1914 the same firm won the Grand Prix for safety in flight at a French aeronautical meeting with an all-electric gyro stabiliser fitted to a Curtis flying boat, shown in flight in Fig. III. 56.

Historical note

This stabiliser was actually an automatic pilot controlling elevator and ailerons, similar in many ways to current practice in automatic pilot design. Although it reads rather quaintly to modern ears, the following extract from the original handbook of this historic apparatus, is worth quoting.

"The Sperry Aeroplane Stabiliser is a carefully-designed, substantial and thoroughly tested instrument which has for its purpose the conception and correction of the slightest departure of an aeroplane from any desired attitude of flight.

"This apparatus first came into prominence when it entered the Concourse par L'Union pour la Securite en Aeroplane en France in the summer of 1914, where the marvellous feats accomplished by it caused the judges to unhesitatingly award it the first prize. A picture, taken by a moving camera the day of the contest, is shown on the preceding page. The mechanician is shown standing out on the wing, where he walked back and forth, generating a strong upsetting couple while the pilot, as can be seen, stood with both hands over his head, the equilibrium of the aeroplane being automatically maintained by the gyroscopic stabiliser. An interesting feature is the proximity of the ground at which the demonstrations were conducted.

"The full value of such an apparatus can only be appreciated by those who have experienced the difficulties of flying under unfavourable atmospheric conditions. The pilot is not only relieved of the nervous and physical fatigue of maintaining equilibrium of his machine, but, his hands being free, is enabled to draw maps, drop bombs, etc., for which an observer has heretofor been required. The increased ability for carrying fuel and war munitions due to the elimination of the passenger, will at once be recognised as a most important factor."

The main credit for the development of automatic pilots in this country goes to Messrs. P. A. Cooke, F. W. Meredith and P. S. Kerr, who were responsible for the work in the nineteen twenties at the Royal Aircraft Establishment, Farnborough, which resulted in the R.A.E. Automatic Pilot. Various models of this pneumatic design have been used exclusively by the Royal Air Force on British aircraft for the last 15 years. A description is given later of the Mk. I and Mk. VIII R.A.E. Automatic Pilots, the first and latest in the series.

In Germany the firms of Siemens and Askania each made a single-axis rudder automatic control.

Apart from these and the French Alcan automatic pilot, made in small numbers, the great majority of automatic pilots fitted in civil and military aircraft throughout the world before the second World War were either of Sperry or R.A.E. design. The electric gyro stabiliser designed by the Norden Company of the U.S.A. for use with their bomb-sight has since been developed into the Minneapolis Honeywell control, the gyro system of which is also described later.

Several firms have entered the field in the war years, but for space consideration and reasons of security, it is not possible to describe all, and still less the latest, applications of gyroscopes to the automatic control of aircraft.

Function of the automatic pilot

Before studying actual systems of gyro-controlled automatic pilots, and the different methods of detecting and counteracting disturbances of the aircraft, it will be worth while to consider the nature of these disturbances.

Provided the aircraft is reasonably stable, as is the case with most large modern types, it can be trimmed to fly in still air without appreciable change of attitude about the three axes of control. Fuel tanks emptying or movements of the crew, for instance, can cause changes of trim that

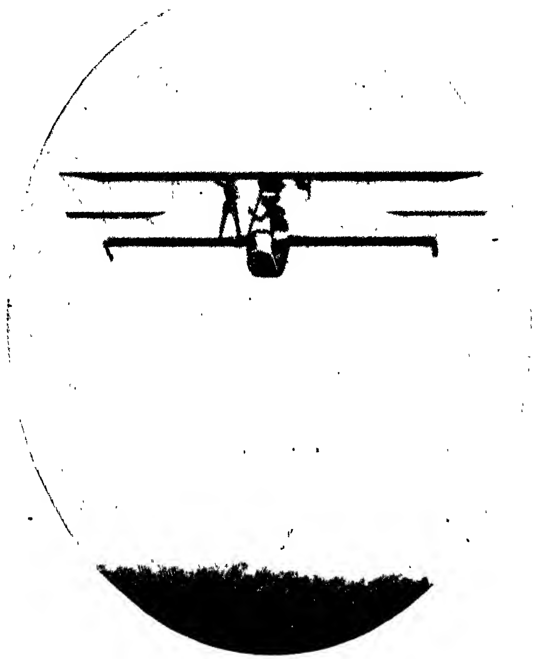


Fig. III. 56. Curtis flying boat demonstrating the original Sperry automatic pilot in 1914. Notice the mechanic standing on the wing and the pilot with hands off the controls, also the very low altitude.

will disturb the attitude of the craft unless corrected by the human or automatic pilot. By far the largest and most frequent disturbances, however, are due to turbulence of the air in certain atmospheric conditions. These are equivalent to gusts which may strike the aircraft in any direction and act on the whole or a part of it.

Let us consider what happens in a yaw disturbance, for example. Fig. III. 57 represents an aircraft, assumed to be under automatic control, and the intersection of the vertical line on the time abscissa of the graph represents a point at which a gust force strikes the aircraft on the port side. Since the craft is stable about the yaw axis, the mean gust pressure will act aft of the centre of gravity, causing a yawing moment to port. This typical gust moment can be represented by the curve A, whose ordinate is yaw moment to a convenient scale. Completely to prevent any disturbance of the aircraft's heading it would be necessary to apply an "ideal" control moment, by means of the rudder, exactly equal and opposite at every instant, as represented by the "mirror" curve B.

As both the human and automatic pilot can only detect movement as it occurs, it is obvious that some disturbance or yaw must take place before it can be detected, and, since mechanical limitations prevent instantaneous application of rudder, a further time lag will occur before

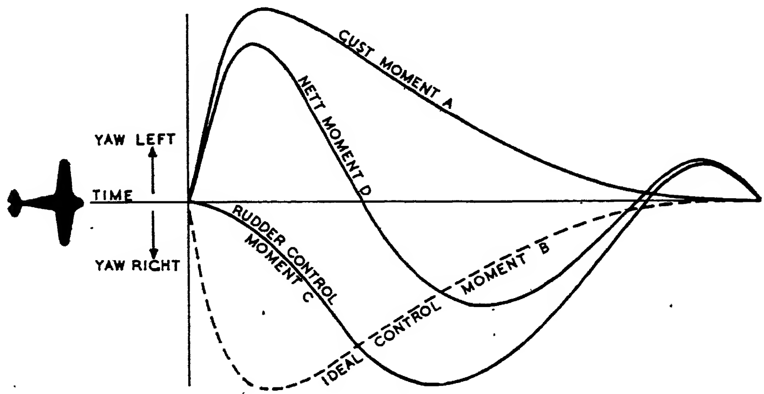


Fig. III. 57. Moments acting on an aircraft in a hypothetical side gust. The "ideal" control moment is that which would prevent any disturbance of the aircraft. Moment C represents a practical control.

the corrective right rudder control can be made to overcome the gust yawing moment to the left. Consideration will also show that, as in the case of steering a ship, it will be necessary to reverse the rudder control before the aircraft recovers to the original heading in order to prevent overshooting. A desirable practical control moment might therefore be represented generally as the curve C.

Combining algebraically the ordinates of control moment curve C with the gust moment curve A, we get a curve D which is the nett moment acting on the aircraft about the yaw axis, at any instant. Neglecting, for our purposes, any damping moment due to air resistance, the angular acceleration of the aircraft in yaw will (by the ordinary laws of dynamics) be proportional to the nett yawing moment at any particular instant. Curve D can therefore be duplicated as curve E in Fig. III, 58 to represent yaw acceleration of the aircraft to a different scale, due to the combined effects of gust and rudder control by the automatic pilot. By integrating this acceleration curve, on the time base, we can deduce the curve F whose ordinate represents rate or angular velocity in yaw at any instant to a suitable scale. By a second integration, a curve of the form G is obtained representing, by its ordinate, the angular displacement of the aircraft's heading during the disturbance and recovery. The form of this displacement curve could be deduced in the first place on the assumption that it is impossible to prevent some disturbance, but that it will be checked at some maximum value and the aircraft returned to the original heading at approximately the same rate, without overshooting.

Reversing the previous procedure, if the assumed displacement curve G is differentiated by drawing ordinates proportional to the slope of the curve, we arrive at the rate curve. By repeating the process from the rate curve we can derive the acceleration curve, which in turn corresponds to the nett moment (curve C) acting about the yaw axis. Since the gust does not reverse direction but is assumed to die away, it is clear that the reversal of curve C above the line could only be due to rudder control or equivalent damping. This is an interesting graphic confirmation of the original assumption that reverse rudder is essential to produce a recovery from yaw without overshoot, of the form of curve G.

