The Triplane and the Stable Biplane

BY

J. C. HUNSAKER, D.Sc.

PRICE 3/- NET

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0, Essex St., Strand, London, W.C. 2

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and
The Stable Biplane

Reprinted from "Engineering."

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WITH NUMEROUS ILLUSTRATIONS.

JAMES SELWYN & CO., LTD.
20, ESSEX STREET, STRAND, LONDON, W.C. 2.
1918.

PUBLISHER'S NOTE.

In a press comment on Judge's book, "The Properties of Aerofoils and Aerodynamic Bodies," reference was made to the fact that in England we are not sufficiently acquainted with Dr. Hunsaker's researches. We agree with this view, and the present volume is an effort toward obtaining a wider publicity for the two most important investigations. Our very best thanks are due to the Publishers of *Engineering* for their courtesy in allowing us to reprint the articles.

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PART I.

AERODYNAMICAL PROPERTIES OF THE TRIPLANE.

General Problem.—The demand for increased size and weight of aeroplanes, especially sea-planes, must be met without material increase in the landing speed. On this account the wing loading remains at about 5 lb. per sq. ft., and for an aeroplane of four-fold the ordinary weight the wing area must be increased in like proportion. Monoplane construction is obviously impractical for such great spread of wings, and even the customary biplane arrangement leads to a span from tip to tip of wings of over 100 ft. The difficulty of handling and housing such a great structure has led to the consideration of wings in a tier of three, or a triplane, to provide the wing area necessary to sustain a great weight at a speed of not more than 50 miles per hour, and at the same time not unduly to extend the span.

The following aerodynamical investigation was undertaken to determine the suitability of the triplane arrangement for weight-carrying as compared with the biplane. It appears that the triplane is not so effective as the biplane, and will require somewhat more power to drive; but with sufficient power the triplane can support nearly the same weight as the biplane at its attitude of maximum lift. The loss is only about 1.1 per cent. At small angles near 4 deg., for the same lift the triplane requires some 6 per cent. more power than the corresponding biplane. At 4 deg. incidence the ratio of lift to resistance is 13.8 for the biplane against 12.8 for the triplane.

Experiments on R.A.F. 6 Profile.—The experiments were conducted in the Wind Tunnel of the Massachusetts

Institute of Technology, on wing models made of laminated maple scraped to a profile known as R.A.F. 6* to the nearest 0.005 in. Each aerofoil was 15.75 in. span by 2.5 in. chord, giving an aspect ratio of 6.3. The models were all tested at a wind velocity of 30 miles per hour; air density, 0.07608 lb. per cub. ft.

Models were mounted vertically on a spindle, with necessary bracing in a manner described later. In every case the effect of the supporting apparatus has been determined by separate tests and subtracted, as well as the effect of such struts or wires as were used to ensure parallelism in the biplane or triplane combinations. The results here recorded, therefore, apply to the bare aerofoils only.

Biplane and triplane models had a constant gap between planes equal to 1.2 times the chord length, and there was no stagger or overhang.

A single aerofoil was first tested as a monoplane to serve as a standard for reference. The lift and resistance, or "drift," are expressed as lbs. per sq. ft. wing area per mile hour velocity The coefficients found are in fair agreement with previous tests upon aerofoils of this section made both at Teddington and at this place. The precision of measurements in our wind-tunnel work is better than 1 per cent., but minor variations in workmanship of model, too slight to be detected, may lead to discrepancies of the order of about 3 per cent. between the results of tests on two apparently identical models.‡ The "centre of pressure," defined as the intersection of the line of action of the resultant force on the aerofoil with the plane of the chord, has been found by a graphical construction from the observed force components, and the moment about the supporting spindle. In the biplane tests the centre of pressure is taken in the plane parallel

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* Technical Report of the Advisory Committee for Aeronautics, 1912-13, London.

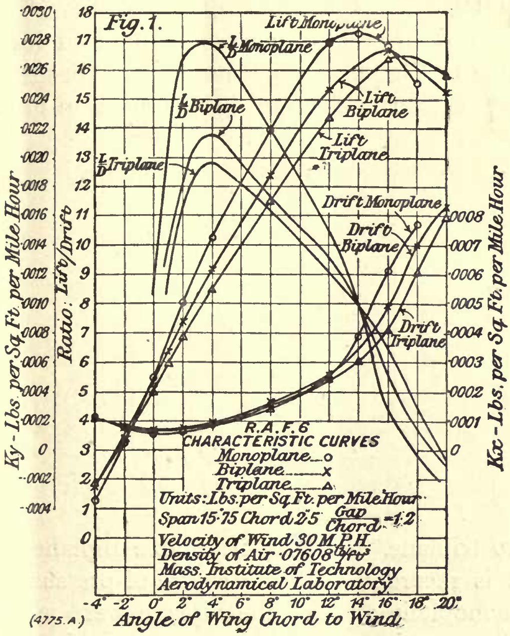
‡ Smithsonian Miscellaneous Collections, vol. 62, No. 4, "Characteristic Curves for Wing Section, R.A.F. 6."

to and midway between the planes of the chords of upper and lower wings, and in the triplane tests the centre of pressure is referred to the plane of the chord of the middle wing.

The curves for lift coefficient K_y and drift coefficient K_x, is defined by

$$\text{Drift} = K_x S V^2$$
$$\text{Lift} = K_y S V^2$$
$$\text{(lb.)} \quad \text{(sq. ft.)} \quad \text{(miles/hour)}$$

are plotted in Fig. 1 with the angle of incidence between the chord and wind direction as abscissæ. The coeffi-



(4775. A.)

cients calculated as above from the observed forces are plotted to show the consistency of the observations.

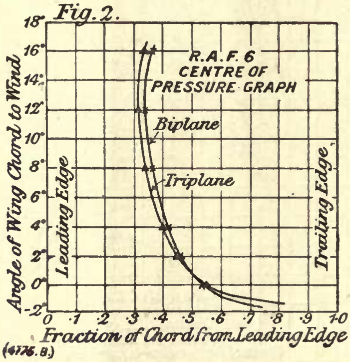
It appears by comparison of the lift curves for the three cases that the triplane and biplane give nearly the same maximum lift at about 16 deg., but that for smaller angles of incidence the triplane lift is appreciably reduced.

Confirming previous tests on biplane *versus* monoplane, we find the lift coefficient for the monoplane superior at all angles above zero. The drift coefficient for angles below 12 deg. is not greatly different in the three cases, but at very great angles of incidence, near 16 deg., the triplane has a materially lower resistance, and has a real advantage in such a "stalling" attitude.

The curves of ratio lift/drift bring out the relative effectiveness of the wings. Thus the best L/D ratio is 17 for the monoplane, 13.8 for the biplane, and 12.8 for the triplane. These values refer to small angles of attack corresponding to high flight speed. For a large angle of attack, 16 deg., the ratios are respectively 4.5, 5.6 and 6.5.

The centre-of-pressure curves are plotted for biplane and triplane in Fig. 2. It does not appear that the centre-of-pressure motion is changed in character in going from

Fig. 2.



biplane to triplane. In Part II. Stable Biplane Arrangements, it is recorded that the centre-of-pressure motions for the monoplane and for the biplane were nearly identical. The present experiments confirm this conclusion, but the monoplane curve is omitted for the sake of keeping the figure clear.

The following table of experimental points brings out the relative values of the coefficients in the three cases, taking the monoplane coefficients as standard, and expressing those for the biplane and triplane as a percentage of them.

i	Monoplane.		Biplane.		Triplane.	
	Actual K_{ym}	Percentage K_{ym}	Actual K_{yb}	Percentage K_{yb}	Actual K_{yt}	Percentage K_{yt}
0	·000486	100	·000432	88·8	·000404	83·0
2	·00103	100	·000864	83·8	·000776	75·4
4	·00145	100	·00123	85·4	·00109	75·7
8	·00218	100	·00186	85·2	·00169	77·4
12	·00278	100	·00244	87·6	·00226	81·2
16	·00277	100	·00273	98·5	·00267	96·4
	L/D	L/D	L/D	L/D	L/D	L/D
0	8·6	100	6·3	73·2	6·1	70·8
2	16·3	100	12·2	74·7	11·4	69·8
4	16·8	100	13·8	82·0	12·8	76·1
8	13·8	100	11·3	81·9	11·1	80·4
12	10·0	100	9·5	95·0	8·9	89·0
16	4·5	100	5·6	124·0	6·5	145·0

It may be noted that the drop in lift after passing the maximum is less rapid for the triplane than for the other combinations. The advantage here, if any, is of slight importance, because aeroplanes ordinarily cannot be operated at such great angles of incidence.

Experiments on Curtiss Profile.—To verify the tests just described the work was repeated for a monoplane, biplane and triplane, made from an aerofoil cast in type metal, having a profile similar to that at one time employed by the Curtiss Aeroplane Company. This profile differs from the R.A.F. 6 shown in Fig. 3, by the thickness of the edges.