In practice the rudder control curve C may be compounded of proportions of one or more of the displacement, rate, and acceleration curves.

It is apparent from the curves of Figs. III. 57 and III. 58 that the more a control is responsibe to acceleration, and to a lesser extent rate, the nearer will it approach to the ideal of neutralising the disturbing force altogether. It can also be seen that the rate curve is the only one that is in the opposite sense to the displacement near the end of recovery. Acceleration responsive control is chiefly valuable for its anticipatory effect in reducing displacement, whereas rate responsive control is also valuable for its positive damping effect.

All automatic pilot systems use detection of angular displacement from a stabilised reference as a means of generating a control impulse that actuates the aircraft controls to oppose the disturbance. Some very successful designs have relied entirely on displacement control. In the absence of damping, displacement control alone would result in overshoot or hunting, a continuous oscillation about a mean attitude or heading. The aerodynamic damping on the aircraft itself is usually sufficient to prevent this. Certain automatic pilot systems, especially later designs, employ in addition to displacement control, either rate or acceleration control terms, or both. In addition, the automatic pilot may be made responsive to other variables such as airspeed, linear accelerations, altitude, etc. By these means still closer control can be maintained.

Before leaving the subject of control theory, it should be pointed out that the term "ideal control" has been used in a narrow theoretical sense

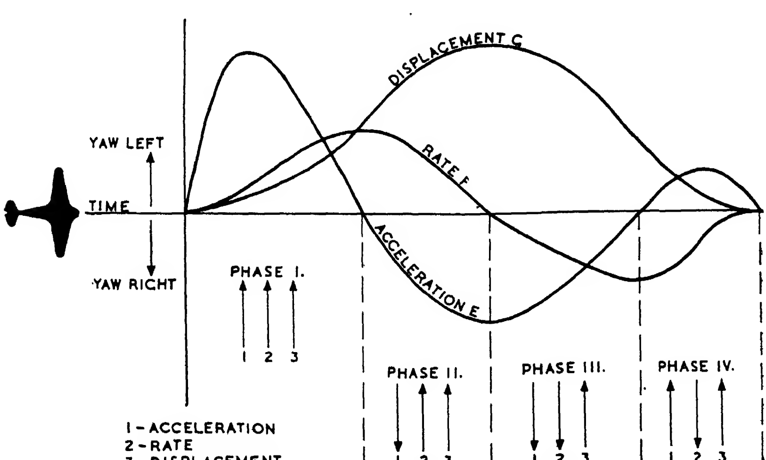


Fig. III. 58. Relation of disturbance and time derivatives. Showing the anticipatory nature of the acceleration component in phase I and the characteristic damping of the rate curve in phases III and IV.

only. In practice it has not been possible to specify the ideal automatic control characteristic, as this depends on the object of the stabilisation. For the very close stabilisation required for precision bombing or mosaic photography for instance, it is possible with at least one existing automatic pilot to keep the aircraft within $\frac{1}{2}$ degree of the desired attitude in moderately gusty conditions. However, when the control system is adjusted to achieve this result, its operation is more fierce and "fussy" than would be necessary or desirable in an air freighter or passenger aircraft. For these civilian purposes, a compromise is required between a "soft" control of the "lazy helmsman" type, and a too close control that imposes excessive wear on the controls and even dangerous loads on the aircraft structure.

The properties of the displacement and other control terms, if any, and the aerodynamic characteristics of the aircraft determine the stability and accuracy with which the aircraft maintains the desired path through the air.

In addition to stabilising, the automatic pilot must provide means for enabling the human pilot to manoeuvre the aircraft while under automatic control.

Automatic pilots are single, two, or three-axis type depending on the number of aircraft axes they control. Single-axis control of rudder only has been used, but the majority of successful designs control rudder ailerons and elevator, or a combination of two, e.g., rudder and elevator or rudder and ailerons.

Functioning

A human pilot uses his brain (through the eyes) to detect the motion of a disturbance, and through his nervous system and muscles applies corrective power to the aircraft controls. An automatic pilot duplicates the functions of brain, nerve and muscle.

Apart from any additional control terms that may be used, all automatic pilot systems employ a device known as a "pick-off" for detecting angular motion (displacement) of the aircraft with respect to a gyro datum for one or more axes. This is the "brain." The pick-off may be pneumatic, hydrualic, or electric for example, depending on the particular system. In order to cause as little reaction as possible on the gyro, the impulse or signal from the pick-off is necessarily very small, so that some form of relay or amplifier "nerve system" is used to magnify it into a force capable of operating the servos which act as muscles to move the aircraft controls to correct the disturbances.

We will now see how a typical displacement control automatic pilot works, in this case a three-axis pneumatic-hydraulic system.

Sperry A3 gyropilot

The elevator and aileron control is derived from an elaboration of the artificial horizon vertical gyro with pick-offs about the pitch and roll axes for elevator and aileron respectively. A similar type of pick-off on a directional gyro acts as the brain which detects yawing motion.

As all three controls are similar in principle, it is only necessary to explain one, for example the aileron system.

Fig. III. 59 represents the vertical gyro control unit known as the bank and climb unit, with the roll pick-off mounted about the roll axis, the attitude of the aircraft being level laterally. In actual practice the air pick-off consists of a plate attached to the gyro element, with knife-edges which intercept the air flow at two nozzle ports mounted in the gyro case. For clarity, the air pick-off is shown here diagrammatically. Air is drawn into the bottom of the case by a vacuum pump, and directed to spin the gyro, as in the artificial horizon. Air is also drawn in equally through the two pick-off ports, which in the position shown are both partially obstructed by the knife-edge plate.

The vacuum in the gyro unit is maintained at 4 inches of mercury by a vacuum regulator irrespective of the speed of the engine-driven vaccum pump.

When the aircraft deviates from level flight laterally, as in a roll displacement to the right, say, the air pick-off ports take up the position shown in Fig. III. 60. One port is shut off while full suction is applied to the open port.

Referring now to Fig. III. 61, we see diagramatically the gyro unit in relation to the complete automatic pilot system, with the aircraft rolled to the right.

The "nerve" system consists of an air relay and a balanced oil valve. The pick-off ports are connected to either side of the air relay, which has a small bleed hole to atmosphere at each side of the case.

The increased suction on port D and the closing of port D^1 unbalances the partial vacuum in the relay and draws to the left the air relay diaphragm and the spring-centralised piston of the balanced oil valve, to which it is connected.

The space between the two centre lands of the balanced oil valve is continuously fed with oil under pressure from an engine-driven oil pump supplied from a sump, the pressure being maintained by a pressure regulator set at between 100 and 200 lbs. per sq. in., depending on the type of aircraft.

When the piston of the balanced oil valve is central, oil flow through the valve is blocked, but under the influence of a right roll pick-off signal

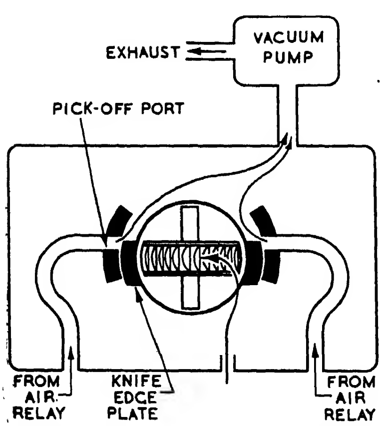


Fig. III. 59. Sperry A.3. Diagrammatic view of aileron pick-off in bank-and-climb gyro unit with aircraft level laterally.

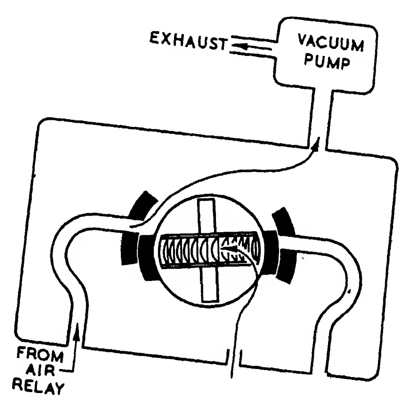


Fig. III. 60. Sperry A.3. Diagrammatic view of displacement of pick-off with aircraft banked to the right.