These Curtiss aerofoils were made of the same over-all dimensions as the R.A.F. 6, arranged, as before, with gap 1.2 times chord, and tested in an identical manner. The results for the monoplane, biplane and triplane are shown in Fig. 4. These curves are of the same general character as those for R.A.F. 6 given in Fig. 1. We have then confirmation of the conclusions that:—

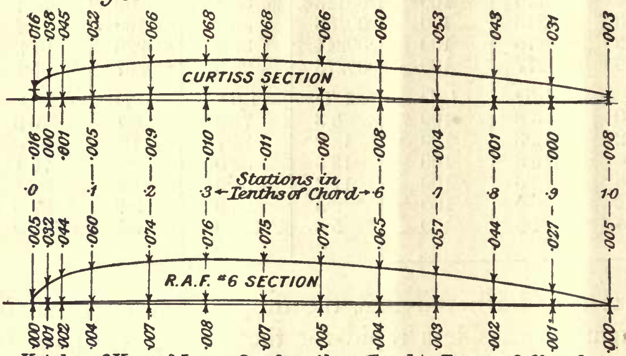
1. The maximum lift of the triplane is very nearly as great as that of the biplane;

2. At angles of incidence between 2 deg. to 12 deg.

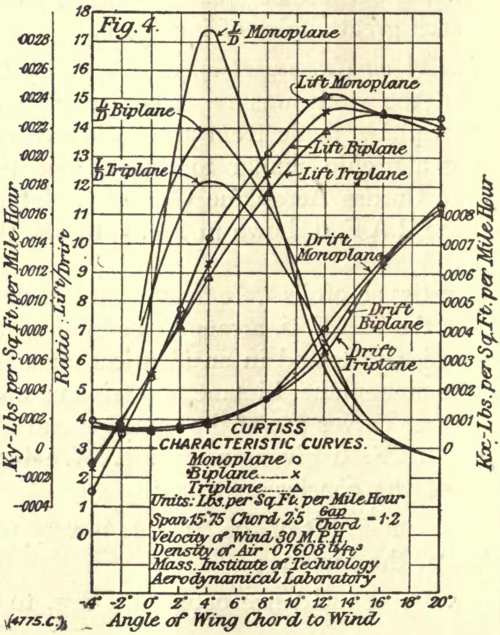
the lift and ratio L/D of the triplane are materially less than the corresponding values for the biplane.

Applied to an aeroplane, we should expect to obtain about the same landing speed on given wing area, whether the biplane or triplane arrangements were used. The

Fig. 3.



Height of Upper & Lower Surface Above Chord in Terms of Chord



(4775.C.)

maximum speed for given engine power would, however, be less for the triplane on account of lower L/D ratio at small angles.

Interference.—Experiments were next undertaken to determine the distribution of load upon the three wings of the triplane made of aerofoils of R.A.F. 6 profile. A special apparatus was designed (Fig. 5) by which two wings of the combination could be supported independently in their proper attitude, while the remaining one was attached to the balance, and its characteristic coefficients found by experiment. It was convenient to measure the lift and resistance components for the upper wing, and for the lower wing as influenced by the others, and then to find the forces on the middle wing by subtraction from the values previously found for the complete triplane.

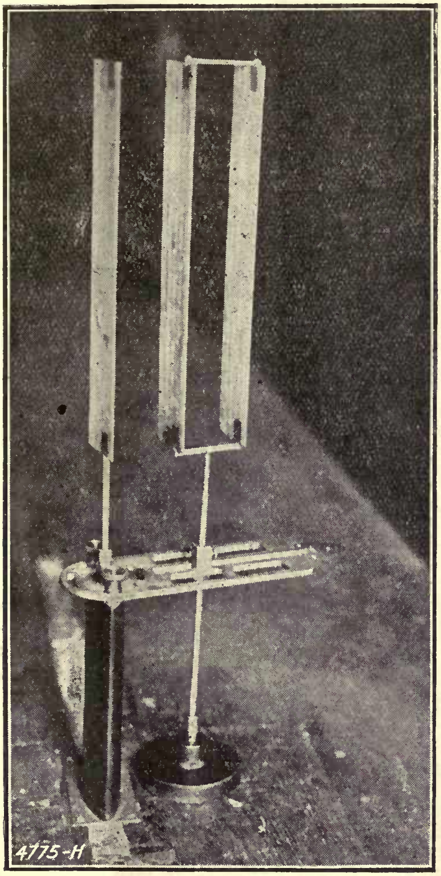


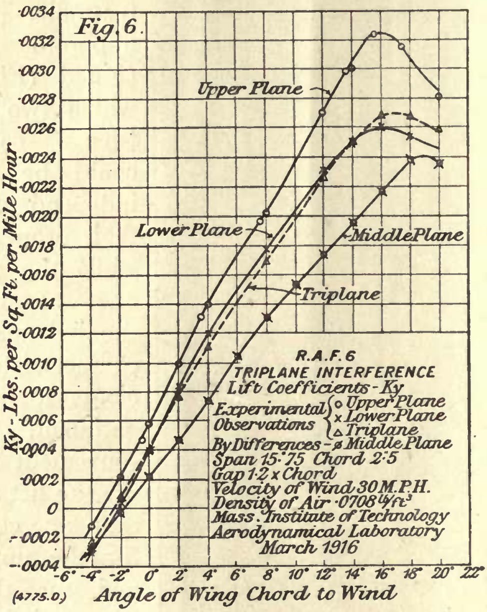
Fig. 5.

The results are shown by the curves of Figs. 6, 7, and 8.* It appears that the upper wing is very much the most effective of the three, and that the middle wing is the least

* Lift/drift plotted from faired curves.

effective. The coefficients for the lower wing are very nearly those for the three in combination as a triplane.

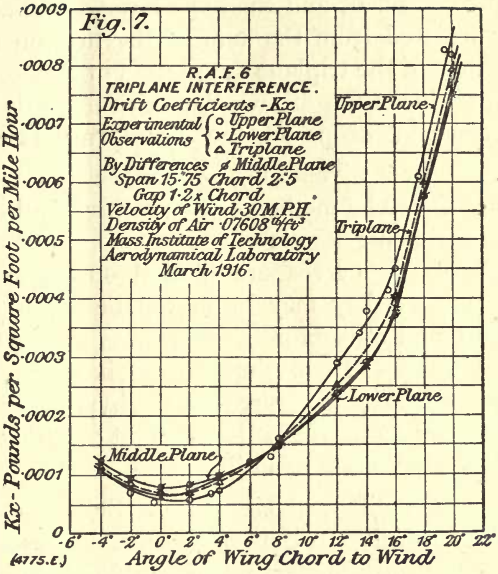
To estimate the lift on each wing for use in structural design of the wing girder, we give below a table showing the lift and ratio lift/drift of each wing in terms of the corresponding values for the middle wing taken as unity.

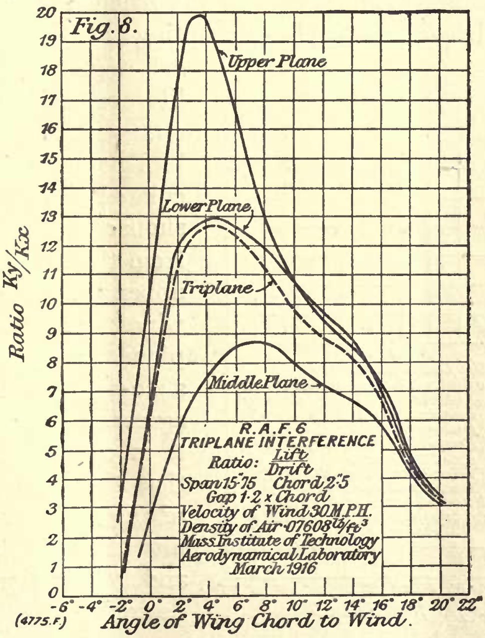


The very poor lift of the middle wing must be caused by interference with the free flow of air due to the presence of the upper and lower wings. It would be

Angle of Incidence.	Lift Upper.	Lift Middle.	Lift Lower.	L/D Upper.	L/D Middle.	L/D Lower.
0	2·68	1·0	1·82	3·63	1·0	2·30
2	2·14	1.0	1·76	3·18	1·0	2·13
4	1·91	1·0	1·64	2·59	1·0	1·69
8	1·56	1·0	1·36	1·49	1·0	1·37
12	1·56	1·0	1·31	1·30	1·0	1·34
16	1·49	1·0	1·20	1·22	1·0	1·17

reasonable to suppose that the middle wing influences the lower wing to the same degree that the upper wing of a biplane influences the lower wing, and that it influences the upper wing of the triplane to the same degree that the lower wing of a biplane influences the upper wing of that combination. Consequently, if this reasoning hold, we should expect the sum of the observed lifts on the upper and lower wings of the triplane to be equal to the observed lift on the biplane R.A.F. 6 previously tested.





The observed biplane

lift coefficient and the hypothetical biplane lift coefficient, calculated from the sum of the lifts on upper and lower wings of the triplane are plotted in Fig. 9. It appears that for all angles below the critical angle where the lift coefficient drops off, the discrepancy is slight.

For a given wing profile there is a definite angle of no lift. The method of measuring wind direction in these experiments admits of a precision of about 0.25 deg. Since all of our curves are plotted on angle of incidence as abscissæ, they may be moved bodily to right or left 0.2 deg. and still express the results within the limit of precision of the experiments. It has been found necessary to correct the lift curve for the hypothetical biplane in this manner by moving it to the right 0.25 deg. in order to give the same angle of no lift.

The lift coefficient at 16 deg., the critical angle, is very difficult to determine with any certainty on account of the unstable nature of the fluid motion at this angle. Violent eddy-making begins here, and the balance tends to oscillate unless heavily damped. Excepting at the critical angle, the lift coefficients observed for the biplane and calculated for a similar biplane from the lift on upper and lower wings of triplane, are in such good agreement that it is concluded that the curves of Fig. 9 furnish the check and verification desired.

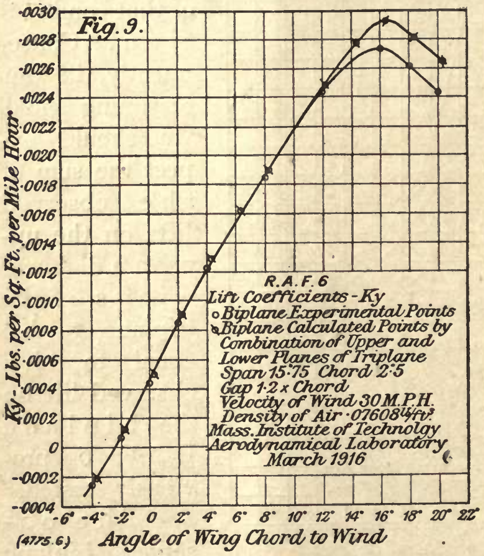


Fig. 9.

PART II.

STABLE BIPLANE ARRANGEMENTS.*

1. *Introduction and Summary.*—It is well known that the typical cambered aeroplane wing is longitudinally unstable, whether used singly as a monoplane, or in pairs as a biplane. The following is an account of a research carried out in the wind tunnel of the Massachusetts Institute of Technology, with a view to discovering whether this instability may be overcome without material sacrifice of life, or increase in resistance.

It is believed that our experiments will show that the ordinary biplane, using wings of standard section, may be made longitudinally stable by giving the upper plane a stagger forward of 50 per cent. of the chord, and at the same time inclining its chord about 2½ deg. to the lower chord, "decalage" 2½ deg. The loss in minimum lift to drift ratio ("efficiency") is less than 5 per cent.

The maximum possible lift is not diminished, but increased slightly. The landing speed of the aeroplane is thus the same whether this arrangement or the ordinary one be used. Furthermore, the maximum speed, which is limited by the drift at the value of lift necessary to sustain the weight of the aeroplane, is identical in both cases. Hence, by the proposed alteration in wing arrangement, an existing biplane should be practically unaffected in performance, while it has been made immensely more safe to fly. In practice, the unstable pitching moments of ordinary biplane wings (orthogonal biplane) are balanced by a large horizontal tail surface. The increased structural weight due to inclined struts in a staggered biplane

* An account of a research conducted at the wind tunnel of the Massachusetts Institute of Technology.

should be compensated, at least in large part, by the saving in weight due to a smaller tail surface and lighter supporting structure.

Both the monoplane and orthogonal biplane arrangements show a critical angle or "burble point" beyond which, if the angle of the chord to the wind be increased, the lift drops off. Such a machine may easily be "stalled" in the air if the pilot attempts to head up too steeply, when it will sink instead of climb. The probability of stalling is not directly affected by the stability or instability of the aeroplane, but, of course, its effects are less disastrous if the machine be stable. If the curve of lift on angle at the burble point be flat, the probability of stalling is greatly reduced. The staggered biplane with $2\frac{1}{2}$ deg. decalage is shown by the diagram,† Fig. 12, to have a fairly flat burble point. Thus the burble point comes at 20 deg., but the drop in lift to 24 deg. is only 3 per cent.

The orthogonal biplane has an early burble point at 14 deg., with a drop in lift of 5 per cent. to 18 deg. A greater degree of longitudinal stability may be obtained by greater decalage of the upper wing, but a material loss in lift must be expected. On the other hand, a decalage of only 1 deg. gives a neutral wing, practically equal in lift to an orthogonal biplane.

An alternative arrangement was tested, in which the lower wing chord was made 83 per cent. of the upper, stagger 50 per cent., decalage 2.1 deg. This type 3A is stable for a low centre of gravity, or neutral for a high centre of gravity. The maximum lift-drift ratio is about 5 per cent. less than the ordinary biplane; the maximum lift is 3 per cent. greater. At high speeds corresponding to a small value of lift coefficient, the type 3A offers about 5 per cent. more resistance. At low speeds, however, the resistance for given lift is about 10 per cent. less in type 3A than in an ordinary biplane. The burble point is flat from 12 deg. to 24 deg. This is the principal advantage

† This diagram appears on page 26.

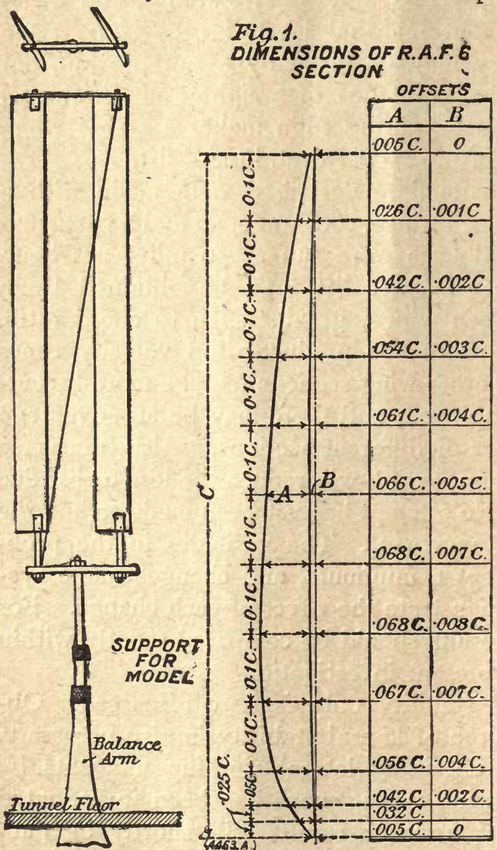
of this arrangement, and an aeroplane with such wings should be unlikely to stall, and a pilot should be able to land at a very low speed by using his wings as an air break.

The combinations of stagger and decalage described above give a degree of longitudinal stability, and a flat burble point without material loss of lift. The same degree of stability may be given by a suitable tail, but with attendant disadvantages of weight and resistance. Likewise, a reversed trailing edge makes a stable wing, but involves from 10 to 20 per cent. loss of lift.

The experiments here described were made with a constant gap between wings, constant span and a particular wing section. All tests were run at 30 miles per hour. It is obvious that greater lift may be obtained by a greater gap between wings, greater span to chord ratio, and a higher value of the product wind velocity times span. Likewise, other wing sections may be more favourable than that employed, and there may be an advantage in using two wings of different sections. Also transverse overhang of the upper wing will reduce the loss of lift due to interference. No attempt has yet been made to find the best all-round arrangement. The variables in the problem have been kept a minimum, and changes made systematically to demonstrate the effect of each change. For this reason, the results should be compared strictly within the limits of the present investigation.

Longitudinal stability only is here discussed. Obviously, some degree of lateral stability is also necessary. The problem of obtaining lateral righting moments by modifications in wing arrangement has been investigated at this laboratory, and the results will shortly be published. It was found that a dihedral angle upwards of 175 deg. for the wings is equivalent to sweeping back each half wing about 15 deg. from the transverse axis of the aeroplane. Each of these arrangements was found to have no material effect on the properties of the wing, and each was found to give powerful lateral rolling moments to resist rolling and side slip. It therefore appears possible to obtain without sacrifice a wing arrangement which shall be laterally and longitudinally stable. Indeed, there is good evidence that the designers of at least two foreign military aeroplanes have succeeded in obtaining inherent stability.

Stability in the sense used in this paper is static. In



the theory of small oscillations, the rate of change of righting moments is used instead of the actual values of those moments. However, the existence of such righting moments must first be assumed. If an aeroplane is not statically stable, or is not in stable equilibrium in steady flight, dynamic stability is impossible. But if it is statically stable, dynamic stability is not only possible, but very probable. The present investigation is preliminary to a dynamical study of flight. We are concerned with the provision of a restoring moment to resist the pitching of the machine. The damping of the pitching by a tail or other means is a separate problem, but fortunately presenting no difficulty.