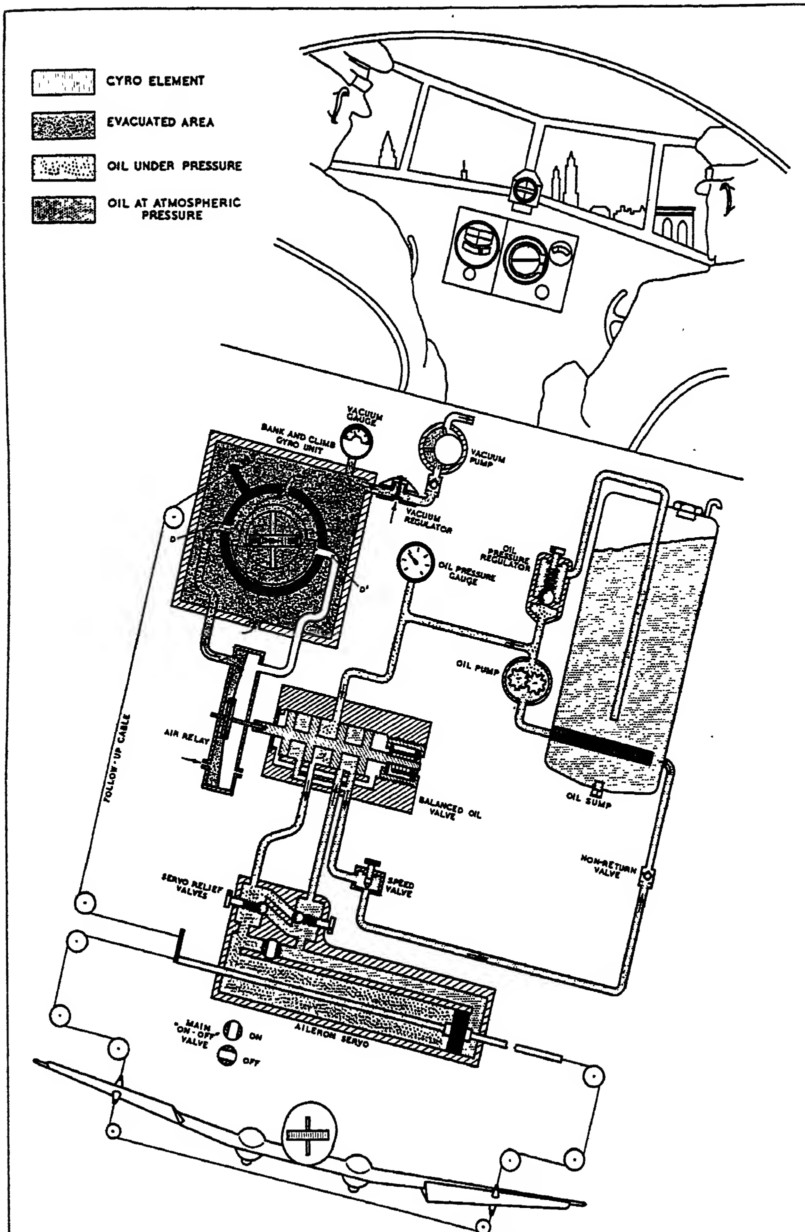


Fig. III. 61. Sperry A-3 Schematic arrangement showing relation of units in the complete system, during right bank displacement. The piston normally does not move far from the centre of the servo and is here shown in an exaggerated position.

as already described, the valve piston moves to allow oil to flow by the left-hand pipe to the aileron servo cylinder. If the main "on-off" bye-pass valve in the servo is in the "on" position, i.e., closed, as shown, the servo piston is forced by the oil pressure to the right, applying left bank control on the ailerons, and, at the same time, expelling the oil from the right-hand end of the servo, via the balanced oil valve, speed-valve and non-return valve, back to the sump.

In a displacement type of control such as this, the amount of control is made to be proportional to the angular disturbance, which in this case means that the servo piston travel must be proportional to roll angle.

This ensures that not only is aileron control applied progressively to an amount determined by the extent of the roll disturbance, but also that control is reduced as the aircraft recovers, so that the ailerons will be neutral when the aircraft is again level.

This control proportionality is effected by a follow-up system from the servo back to the pick-off. The pick-off ports are not fixed rigidly to the control unit case, but instead, can be moved in angular relation to it by the follow-up mechanism. A cable connected to the servo piston rod runs to a spring-tensioned follow-up pulley mounted in bearings on the control unit, the pulley in turn actuating a gear arranged to rotate the pick-off. When the piston moves to the right, as in the case we have been considering, the follow-up cable moves also, and through the action of the pulley, moves the left pick-off port down and the right port up. When they reach a neutral position (both half-open) the air relay and oil valve are centralised and servo piston movement applying control is stopped. During this time the control surface movement which the servo has been producing has been bringing the aircraft back to level flight. As the aeroplane continues to approach the true level, the air pick-off ports, which have been driven ahead of the gyro case anti-clockwise, pass beyond the neutral point and begin to cause servo movement in the opposite direction, not to apply opposite aileron control, but removal of the control previously applied. The mechanism and its ratios are so arranged that the desired amount of control will be applied and also removed at the proper rate as the aircraft returns to level.

Directional gyro control unit (Figs. III. 62 and III. 63)

This unit contains a directional gyro which is the directional reference for both manual and automatic steering control. It also contains the air pick-offs and follow-up mechanism for directional control, and a means, operated by the rudder knob, for setting the gyropilot to steer any selected heading. The upper (follow-up) card of the D.G. unit is attached to the pick-off port member and the lower card to the vertical ring of the gyro which carries the knife-edge plate. The two card readings agree when the pick-offs are neutral. The directional gyro control unit, together with the bank and climb gyro control unit, is carried in the mounting unit and the whole is installed as a part of the instrument panel.

Bank and climb gyro control unit (Figs. III. 62 and III. 63)

This unit contains the bank and climb gyro which is used for lateral and longitudinal indication and control, as described, and also the air pick-offs, together with the means for making manual adjustments.

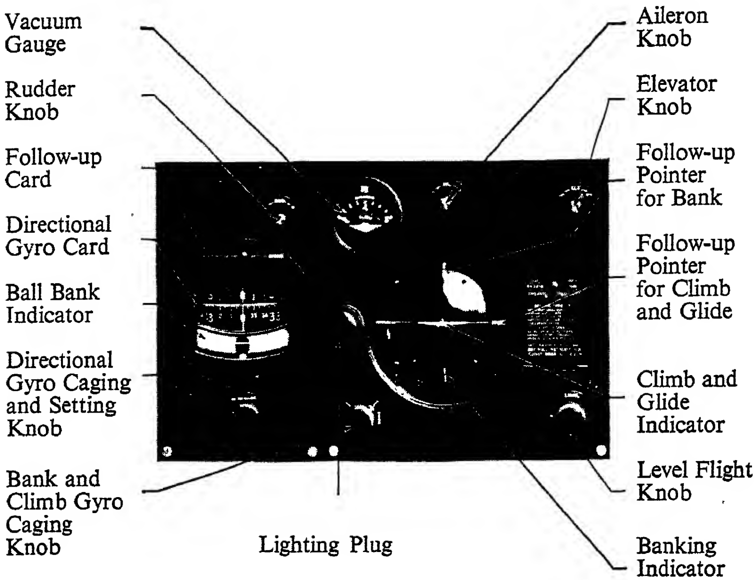


Fig. III. 62. Sperry directional gyro and bank-and-climb control units, front view. The instruments are mounted side by side on the instrument panel in a special shock-absorbing mounting unit.

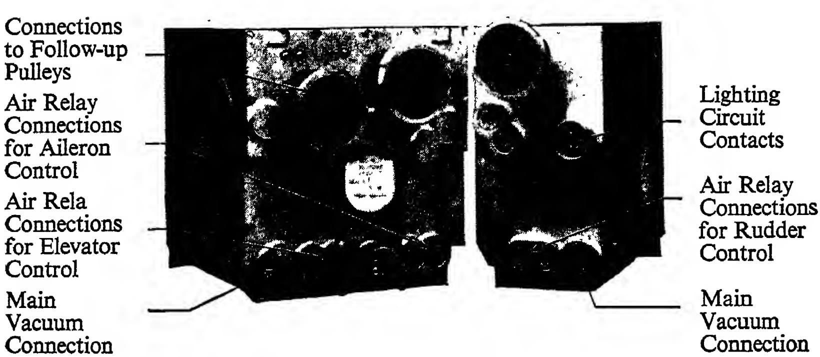


Fig. III. 63. Sperry control units, rear view. Showing the connections which are made automatically when the instruments are in place in the mounting unit.

Through a differential mechanism the aileron knob permits the roll pick-off to be adjusted for the desired lateral attitude, and similarly the elevator knob controls the setting of the pitch axis pick-off for longitudinal control, a follow-up indicator on the dial showing the lateral and

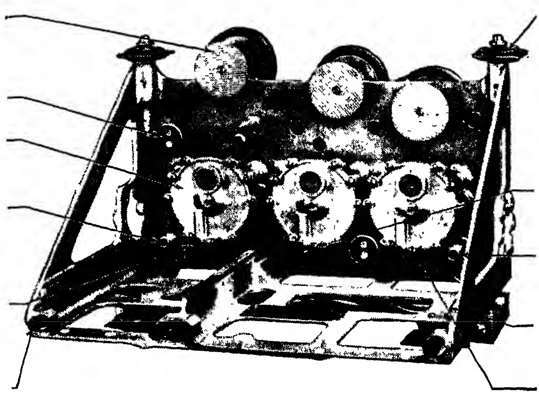


Fig. III. 64. Sperry mounting unit. Two bolts are all that secure each control unit in the mounting frame. Both units can be changed in two or three minutes.

longitudinal settings that are made. The bank and climb gyro control unit is carried next to the directional gyro control unit in the mounting unit.

The Mounting Unit. The mounting unit (Fig. III. 64), supported on shock-absorbers behind the instrument panel, is provided with tracks on which the control units slide into place, where they are secured by four attaching bolts. Air, follow-up and lighting connections are made automatically when the bolts are tightened and disengaged when the control units are withdrawn. Either of the two control units can thus be replaced in a few minutes. Fig. III. 63 shows the rear of the control units with the connections which engage with those on the mounting unit, the latter carrying the balanced oil valves, air relays and follow-up pulleys.

Servo Motors. The servos for rudder, aileron and elevator consist of three hydraulic cylinders with pistons which are approximately at centre when the aircraft control surfaces are centralised. The servo piston rods are connected directly to the main control cables of the aircraft. They are also connected, through the follow-up cables, to the control units, so that control will be properly applied, as previously explained. The "On-Off" valve, with control lever accessible to the pilot, by-passes the servo oil from one side of the pistons to the other when manual control is desired. Spring-loaded servo relief valves are also built into the servo unit and set so that they blow-off at a pressure slightly above the working pressure.

How the Gyropilot is Used. As soon as the aircraft is clear of the aerodrome and on its course, the pilot rotates the adjusting knobs on the gyropilot control units so that the three follow-up indicators match the gyro indications for direction, bank and climb. Then he moves the servo "On-Off" lever slowly to the "On" position. The elevator knob is adjusted to obtain the desired rate of climb. Once this is set, the aircraft continues climbing steadily until the cruising altitude is reached, at which time another slight turn of the elevator knob by the pilot puts the aircraft in level flight.

If a small course change is desired, it is only necessary to rotate the rudder knob slowly to the right or left. Continous banked turns may be made by caging the gyroscope of the directional unit and applying bank with the aileron knob. A slight turn of the elevator knob is all that is necessary for the gyropilot to maintain a steady rate of descent until the pilot is ready to take over the controls, and make his landing. Fine adjustment "speed-valves" mounted on the instrument panel enable the pilot to throttle the flow of oil in the return lines from the servos to the sump, and so to adjust the rate at which control is applied to suit different atmospheric conditions.

To disengage the gyropilot, the pilot takes over the controls and moves the engaging lever "off." In an emergency he can overpower the gyropilot while it is in operation, by applying extra force on the controls to cause the servo relief valves to open and act as a by-pass instead of the main "on-off" valve.

Rate and acceleration pick-off systems

It will be recalled that the gyropilot just described was a system using displacement control only. Before going on to other systems the reader should have some idea of possible methods for making the applied control

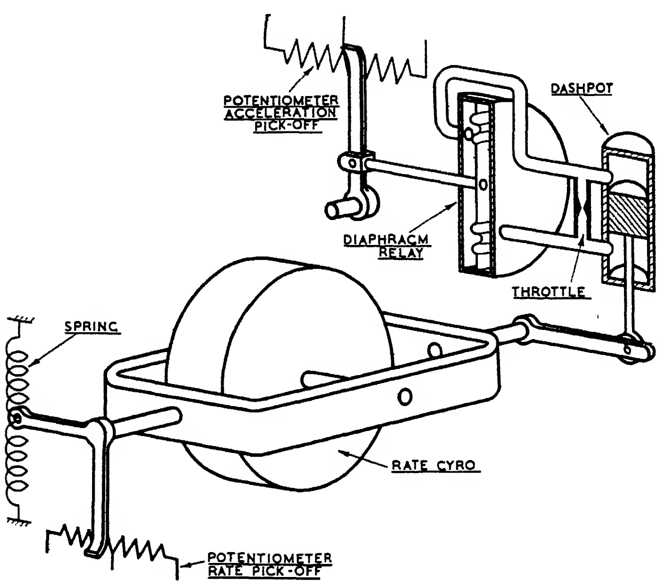


Fig. III. 65. Rate gyro and viscosity throttle pick-off for generating electric rate and acceleration signals. Diagrammatic view to illustrate principle.

responsive not only to angular displacement of the aircraft, but to angular rate and angular acceleration also.

The type of displacement pick-off commonly employed is in effect a valve, whether pneumatic or hydraulic, or in the case of electric systems, an "on-off" contact, a potentiometer, or inductive device. In every case a device for detecting angular movement.

Rate Pick-offs. The devices for detecting angular rate or velocity are commonly one of the following :

1. *Rate Gyro.* A rate pick-off for an electric control is illustrated diagrammatically in Fig. III. 65, in which the movement of a potentiometer is controlled directly from a rate gyro. The resultant rate voltage signal would be added to the voltage from a displacement signal.

2. *Viscosity Throttle.* A viscosity throttle or dash-pot is a device applicable to fluid type pick-offs and in essence is a fixed cylinder with a piston actuated by the pick-off displacement. The two ends of the cylinder are connected through a restriction which will have a fluid pressure across it as a function of the rate of movement of the piston. This differential pressure is used to apply the rate component of control. This type of control is used in the rudder pick-off of the Minneapolis Honeywell Autopilot, described later.

3. *Rate Circuit.* An example of this is an electrical version of the viscosity throttle, with voltage, capacity, and resistance, taking the place of their physical counterparts, pressure, resilience and friction. It is used in the latest types of Sperry electric gyropilots.

The Sperry A.5 Gyropilot, for instance, has 3-phase electric gyros, each carrying a soft iron pole piece, in conjunction with an inductive pick-off in the form of a three-legged "E"-shaped transformer core, the pole piece just bridging the ends of the three legs with a small air gap. The centre transformer leg carries an exciter winding which produces an alternating flux in the other two legs, which carry windings connected in series opposition. When the transformer pick-off is neutral compared with the gyro, the output from the two series windings is zero.

A displacement of the pick-off core causes unequal gaps between the pole piece and the two end legs, producing a differential change in the magnetic reluctances and hence a differential A.C. voltage output from the series windings in a phase relation to the exciter supply depending on the direction of displacement.

An amplifier circuit is used to discriminate the sense of the displacement signal, rectify and smooth it, and by means of a differentiating capacity-resistance filter, generate voltages proportional to the first derivative of the displacement signal, i.e., rate. This rate signal is then combined in predetermined proportion with the displacement signal and made to produce a proportional torque from the servo motor. It is a feature of the system that no follow-up mechanism is required.

Acceleration Pick-offs. Acceleration term methods include :

1. *Viscosity throttle operated by rate-gyro.* A viscosity throttle and rate-gyro are both velocity detectors and used together can be made to give the rate of a rate, i.e., acceleration. Such a method is shown diagrammatically in Fig. III. 65 in which the acceleration signal is in the form of a voltage suitable for combining with an electric displacement signal.

2. *Rate-gyro with two spring-loaded gimbal rings.* A method of deriving both a velocity and an acceleration term from a rate-gyro was used in an Askania automatic pilot, and is illustrated diagrammatically in Fig. III. 66. The pick-off consists of a rate gyro with its ring pivoted

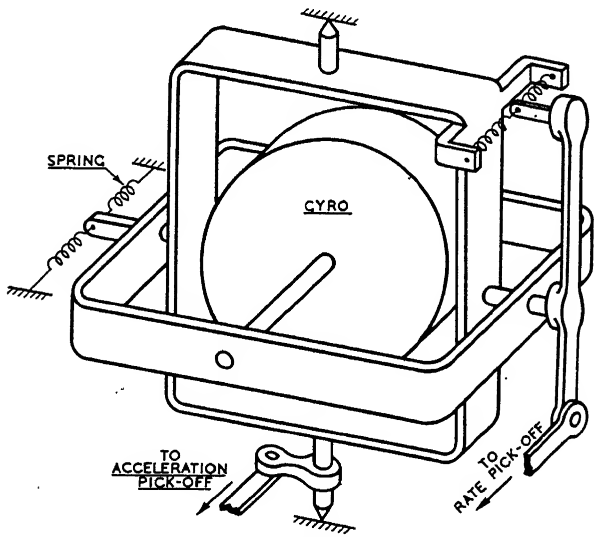


Fig. III. 66. Gyro rate and acceleration pick-off by two spring-restrained gimbals. Diagram to illustrate principle.

horizontally and spring-centralised, not in a fixed mounting, but in a second ring which is itself pivoted vertically in a casing. The vertical ring is spring restrained and carries a lever connected with a pneumatic acceleration pick-off valve. (Not shown.)