2. *Model-Making and Mounting.*—Wing models of 18 in. span used in these tests were scraped from kiln-dried black walnut, finished to templet, smoothed and shellaced. The section contour, R.A.F. 6, is believed to be correct to one-hundredth of an inch. The wing-tips were fitted with an inserted brass piece to take the screws of the supporting device. The biplane wings were mounted vertically in the tunnel as shown in Fig. 1. Lift and drift were measured on the two horizontal balance-arms, and pitching moment by a vertical torsion wire. The observed forces and moments were corrected for the effect of the supporting device determined by separate tests. The results reported therefore apply to bare wings without struts, wires, etc.

3. *Graphical Representation.*—Since the models were all held vertical, and rotated about a vertical axis only, the resultant force of the wind must lie in the horizontal plane of symmetry. The balance measured the lift or component force directed across the stream, the drift or component force directed along the stream, and the pitching moment about the vertical axis of the balance, for various angles of the wings to the wind. The axis of moments is taken arbitrarily, and since in practice one wishes to know the moments about any assumed location of centre of gravity of machine, the following method of representation of moments has been adopted:—

Let $D =$ observed drift, $L =$ observed lift, and $M =$ observed pitching moment about the balance axis. The resultant force $R = \sqrt{D^2 + L^2}$. The inclination of this force to the wind direction is $\theta = \tan^{-1}\frac{L}{D}$. The perpendicular distance of this resultant force from the axis of moments is given by $X = \frac{M}{R}$. We may then locate as a vector the resultant force R in position, magnitude and direction. The location of R for various attitudes of the model is shown by Figs. 2 to 9.

In order to avoid drawing a new model for each inclination to the wind, the model is drawn once and considered fixed in space while the wind direction is considered to change. The resultant forces R are then located with reference to the wings. The axis of moments is of no interest and is not shown.

It should be noted that R is no physical force, but is the result of an algebraic manipulation. It should be defined as that force which, if acting, would have produced the same lift, drift, and moment as were observed. R need not intersect the model. For example, at a certain angle there may be little, if any, force, but due to eddy motion there may be a couple acting which shows as a large pitching moment. To represent both the small force and the large moment, we must draw a small R acting at a great distance from the axis of moments used. Thus, on Fig. 2, at $-3\frac{1}{2}$ deg., the resultant force lies forward of the wings.

In an aeroplane, for simplicity, let us consider that the only forces acting are due to the wings. In order to fly at an incidence of 4 deg., for example, the centre of gravity must lie on the force vector for 4 deg. There is then no moment about this point, and the machine is in equilibrium. For equilibrium, the centre of gravity may lie anywhere along the line of action of R for 4 deg. The centre of gravity once located is fixed for the machine, and usually there will be only one position of equilibrium.

Consider the orthogonal biplane of Fig. 2, with a centre of gravity on the line R 4 deg. If this machine stall to 6, 8, 10, 14, or 18 deg., the resultant forces in each case lie forward of the centre of gravity, and give a moment tending to swing the machine to greater angles. Likewise, any dive started is increased. The wings are therefore longitudinally unstable for any given position of the centre of gravity. On the other hand, consider Fig. 6 in the same manner. If the machine stall or dive, a righting moment is at once produced to throw the machine back to its former equilibrium position. Here we have stable eqilibrium as distinguished from unstable equilibrium in Fig. 2.

Fig. 2.

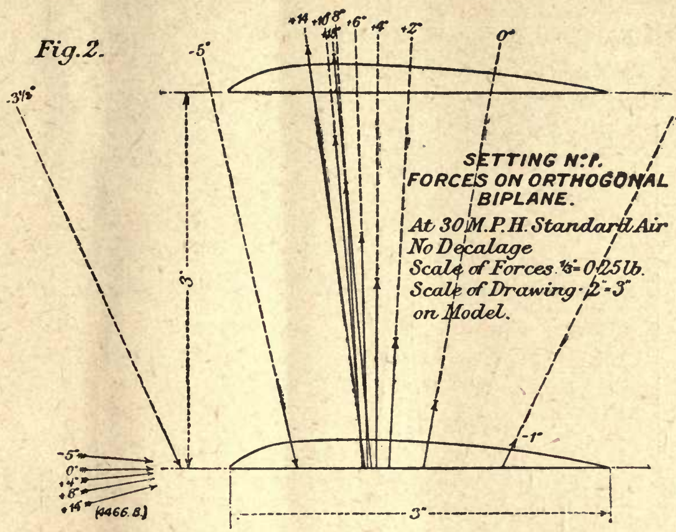

SETTING Nº 1.
FORCES ON ORTHOGONAL BIPLANE.
At 30 M.P.H. Standard Air
No Decalage
Scale of Forces ⅛" = 0·25 lb.
Scale of Drawing · 2" = 3" on Model.
3"
3"
(4466. B.)

Fig. 3.

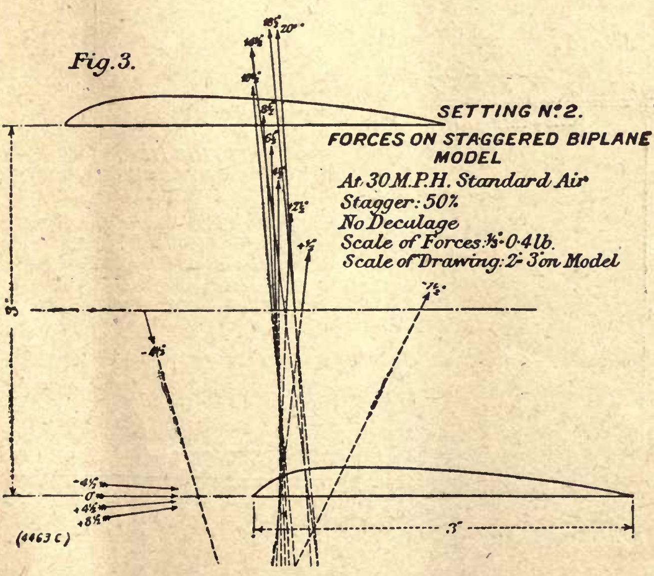
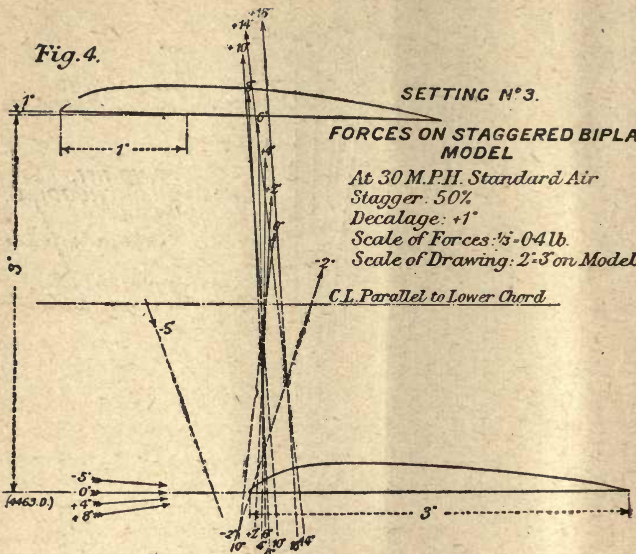

SETTING Nº 2.
FORCES ON STAGGERED BIPLANE MODEL
At 30 M.P.H. Standard Air
Stagger: 50%
No Decalage
Scale of Forces ⅛" = 0·4 lb.
Scale of Drawing: 2" = 3" on Model
3"
3"
(4463 C)

Fig. 4.

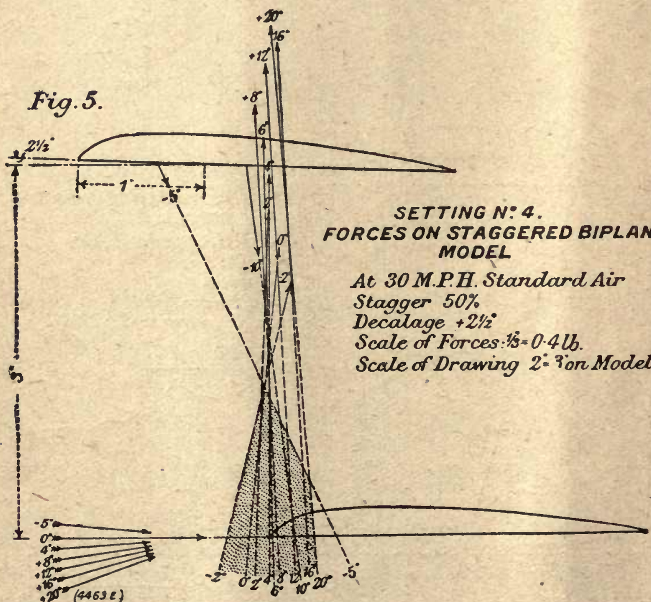


SETTING No. 3.

FORCES ON STAGGERED BIPLANE MODEL

At 30 M.P.H. Standard Air
Stagger. 50%
Decalage: +1°
Scale of Forces: ⅓" = 0·4 lb.
Scale of Drawing: 2" = 3" on Model

Fig. 5.



SETTING No. 4.

FORCES ON STAGGERED BIPLANE MODEL

At 30 M.P.H. Standard Air
Stagger 50%
Decalage +2½°
Scale of Forces: ⅓" = 0·4 lb.
Scale of Drawing 2" = 3" on Model

Fig. 6.

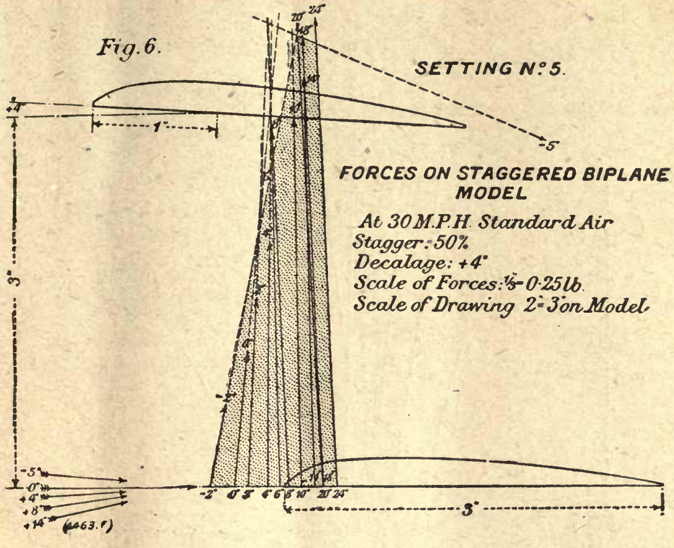

SETTING N°5.
FORCES ON STAGGERED BIPLANE MODEL
At 30 M.P.H. Standard Air
Stagger: 50%
Decalage: +4°
Scale of Forces: ⅕" = 0·25 lb.
Scale of Drawing 2" = 3" on Model
(4463.F)

Fig. 7.

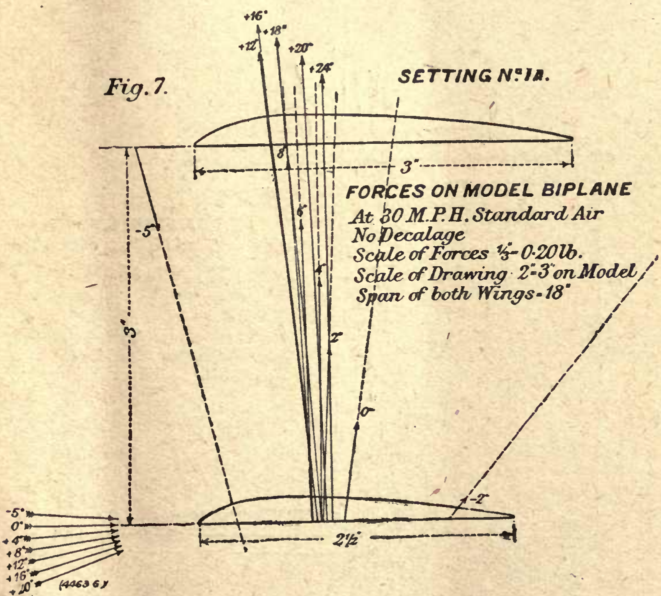

SETTING N°1A.
FORCES ON MODEL BIPLANE
At 30 M.P.H. Standard Air
No Decalage
Scale of Forces ⅓" = 0·20 lb.
Scale of Drawing 2" = 3" on Model
Span of both Wings = 18"
(4463 G)

Fig. 8.

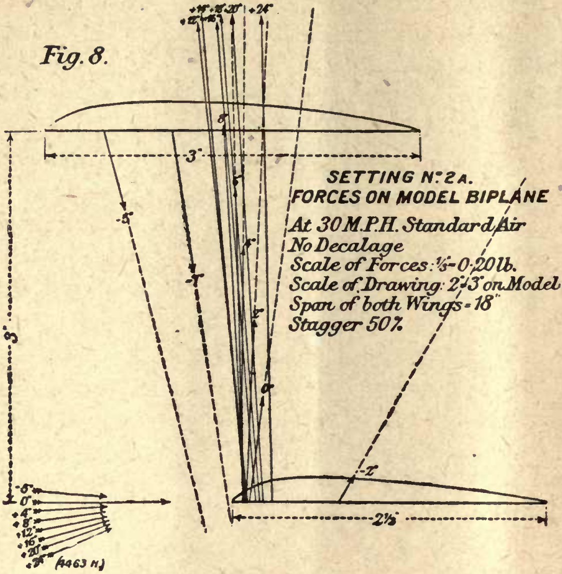
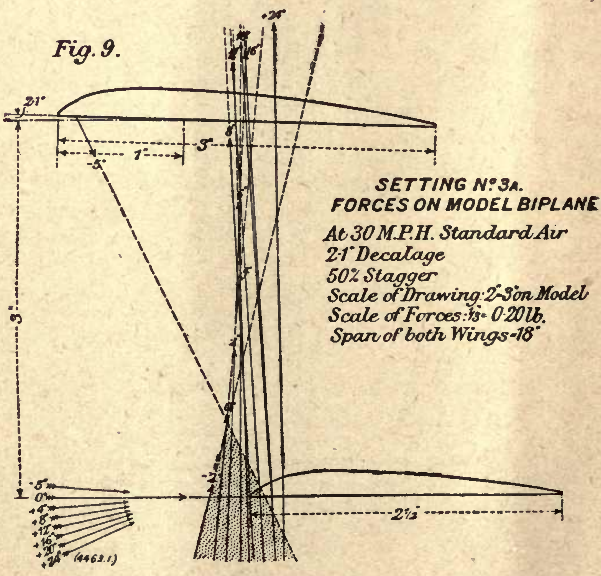

SETTING N° 2A.
FORCES ON MODEL BIPLANE
At 30 M.P.H. Standard Air
No Decalage
Scale of Forces: ⅕" = 0.20 lb.
Scale of Drawing: 2" = 3" on Model
Span of both Wings = 18"
Stagger 50%
3"
2½"
(4463 H.)

Fig. 9.


SETTING N° 3A.
FORCES ON MODEL BIPLANE
At 30 M.P.H. Standard Air
2·1° Decalage
50% Stagger
Scale of Drawing: 2" = 3" on Model
Scale of Forces: ⅕" = 0.20 lb.
Span of both Wings = 18"
2·1°
3"
1"
2½"
(4463.1)

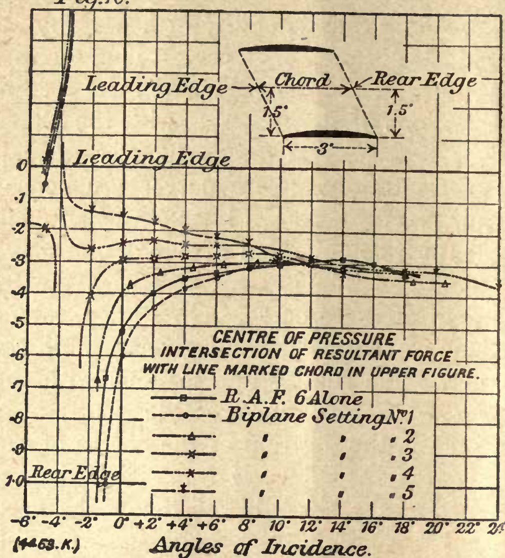
4. *Centre of Pressure.*—It has been customary to represent the longitudinal stability of a wing by means of a so-called centre-of-pressure curve. This curve is constructed by plotting the distances from the leading edge of the intersections of the forces R with the plane of the chord. Since R is no real force, there is no real centre of pressure. Centre-of-pressure curves are hence purely artificial, and, as will be shown later on, often misleading. For example, in a combination of wings one may choose any plane on which the intersections with the forces R give a centre-of-pressure curve. On Fig. 9, intersections with the plane of the lower wing give a stable centre-of-pressure curve, while similar intersections with the plane of the upper wing give an unstable centre-of-pressure curve. In reality, the location of the centre of gravity is the governing factor. Thus, if for Fig. 9 the centre of gravity be within the shaded area below the vectors for -2 deg. and $-5\frac{1}{2}$ deg., the aeroplane is stable. If without, it is unstable for a steep dive.