Provided that the angular deflection of the vertical ring against its spring is small, it constitutes an approximate measure of the torque exerted by the case in causing the precession of the horizontal rate-indicating ring.

Since angular acceleration is proportional to the torque producing it, the deflection of the vertical ring is a measure of aircraft angular acceleration, in this instance, in azimuth. Both the rate and acceleration indications are only accurate for infinitely small deflections of the rings, so that a very stiff spring is employed and the pick-off movement magnified by a linkage.

3. *Double differentiation of an electric displacement signal by an amplifier circuit.* For example, in the A.5 rate pick-off system, already described, the rate signal is put through a second differentiating circuit and the resulting acceleration voltage combined with displacement and rate signals.

This is the only electric automatic pilot in production to date that uses all three control terms. By altering the ratio of rate and acceleration to displacement, the character of the automatic control can be varied from mild to extremely powerful and accurate.

Pollock Brown

An automatic pilot introduced about 1930 has some unique features, and is believed to be the only successful type to be entirely hydraulic in operation, including driving of the gyros. The control is of the simple displacement type and designed to be comparatively light and easy to maintain.

Fig. III. 67 illustrates schematically the gyro unit used for rudder and elevator control of the first two-axis type. Later a three-axis model was flown successfully, using a similar type of gyro for the aileron control.

Referring to the figure, the gyro is a rotor universally mounted on a ball-ended shaft. The method of attachment is similar to a ball and socket joint, with the centre of gravity of the rotor at the centre of the ball, so that the rotor can tilt in the vertical and horizontal planes and turn about the ball on its own axis. It virtually floats on an oil film between the ball and the socket in the wheel, so that friction between the two is low. The shaft is mounted in bearings and at its other end has a small Pelton wheel which is driven by an oil jet supplied from an oil pump at about 40 lb.sq.in.

The casing containing the shaft and gyro is mounted so that the axis of the shaft is in the fore-and-aft axis of the aircraft.

When the shaft is spun by the oil jet, the slight friction at the ball joint tends to drag the rotor round in the same direction until it reaches a speed a little lower than that of the shaft. If the axis of the gyro is not aligned with the shaft it becomes "erected" into line by the action of the slip between ball and cup of the universal joint. The action of the ball within the cup of the rotor is very similar to the action of the jets on the Griffin gyro vertical, and the erection system of the Sperry directional gyro described in Chapter 2 (Section III).

Suppose the wheel axis is inclined down from the shaft axis. As the ball is turning faster than the cup, and due to the angularity between the axes, a point on the equator of the ball at each side has sliding motion in the cup, with one component at right angles to the gyro axis and another component parallel to the gyro axis.

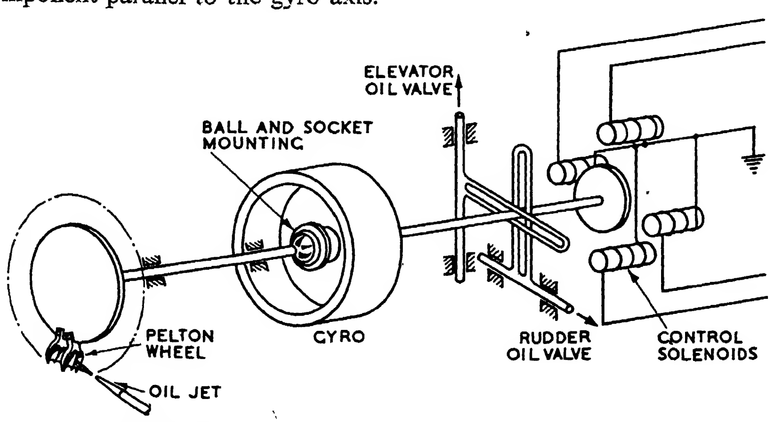


Fig. III. 67. Pollock Brown. Schematic diagram of principle of operation. The drag of the ball and socket drive tends to align the gyro with the Pelton wheel shaft. An extension of the gyro shaft operates control valves and also carries an armature for solenoid precession control.

The first component is applying the friction torque which drives the wheel and the second is applying a torque about an axis in the vertical plane perpendicular to the gyro axis. Consideration will show that the precession of the gyro axis due to this second torque reduces the droop

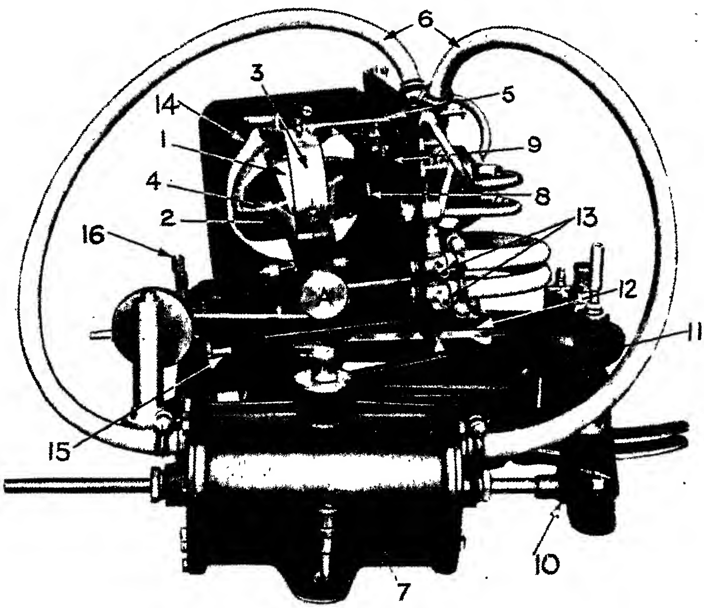


Fig. III. 68. R.A.E. Mk. 1 rudder and elevator unit.

1. Rotor
2. Inner gimbal
3. Outer gimbal (1° tilt from vertical)
4. Azimuth balance weight
5. Rudder valve
6. Piping to servo
7. Servo motor
8. Centraliser
9. Course change cylinder
10. Dummy rudder bar
11. Clutch pin
12. Follow-up levers
13. Unions for elevator valve
14. Spring-loaded lever
15. Pitch control spring
16. Pitch control bowden connectors

A and B. Watts linkage weights

and only ceases when the gyro and shaft axes are aligned. This aligning action takes place whatever the direction of misalignment, so that the gyro normally aligns itself with the mean position of the aircraft fore-and-aft axis.

The gyro rotor carries an axial extension pin the end of which engages in a pair of slides, one vertical and one horizontal. These slides are connected to balanced relay valves which control the admission of oil under pressure to one side or other of the rudder and elevator servo motors. Relative movement of the gyro axis in the vertical plane allows the extension pin to move freely in the vertical slide, but to carry up or down the horizontal slide which actuates the elevator. The vertical slide controls the rudder if there is relative azimuth movement between aircraft and gyro axis.

Manual Control. Manual control of the automatic pilot is provided by the application of precessing forces to the gyro axle. Four electro-magnets are arranged in pairs close to an iron pole piece carried on the extreme end of the valve actuating extension pin, one pair symmetrically in the vertical plane and the other in the horizontal plane. By means of a switch the pilot is able to energise any one magnet, which exerts a pull on the pole piece, and thus a precessing torque on the gyro itself. For instance, to produce a turn in azimuth, the upper or lower magnet would be energised to cause a vertical force on the end of the gryo axle extension. Depending on the direction of rotation of the gyro, this would cause a precession in azimuth to right or left and so operate the valve controlling the rudder servo to keep the aircraft turning as long as the magnetic control force were applied.

Similarly, to cause clmb or dive one of the lateral magnets would be energised to precess the gyro axle up or down and cause the aircraft to follow by the control action of the elevator valve and servo.

There is no gravitational control on the gyro, so that adjustment of the manual trimming controls is necessary from time to time to correct for gyro wander due to any out-of-balance of the rotor, or apparent drift due to the earth's movement.

In effect, the aircraft is controlled to the gyro attitude, but as the gyro takes its axis datum from the aircraft, any disturbance of either will gradually change the absolute attitude of both. For this reason it is essential to trim the aircraft accurately in pitch and azimuth to prevent the "erecting" action of the gyro ball and socket mounting from slowly precessing the gyro in the direction of the out-of-trim.