For purposes of comparison, the centre-of-pressure curves are drawn in the diagrams,* Figs. 10 and 11, by plotting the intersections with a plane midway between the wings and parallel to the chord of the lower wing. This plane is chosen arbitrarily, but is the same for all models.

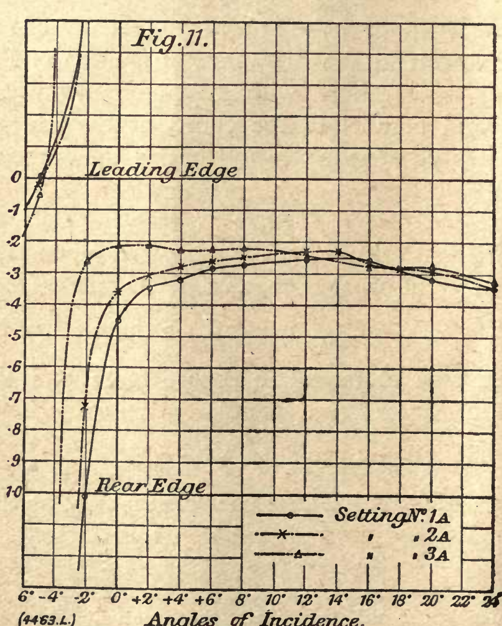
5. *Lift and Drift*; *Units*; *Density*; *Velocity*; *Precision.*—In Figs. 12 and 13, page 26, are plotted the lift coefficients for the various models. The lift coefficient is defined to be $K_x = \frac{L}{A\ V^2}$, where L is the observed lift in pounds; A, area of model in square feet; and V, wind velocity in miles per hour. Similarly, the drift coefficients are plotted in Figs. 14 and 15, where $K_x = \frac{D}{A\ V^2}$ in the same units as above. These coefficients vary as the density of the air, and are referred to air of density 0.07608 lb. per cub. ft.

* These diagrams will accompany the concluding portion of the book.

Fig. 10.



(4463.K.)



(4463.L.)

The ratio of lift to drift is a measure of the effectiveness of a wing. This quotient is sometimes called "efficiency." Curves are given for comparison in Figs. 16 and 17, on page 28. The wind speed was kept at 30 miles per hour for all tests.

Individual measurements of force, moment, angle, wind velocity, etc., are believed from previous calibration tests to be precise within 1 per cent. Calculated coefficients, vector co-ordinates, centres of pressure, etc., in which all measurements have been combined, should be precise within 3 per cent.

6. *Biplane Interference Losses.*—Monoplane *versus* Biplane No. 1. A single wing, 18-in. span, by 3-in. chord, with square wing-tips, was first tested for comparison with results obtained at the National Physical Laboratory, England, for a similar model made to the same wing section, R.A.F. 6.* The measurements are found to agree within the probable experimental errors. To determine the extent of losses due to biplane interference, an orthogonal biplane was next tested. It was made up of two wings identical with the above, chords parallel, and spaced with a gap between them equal to the chord. This biplane is designated as Biplane No. 1.

The resultant forces for the biplane are shown in Fig. 2, on page 10, and centre of pressure in Fig. 10. It appears from the latter that the centre-of-pressure motion, and hence the degree of longitudinal instability, is practically the same for the two cases. This is of interest in that it demonstrates the correctness of an assumption commonly made.

The lift curves of Fig. 12 show a pronounced loss in lift from the monoplane to the biplane (No. 1). The loss in maximum lift is about 10 per cent. The burble-point comes at 14 deg. for both, and the curves are of the same general character. The drift curves of Fig. 14 are not greatly different, the biplane drift being somewhat less at small angles. The biplane and monoplane are best com-

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* Technical Report of the Advisory Committee for Aeronautics, 1912-13, page 90.

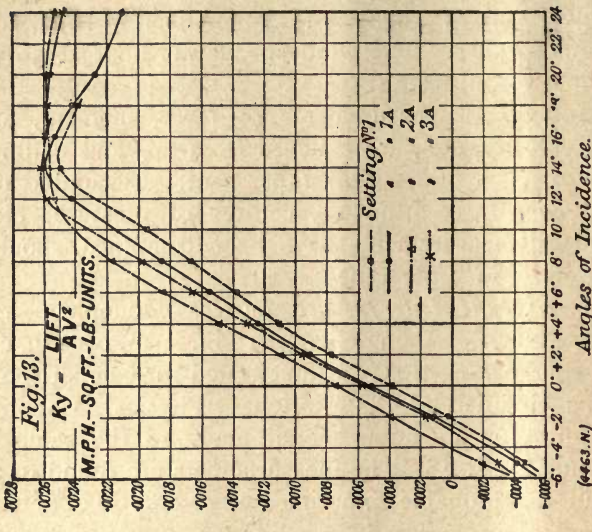
Fig. 13.
Ky = LIFT / AV²
M.P.H.-SQ.FT.-LB.-UNITS.
Setting Nº 1
" " 1A
" " 2A
" " 3A
Angles of Incidence.
(4463.N.)

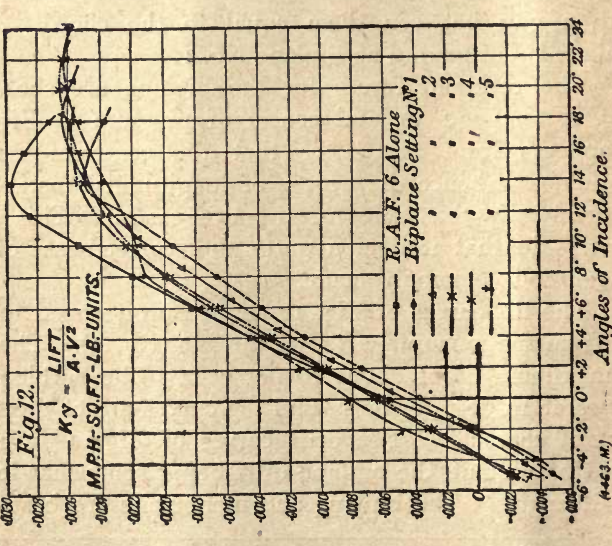
Fig. 12.
Ky = LIFT / A·V²
M.P.H.-SQ.FT.-LB.-UNITS.
R.A.F. 6 Alone
Biplane Setting Nº 1
" " " 2
" " " 3
" " " 4
" " " 5
Angles of Incidence.
(4463.M.)

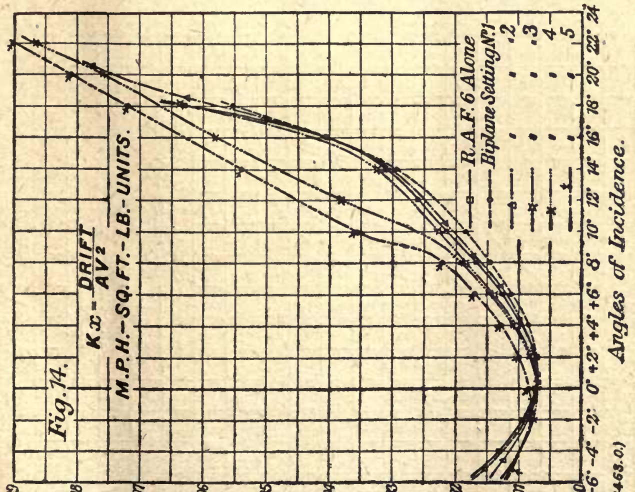
Fig. 14.
Kx = DRIFT / AV²
M.P.H.–SQ.FT.–LB.–UNITS.
·0009
·0008
·0007
·0006
·0005
·0004
·0003
·0002
·0001
0
−6° −4° −2° 0° +2° +4° +6° 8° 10° 12° 14° 16° 18° 20° 22° 24°
R.A.F. 6 Alone
Biplane Setting No. 1
" " 2
" " 3
" " 4
" " 5
Angles of Incidence.
(4463.0.)

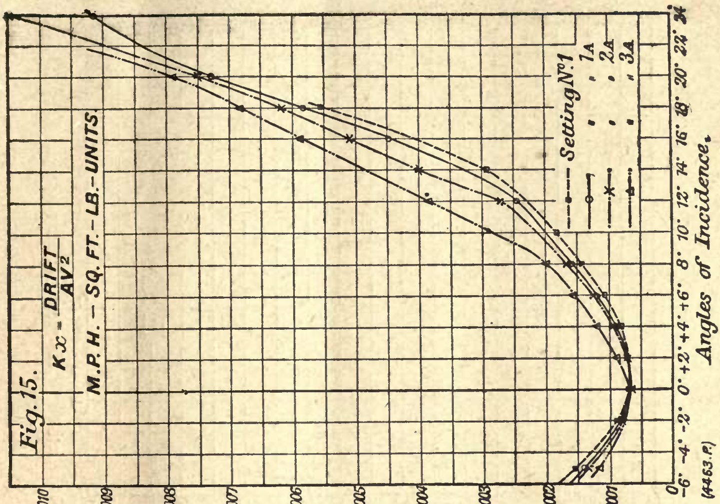
Fig. 15.
Kx = DRIFT / AV²
M.P.H. – SQ. FT. – LB. – UNITS
·0010
·0009
·0008
·0007
·0006
·0005
·0004
·0003
·0002
·0001
0
−6° −4° −2° 0° +2° +4° +6° 8° 10° 12° 14° 16° 18° 20° 22° 24°
Setting No. 1
" " 1A
" " 2A
" " 3A
Angles of Incidence.
(4463.P.)

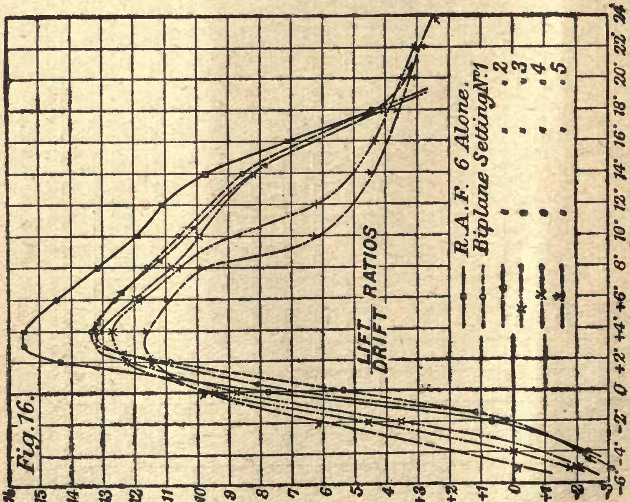
LIFT / DRIFT RATIOS
R.A.F. 6 Alone.
Biplane Setting No. 1
" " " 2
" " " 3
" " " 4
" " " 5
Angles of Incidence.
(4463.0)

Fig. 16.

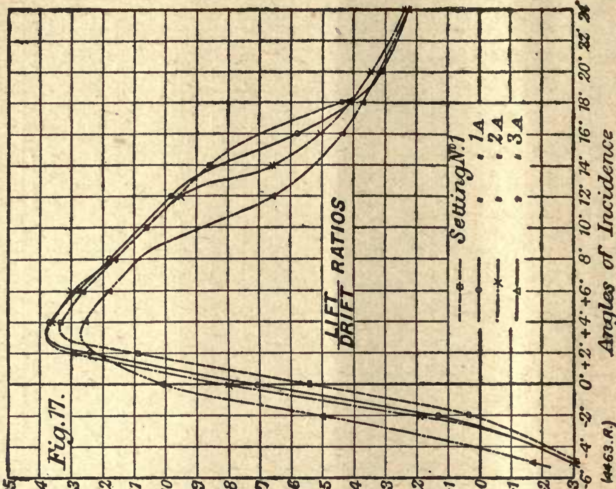
LIFT / DRIFT RATIOS
Setting No. 1
" " 1A
" " 2A
" " 3A
Angles of Incidence
(4463.R.)

Fig. 17.

pared on a basis of equal lift rather than on angle of incidence of chord to wind.

The general summary sheet, Fig. 18, on page 30, gives lift-drift ratio plotted on lift coefficient as abscissæ. Curves for the monoplane and biplane No. 1 show a slight difference for values of lift coefficient below 0.0007, indicating that for high speeds the biplane is better than the monoplane. However, at all other values corresponding to high lift coefficient and low aeroplane speed in practice, the biplane is considerably less effective.

Lift-drift ratio for the biplane is given in the annexed Table I. as a per cent. of the corresponding lift-drift ratio for the monoplane. For any point K_y is constant for monoplane and biplane, and a percentage decrease in lift-drift indicates the same percentage increase in K_x or drift, and *vice versâ*.

TABLE I.—*Lift-Drift Ratio for Biplane given as Percentage of Lift-Drift Ratio of Monoplane.*

K_y	$\frac{K_y}{K_x}$	K_x Biplane
0.0004	110	90
0.0006	107	93
0.0008	99	101
0.0012	85	115
0.0016	85	115
0.0020	75	125
0.0024	73	127

This table shows clearly the advantage of the biplane arrangement for a high-speed scout, such as the British "Tabloids." At a high aeroplane speed, and hence a low drift coefficient, the biplane resistance is 10 per cent. less than the monoplane resistance. This is an appreciable saving. For a machine which must fly slow, and consequently with a high lift coefficient, the biplane resistance is from 15 to 25 per cent. greater than the monoplane resistance.

7. *Stagger*, 50 *per Cent. Biplane No.* 2.—Biplane arrangement No. 2 is the same as the orthogonal biplane No. 1, except that the upper wing is placed ahead of the

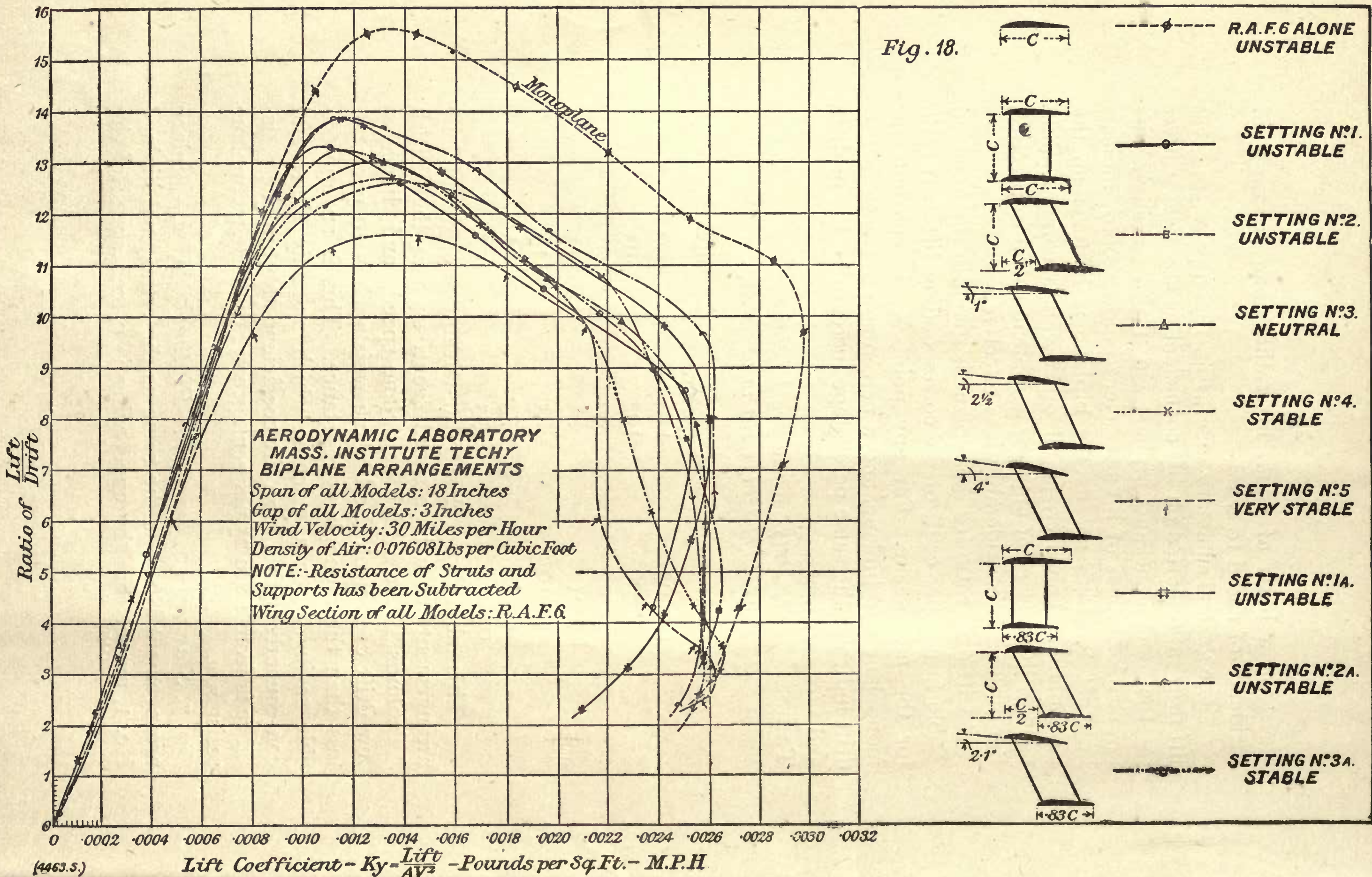

Fig. 18.
AERODYNAMIC LABORATORY
MASS. INSTITUTE TECHY
BIPLANE ARRANGEMENTS
Span of all Models: 18 Inches
Gap of all Models: 3 Inches
Wind Velocity: 30 Miles per Hour
Density of Air: 0·07608 Lbs per Cubic Foot
NOTE:- Resistance of Struts and
Supports has been Subtracted
Wing Section of all Models: R.A.F.6.
Monoplane
R.A.F.6 ALONE
UNSTABLE
SETTING Nº1.
UNSTABLE
SETTING Nº2.
UNSTABLE
SETTING Nº3.
NEUTRAL
SETTING Nº4.
STABLE
SETTING Nº5
VERY STABLE
SETTING Nº1A.
UNSTABLE
SETTING Nº2A.
UNSTABLE
SETTING Nº3A.
STABLE
C
C/2
1°
2½°
4°
2·1°
·83C
Ratio of Lift/Drift
Lift Coefficient - Ky = Lift/AV² - Pounds per Sq.Ft. - M.P.H
0
·0002
·0004
·0006
·0008
·0010
·0012
·0014
·0016
·0018
·0020
·0022
·0024
·0026
·0028
·0030
·0032
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

(4463.S.)

lower by an amount equal to 50 per cent. of the chord. This is defined to be a "stagger" forward of 50 per cent.