R.A.E. Mk.1

The first pneumatic automatic control developed at the Royal Aeronautical Establishment, Farnborough, and manufactured by S. Smith & Sons Ltd., is illustrated in Fig. III, 68, which shows the Mark I rudder and elevator unit. This was a single-gyro design in which the gyro, pick-off relays, control mechanism, and servo, were built as an integral unit for mounting at any convenient point in the fuselage of the aircraft. No flight indications were provided from the automatic pilot, which was intended primarily as a stabilising control for bombing. Although nominally a rudder and elevator control only, a certain indirect control about the roll axis was achieved by means that will be described later.

The power for the whole system was supplied by an air compressor which delivered air at 35 lb. sq. in. pressure for driving the gyro and operating the course control and servo.

Referring to Fig. III. 68, the rotor, which revolves at 11,000 r.p.m., is mounted with its axle fore and aft and inclined upwards 20° from the horizontal at the forward end, in the inner gimbal ring, which is pivoted athwartships in the outer ring, the latter being carried on vertical pivots in a frame.

In the level flight attitude the outer ring axis is inclined back at 5° from the vertical so that normally the rotor axle is at an angle of 15° to the perpendicular to the outer ring axis.

Air for spinning the gyro enters through the bottom pivot to pipes embedded in the outer gimbal ring and issues on to the wheel from jets close to the inner ring pivots.

Yawing motion is detected by the relative movement of the rudder pick-off cylinder valve and its piston which is connected by a link to the top of the vertical ring. The pick-off is a small balanced valve which admits the main air pressure through flexible pipes to one or other side of the rudder servo cylinder, simultaneously opening the other side to the atmosphere. The action is similar in principle to that of the balanced oil valve of the Sperry A.3 already described. One end of the servo piston rod is connected through a clutch-pin to a dummy rudder bar to which the main rudder cables are attached. The clutch enables the pilot, by means of a Bowden control, to disengage the automatic pilot in an emergency.

Follow-up System. The necessary follow-up action is provided by making the frame which carries the pick-off valves, pivotable on the main framework, about the vertical axis. Two levers connect the gyro frame to the dummy rudder-bar. When a yaw displacement of the rudder pick-off valve body relative to its piston initiates corrective rudder control, the movement of the dummy rudder bar is transmitted via the levers to rotate the gyro frame about its "vertical" axis, in a sense that neutralises the movement of the pick-off valve and so limits the control applied.

By the reverse action the amount of control applied by the rudder servo is progressively reduced as the aircraft recovers its original heading.

Pitch Control. The elevator servo (not shown) is operated in a similar manner from a pick-off valve actuated from the inner gimbal pitch ring. In this case, however, a small air relay is interposed in the linkage between the inner gimbal and the main elevator valve, to reduce to a minimum the effort of operating the pick-off. If the elevator valve were operated directly by the gyro element, the extra friction about the horizontal gimbal axis would cause excessive azimuth wander of the gyro.

To maintain the inner ring at its correct tilt angle of 15 degrees and provide a stable pitch reference, a gravity control is provided, consisting of a weight on one side of the outer gimbal ring. The moment of this weight due to the backward tilt of the outer ring axis is normally balanced by the torque transmitted to the outer ring by a lever connected to a helical spring. If the nose of the aircraft rises or falls the change in the inclination of the outer ring axis alters the gravity moment, so unbalancing the torque and causing precession of the inner ring. With the autopilot engaged, this precession of the gyro axle is in the sense to give an elevator pick-off displacement which will cause the aircraft to bring the outer ring axis back to the vertical. Actually two gravity weights are used in the form of a Watts linkage which makes the weights responsive to pitch change, but insensitive to lateral acceleration.

For pitch control, the datum of the gravity control system is alterable by varying the torque from the helical spring. A Bowden cable control to the spring enables the pilot to bias the gravity control to a nose up or nose down condition, determined by the pitch angle at which the spring and gravity torques balance each other.

Course Control. The inner ring assembly is balanced as a directional gyro to have as nearly as possible the same precession rate as the azimuth movement of the earth at the mean latitude of operation, i.e., zero apparent drift. The balance weights are in the form of locking rings screwed on to the rotor shaft itself.

For controlled turns the gyro is precessed in azimuth. The precessing torque is applied by admitting air pressure to one side or other of a small course-change air cylinder, the piston of which is linked to the end of a quadrant lever attached to the inner gimbal ring. Either the pilot or bomb-aimer can operate a valve controlling the course change.

It will have been noticed that, as in the case of the Pollock Brown autopilot, there is a fundamental difference between this principle of control and that used in the Sperry A.3 gyropilot. In the latter, control is effected by leaving the gyro undisturbed and altering the angular datum of the pick-off, so that the aircraft takes up its new attitude while the gyro axie maintains its same absolute direction in space.

In the R.A.E. pilot, the gyro is deliberately precessed so that the aircraft follows the change of direction of the gyro axle without any apparent relative movement between the aircraft and gyro.

Roll Control. Control about the roll axis is obtained indirectly, by virtue of the inclined gyro axle arrangement, through which any movement of the aircraft about the roll axis gives, by gimballing action, a rudder pick-off signal. For instance, if the left wing goes down, the gimballing movement of the inner and outer rings causes a movement of the rudder pick-off equivalent to a yaw to the left, resulting in application of right rudder. The ensuing yaw to the right centralises the rudder pick-off, at the same time causing an increase in the speed of the air over the left wing on the outside of the turn. As the left wing comes up under this influence, the right roll movement, by gimbal action, gives a rudder pick-off signal equivalent to a right yaw so that the applied right rudder is removed as the roll recovery is effected.

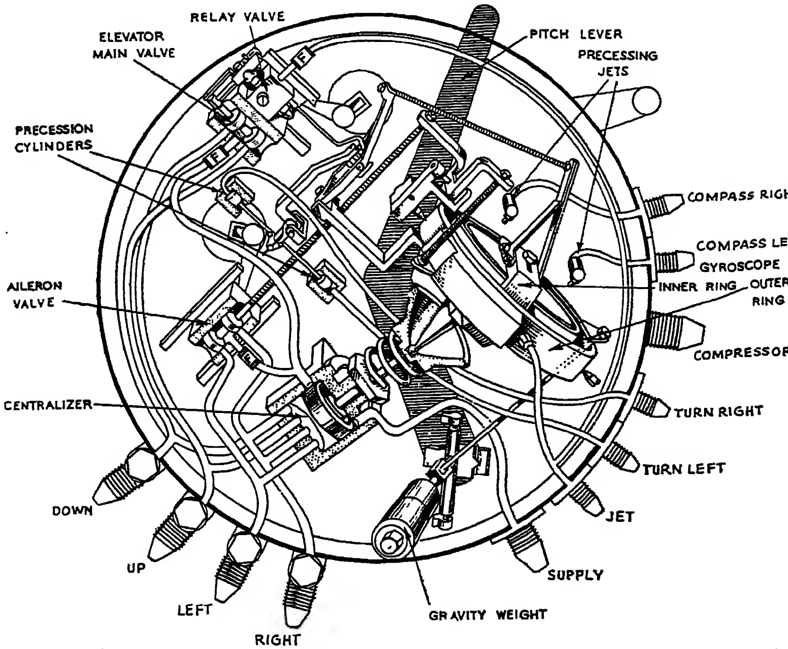
A later version of this R.A.E. design, the Mk. Ia, in common with all others up to the Mark VII, had a separate aileron control gyro, working on the same principle as the gyrorector described in the previous chapter.

A modified version of the R.A.E. Mark I automatic pilot was used in the radio-controlled pilotless Tiger Moth aircraft which was developed for anti-aircraft gunnery practice about 1935 and was known as the Queen Bee target plane.

The automatic control was fitted with a system of relays actuated by a radio receiver, which enabled a ground radio station to control the Queen Bee to take off, fly straight, climb, dive, turn, or land. By means of a code similar in principle to automatic telephone dialling, radio control impulses were selectively received by the relays and applied to the appropriate rudder and elevator controls. The engine throttle was controlled in a similar manner.

R.A.E. Mk. VIII

The latest R.A.E. automatic pilot is a single inclined-gyro type for elevator and aileron control. In this case it is the yaw control that is obtained indirectly by aileron application so that the system is in a sense another embodiment of the principal of the original Mk. I. Modern large aircraft are usually very stable about the yaw axis, and the characteristics of ailerons are such that conditions are favourable for controlling both roll and azimuth movements by ailerons alone. This has undoubtedly been a prime consideration in the development of the Mk. VIII, the design of which also allows of considerable simplification compared with the preceding two R.A.E. designs. Like the Mk. I, this system works on air pressure supplied by a compressor.



Crown Copyright

Fig. III. 69. R.A.E. Mk. VIII. Diagrammatic arrangement of gyro unit. Side elevation, direction of flight left to right.

The gyro control unit, shown diagrammatically in Fig. III, 69 has the rotor mounted in gimbal rings, with its axle fore and aft and the front end inclined upwards at 45° to the horizontal. The inner ring is mounted with its pivots horizontally athwartships in the outer gimbal ring which is pivoted in a frame, its axis inclined back at 45°. The brass rotor is carried on a steel axle with cup ends which form the outer race of the ball bearing, the male pivots being in the inner ring. The inner gimbal pivots each consist of a single $\frac{1}{32}$ in, diam. ball located in cups in the outer and inner gimbal rings.

Air enters through a bush in the spring-loaded cup and cone bearing of the lower outer ring pivot and passes through a tube to a jet projecting through the outer ring close to the buckets on the rotor periphery. A guard helps to direct the air jet on to the rotor. The upper pivot of the outer ring is a parallel-ended screw.

Gravity Control. A so-called gravity weight on a lever is carried on the main frame on vertical pivots and linked to the outer ring so that normally the outer ring is in equilibrium. If the nose of the aircraft drops, for instance, the tendency of the gravity weight to swing forward applies torque to the outer ring, which results in precession of the inner ring to increase the upward tilt of the gyro axle. This applies pick-off control for up elevator (as described later) and causes the aircraft to follow the gyro until the gravity control is in equilibrium again. The reverse process applies to check nose-up tendency, and thus the aircraft is controlled to a pitch datum.

Manual pitch control is effected, not by spring biasing the gravity control as in the Mark I, but by a lever which alters the angle of the gravity weight pivots in the pitch plane, thus causing the gyro to precess and the aircraft to follow the gyro to a new attitude of equilibrium.

Aileron Control. The piston type aileron pick-off valve is connected to the outer ring by spring-tensioned push-pull rods and a rocking lever. Relative movement of the outer ring and frame in roll operates the aileron pick-off valve to pass air via the "left" or "right" union to the appropriate end of the aileron servo motor. Follow up is by means of cables from the servo piston rod to a pulley and crank device on the gyro unit, which moves the pick-off valve body on slides to follow the pick-off piston movement. The throw of the crank is adjustable so that the ratio of movement of servo to that of the pick-off can be varied.

Elevator Control. The elevator pick-off valve is similar in action, but in addition to the elevator valve there is a relay valve. The linkage from the inner (or pitch) ring is to the relay valve, which is a miniature servo operating the elevator main valve. The purpose of this arrangement is to reduce the effort of operating the elevator pick-off valve and thus reduce reaction on the inner ring, which would precess the gyro in roll. This precaution is not necessary in the case of the aileron valve as there is direct gravity control to resist any pitch precession due to reaction from the aileron valve on the outer ring.

Centraliser. When the main air valve (not shown) is turned off, no pressure reaches the supply union of the gyro unit, and a caging device called the centraliser is in the caged position shown, the spring forcing the cup to centralise and lock the ball-ended arm projecting down and back from the inner ring. At the same time the air lines from the elevator and aileron valves to their four servo connections are short-circuited through the centraliser cylinder, leaving the servos free, and the centraliser piston blocks a port supplying air to the aileron and elevator pick-off valves. When the main valve is turned on, air pressure entering the supply union forces the centraliser piston down, uncages the gyro and admits air to the valves, while sealing the four servo by-pass ports.

Azimuth Control. Stabilization in the yawing plane is effected by aileron control as follows. Suppose, for example, that while under automatic control the nose of the aircraft swings to the right. Owing to the inclination of the gyro axle, this azimuth movement displaces the roll pick-off in a direction which applies left bank control on the ailerons. In the ensuing side-slip to the left, the air pressure on the tail-fin surface tends to yaw the aircraft's nose to the left, correcting the original swing to the right. During recovery the reverse gimballing effect takes place, so that the left bank is taken off as the nose of the aircraft regains the original heading. Due to the fact that the rudder function is indirectly performed by the ailerons, the control about the yaw axis is not as precise as the pitch and yaw stabilization.

A corresponding qualification applies to the indirect roll stabilization of the original Mk. 1 design, and is fundamental to two-axis control.

An interesting feature of the R.A.E. Mk. VIII design is that the erection of the gyro about the roll axis is accomplished indirectly by the gravity pitch control and the compass monitoring in azimuth (described below) since it is impossible for random drift of the inclined gyro to occur about the roll axis without initiating corrective precessive control due to the gimballing components of the angular movement, about the other two axes.

Compass Control. The Mk. VIII embodies a compass monitoring control from the R.A.E. D.R. compass described in a previous chapter. Thus when under automatic control, the aircraft maintains a fixed mean magnetic heading.

A pilot's repeater from the D.R. compass is provided with electric pick-off contacts which operate a pneumatic relay valve. The latter controls the supply of air-pressure to one or other of two precessing jets which impinge on the upper side of the rotor and so apply torque to the inner ring to precess the outer ring one way or the other. To steer a given course the pilot sets a course pointer on the repeater to the required heading. One of the pick-off contacts is positioned by this course pointer and the other by the repeater movement. Thus, if there is any discrepancy between the actual heading of the aircraft and the course set, the gyro is precessed or monitored as just described to regain the set compass course.

The monitoring rate is 3 to 4 degrees per minute and maintains a mean course with a slight oscillation.

Turn Control. For small changes of course, the repeater set-course pointer is set to the new heading and the automatic control causes the aircraft to follow the gyro in azimuth at the normal monitoring control rate. This is termed a compass turn.

For large course changes, the pilot can change over to a high precessing rate by means of a 'jinking' switch, so-called because if it is used except when turning a continuous weaving flight results due to 'hunting.' This was originally intended for military avoiding action.

For the fast turn, the air relay valve, instead of supplying precessing jets on the rotor, is switched by the jinking control to supply air pressure to two opposing precession cylinders carried on brackets on the main frame.

Pistons in these cylinders are not connected to, but can push against, the end of a lever attached to linkage between the elevator relay valve and the inner ring. The pistons are normally spring centralized to be clear of the lever, and are arranged to be capable of applying a torque to precess the gyro at between 2 and 3 degrees per second. After switching over to the fast rate the fast turn is carried out in the same way as the compass turn until the aircraft is within a few degrees of the new heading, when the jinking switch is set back to the normal monitoring rate. The aircraft then picks up the new course without appreciable overshoot.

German three-axis

Early German automatic pilots both of the Siemens and Askania firms, were single-axis controls for rudder only. In 1942 an example of a 3-axis type became available in this country, and was found to be a composite production of the firms Siemens, Askania, Patin, and Anschutz.

The equipment, which weighs 135 lbs., is all-electric and rather elaborate in design, there being no fewer than five gyroscopes, all driven by alternating current from inverters supplied from the aircraft's 24-volt supply system. The gyroscopes include a directional gyro and gyro-vertical, and one rate-measuring gyro for each of the three axes.

Control includes factors proportional to angular displacement, angular rate (velocity), linear acceleration, and airspeed, and the control factors for the three axes are derived from eight different detector units, as follows :—

Rudder Control.

Angular displacement term ..	directional gyro. (with compass control).
Angular velocity term ..	rate-of-turn gyro.

Aileron Control.

Angular displacement term ..	gyro-vertical, roll axis.
Angular velocity term ..	rate-of-roll gyro.

Mechanism for computing correct bank angle.

Elevator Control.

Angular displacement term ..	gyro-vertical, roll axis.
Angular velocity term ..	rate-of-pitch gyro.
Linear Acceleration term ..	fore-and-aft linear accelerometer.
Integral of air-speed ..	air-speed meter.

It will be noticed that angle of pitch is not used in any of the controls, so that no pitch pick-off is employed.

Each detector unit, e.g., directional gyro, rate gyro, etc., has a pick-off consisting of a very fine wire potentiometer, which gives a voltage signal proportional to the deflection of the instrument. Each group of pick-off signal voltages is compounded algebraically in a multi-coil galvanometer relay, the combined signal controlling a rotary type of servo. Unlike most types of automatic pilot, the servo *speed*, and not servo *total movement*, is made proportional to the control signals, and no follow-up system from aircraft controls to detector pick-offs is used.

No description is given here of the compass-controlled directional gyro, as this is fundamentally similar to the Askania system described in Chapter 2.

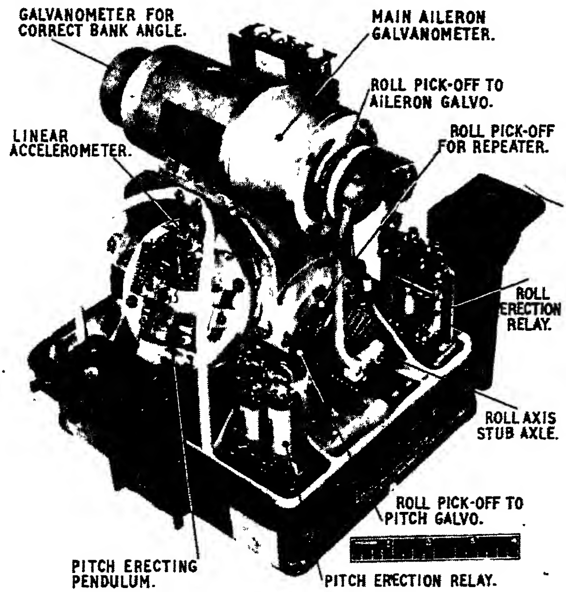
Gyro-Vertical. Fig. III. 70 shows the cover removed from the gyro-vertical unit and the assembly of the main items, including accelerometer, erector relays and horizon galvonometer relay.

The gyro is mounted in a casing which forms the pitch gimbal ring, and which in turn is pivoted inside a drum-type roll-axis gimbal ring, the tilted end of which is visible in the illustration.

Axial point-contact strips are used for conveying electric current across the gimbal axes with minimum friction. The system is the same as that used on the Horn and Sperry electric horizons described in Chapter 4.

Erection System. Erection about the roll and pitch axes is controlled by erecting pendulums, one of which (pitch) is shown. The pendulum carries a contact sliding on a polished contact face on the gyro system, one half being silvered and the other insulating. When the pendulum and gyro axle are both vertical, the contact is on the dividing line.

A pitch erecting torque motor mounted on the roll-axis has four windings, two of which are permanently energised by the gyro supply phases, the other two being fed with A.C., the phase of which differs by plus or minus 90 degrees from the phase of the first pair of coils. These



Crown Copyright

Fig. III. 70. German three-axis automatic pilot; three-quarter view of vertical gyro unit. The 3 phase gyro is carried in an inner ring pivoted in the pitch axis in a drum-shaped outer gimbal case, the end of which is visible tilted in the main frame on its roll axis bearings.

two reversing phases are selected by relays, which are energised by the pitch pendulum contact.

As the pendulum contact has no neutral point and the erection rate is constant, the gyro has no absolutely stable position at the vertical, but hunts as the contact passes to and fro across the dividing line between insulating and conducting surfaces. The oscillation has a period of about one second per reversal, and in practice gives a very close control of the vertical, having an amplitude of less than $1\frac{1}{2}$ minutes of arc.

In order to avoid delay in reaching the vertical when the gyropilot is first switched on, a rapid erection rate is applied for the first half-minute, after which a thermal time switch automatically switches in a resistance in the erection circuit which cuts down the rate to the comparatively slow normal rate of 2.6 degrees per minute.

This erection rate is intended to be slow enough to avoid serious erection turn errors and no means is provided for reducing further or cutting out the erection during controlled turns.

A manual control of the erection rate is also provided, by which the pilot can apply the fast erection rate if for any reason the gyro has not reached the vertical. (A repeater from the gyro-vertical in the form of an artificial horizon dial enables the pilot to see the attitude of the gyro-vertical.)

This quick-erection control switch reverses the direction of the rotor and the roll erection by reversing the sense of the supply phases. The rotor is thus stopped and started up in the reverse direction. Before it can gather speed again, its gyroscopic inertia is naturally very low, so that the erection precession to the vertical resulting from the high erecting torque is extremely rapid.

On the other hand, while the rotor is slowing down before reversing, the erection control is in the wrong sense relative to rotor direction, and for the same reason of low speed the rotor is precessed violently away from the vertical, with somewhat harsh effects on the gimbal pivots, as the gyro system meets the limiting stops.

As it is not subject to acceleration forces in turns, no quick-erection system is provided for the pitch axis, the pitch ring being made pendulous instead.

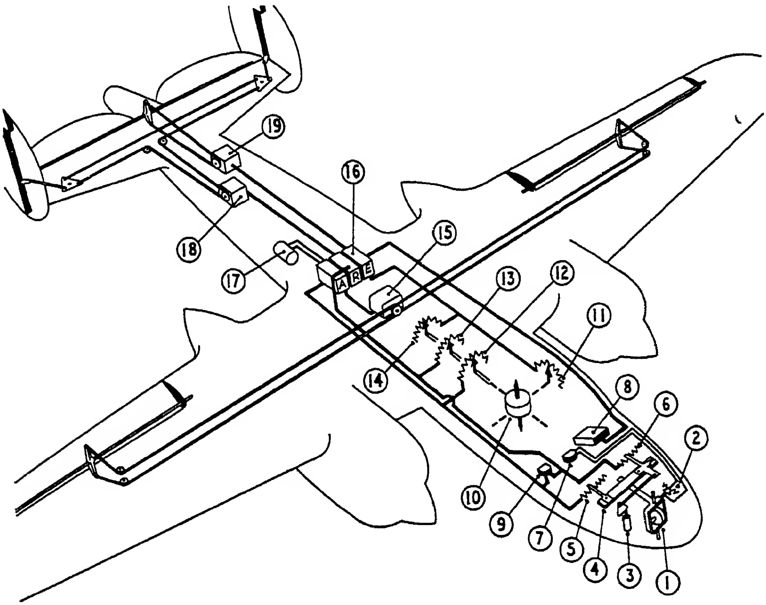
Three roll-axis pick-off potentiometers are indicated in Fig. III, 70. Of the two mounted on the gimbal axis itself, one operates the previously-mentioned horizon repeater, and the other sends a signal to the pitch compounding galvanometer (not shown) to provide up-elevator correction in a turn, as a function of bank angle.

A third pick-off, mounted at one end of the main aileron galvanometer, is remotely operated from the gimbal axis by cranks and connecting rod. This pick-off provides the roll displacement term for aileron control. An additional galvanometer relay, at the other end of the main aileron galvanometer, receives signals from roll, rate of turn, and air-speed pick-offs, to compute and correct the bank angle in turns.

Minneapolis Honeywell C-1

System. Fig. III. 71 is a schematic drawing showing the layout of the various units and the operating principles of the Minneapolis Honeywell Automatic Pilot. It should be noted that the lines connecting the numbered units do not represent actual electric cables, but are intended to indicate that these units are related to each other electrically. The term "pick-up" in the following description is synonomous with "pick-off."

To understand the working of the system, assume that the aircraft is already flying straight and level under automatic control, and that a cross-wind gust suddenly causes it to swing in azimuth away from the set heading. The directional (gyro) stabiliser control panel detects this disturbance by the relative movement of its pick-up contact wipers and their respective banking and rudder pick-up potentiometers, the direction depending of course on which way the aircraft turns. Note that the rudder pick-up potentiometer contact wiper is pivoted on the directional panel and linked to a dash-pot, being held in its normal position by springs (not shown). The more rapid the displacement, the greater the viscosity drag of the dash-pot, causing a pivotal movement of the contact wiper, and thus increasing its movement on the rudder potentiometer by an amount proportional to rate. Thus a combined displacement and velocity signal voltage is transmitted from the rudder pick-up to the amplifier, which energises the rudder servo to apply rudder control.



① DIRECTIONAL STABILIZER. ② P.D.I. POTENTIOMETER. ③ DASH POT.
④ DIRECTIONAL PANEL. ⑤ BANKING POTENTIOMETER. ⑥ RUD. PICK UP POTENTIOMETER.
⑦ P.D.I. ⑧ AUTOPILOT CONTROL PANEL. ⑨ TURN CONTROL. ⑩ VERTICAL FLIGHT GYRO.
⑪ ELEV. PICK UP POTENTIOMETER. ⑫ AILERON PICK UP POTENTIOMETER. ⑬ SIDE SLIP POT. MTR.
⑭ UP ELEV. POTENTIOMETER. ⑮ AILERON SERVO. ⑯ AMPLIFIER. ⑰ ROTARY INVERTER.
⑱ RUDDER SERVO. ⑲ ELEVATOR SERVO.

Fig. III, 71. Minneapolis Honeywell C-I. Diagrammatic view of installation.

The follow-up action is supplied by a potentiometer driven by the rudder servo (not shown) which applies an increasing voltage opposing the rudder pick-up signal, until the rudder movement is stopped. The reverse action takes place during recovery of the aircraft to the original heading. At the same time the banking potentiometer sends a displacement signal voltage to the amplifier and operates the ailerons by the aileron servo in a similar manner, in the direction to assist the rudder to return the aircraft to the proper heading.

Similarly, should the nose of the aircraft drop, the vertical gyro elevator pick-up potentiometer detects the movement and applies an electric displacement signal voltage to the elevator section of the amplifier and thence to the elevator servo to raise the elevators.

In the event of a roll disturbance, the vertical gyro causes relative movement of the wipers of three potentiometers, one aileron pick-up, one sideslip and one up elevator, which send signals to aileron, rudder