Fig. 3, on page 19, shows that the resultant forces from $2\frac{1}{2}$ deg. to $10\frac{1}{2}$ deg. intersect near a single point. If this point be the centre of gravity of an aeroplane, there will be no pitching moment throughout this range of angle. The machine will be neutral as regards its equilibrium. For the extreme range of flying angles from $1\frac{1}{2}$ deg. to $20\frac{1}{2}$ deg. the equilibrium is stable.

A pilot who flew such a machine undoubtedly would pronounce it stable, since he would be unlikely to risk a steep dive, bringing the incidence into negative angles. However, this wing arrangement, though excellent in other respects, is unstable for the range of angles $+\frac{1}{2}$ deg. to $-4\frac{1}{2}$ deg. A sudden dive tends to become steeper, or, as the French put it, to become *engagé*. It might be possible to prevent this in a design by use of a small tail surface.

The centre-of-pressure curve of Fig. 10 is more nearly flat than the orthogonal biplane No. 1, as would be expected. The lift curve of Fig. 12 shows a later burble-point and a maximum lift 6 per cent. higher than for the No. 1. The drift and lift-drift curves are not much different from No. 1.

8. *Decalage* 1 *Deg. Biplane No* 3.—The test was repeated with the same arrangement, except that the upper wing was tilted up so that its chord made an angle of 1 deg. with the chord of the lower wing. This is a divergence or plus "decalage" of 1 deg. This new arrangement, No. 3, is shown by Fig. 4, on page 20, to have improved the stability of No. 2. The force vectors for angles from 0 deg. to 10 deg. intersect near a point. If the centre of gravity be at this point, the equilibrium is neutral from 0 deg. to 10 deg., stable from 10 deg. to 18 deg., and unstable from 0 deg. to -5 deg. However, if the centre of gravity be placed low, at about the intersection of the vector for 4 deg., and the lower chord, the equilibrium is stable for all the range from -2 deg. to $+18$ deg. The unstable region is for angles well below -2 deg.

The centre-of-pressure curve, Fig. 10, is flat for all angles above 0 deg. The maximum lift is about 3 per cent. greater than for biplane No. 1. The lift curve in the neighbourhood of the burble-point is also somewhat more flat. The maximum lift-drift ratio is about the same as for biplane No. 1.

9. *Decalage*, 2½ *deg.*; *Stagger*, 50 *per Cent.—Biplane No.* 4.—The effect of decalage on longitudinal stability was investigated further by giving the previous arrangement a decalage of 2½ deg.

The result appears to be a happy one. The vectors of Fig. 5, on page 20, show that for a centre of gravity located anywhere in the lower triangle, bounded by the vectors for + 2 deg. and − 5 deg., the equilibrium is stable longitudinally throughout the entire range of pitching angles, − 5 deg. to + 20 deg.

Fig. 10 shows that, whereas the centre-of-pressure curve turns to the rear for small negative angles on the monoplane, biplane No. 1, biplane No. 2, and biplane No. 3, the contrary holds for the present arrangement. Thus, for negative angles below − 3 deg., the centre-of-pressure curve turns forward.

The degree of stability given by biplane No. 4 is greater the lower the centre of gravity, on account of the diverging nature of the resultant force vectors. Compared with biplane No. 1, there is a gain of 3 per cent. in maximum lift, with a loss of 5 per cent. in maximum lift-drift ratio. At the small values of lift coefficient corresponding to high aeroplane speeds, biplanes Nos. 1 and 4 give the same resistance (see Fig. 18, above).

In conclusion, then, biplane No. 4 is completely stable, and at the same time practically equivalent to orthogonal biplane No. 1.

10. *Decalage*, 4 *deg.*; *Stagger*, 50 *per Cent. Biplane No.* 5.—In case it be desired to build a very stable machine for amateurs, or for training beginners in aviation, the decalage may be increased to 4 deg.—biplane No. 5. The force vectors of Fig. 6, page 21, show complete stability for any centre-of-gravity location. Like-

wise, the centre-of-pressure curve of Fig. 10 shows a stable motion.

This degree of stability is considered to be excessive, but the circumstances which would justify its use probably would not concern great speed or minimum wing area. The maximum lift is not different from that of the other biplanes. The maximum lift/drift ratio is 13 per cent. less than for biplane No. 1. The lift curve near the burble-point is not sharp, and hence this very stable arrangement could not easily be stalled by an inexperienced pilot. For a school machine this is especially important. A peculiar point (of theoretical interest only) is that the lift curve (Fig. 13) has two burble-points, probably due to the fact that the decalage of the upper wing brings that wing up to its angle of maximum lift before the lift of the lower wing reaches its maximum.

11. *Lower Chord*, 83 *per Cent. of Upper. Biplane* 1A.—It has been shown by M. Eiffel* that the loss of lift of an orthogonal biplane is due in large part to the lower wing. The eddy formed on top of the lower wing is interfered with by the upper wing. The result is that the lower wing lifts much less than the upper. It would seem logical then to expect that if we cut down the area of the lower wing we should reduce this loss.

A model was constructed having a lower wing chord 83 per cent. of the upper wing chord. As an orthogonal biplane, represented as biplane No 1A. in Fig. 7, on page 21, the resultant force vectors indicate longitudinal instability of the same nature as that of biplane No. 1. The centre-of-pressure curve, as given in Fig. 10, is of the same general character as that for biplane No. 1.

The maximum lift, Fig. 13, is 4 per cent. higher, the maximum lift-drift, Fig. 17, about 4½ per cent. higher than for the biplane No. 1. For high speeds when a low lift coefficient is used, biplanes No. 1 and No. 1A are equivalent. For low speeds or high angles of incidence,

* "Nouvelles Experiences sur la Resistance de l'Air," G. Eiffel. Dunod et Pinat; Paris, 1914.

implying a high lift coefficient, the drift of No. 1A is more than 8 per cent. less than for No. 1 (see Fig. 18).

12. *Lower Chord*, 83 *per Cent.*; *Stagger*, 50 *per Cent. Biplane* 2A.—The test was repeated with the same model having the upper wing staggered forward by 50 per cent. of its own chord. No marked change in the properties of the biplane No. 1A are to be noted, except a very pronounced flattening of the lift curve near the burble-point (see Fig. 13). This is a considerable advantage. The flat range is from 12 deg. to 24 deg. A machine with such wings would not easily stall if the pilot were thrown up to an angle greater than the angle of maximum lift.

13. *Lower Chord*, 83 *per Cent.*; *Stagger*, 50 *per Cent. Decalage*, 2.1 *deg. Biplane* 3A.—Reference to Fig. 9, on page 22, shows that the force vectors for this biplane give longitudinal stability for any centre of gravity located within the lower triangle formed by the vectors for −2 deg. and −5 deg. This will be the case for a heavy seaplane. A high centre of gravity will show instability for negative angles of incidence. The centre-of-pressure curve (Fig. 11) is misleading, as was pointed out above, since it is given by intersections with a plane midway between the wings. The centre of gravity must be lower than this to give stability. The lift curve of Fig. 13 shows a maximum lift equal to that of biplanes Nos. 1A and 2A, and a burble-point even more flat than biplane No. 2A. The flat lift curve near the burble-point is the principal merit of biplane No. 3A. The maximum lift of No. 3A is about the same as that of No. 3, a similar arrangement with equal wing chords top and bottom. For low values of lift coefficient No. 3A is not quite so good as No. 3; for high values of lift coefficient No. 3A is slightly superior.

The biplane No. 3A appears to unite a fair degree of longitudinal stability with a very flat burble-point. The other properties of the wing are not greatly altered.

14. *Reverse Curvature.*—A wing whose section shows a reverse curve near the trailing edge is well known to be longitudinally stable. Tests at the National Physical Laboratory, England, give the properties of the R.A.F. 6

TABLE II.—CHIEF PARTICULARS OF MODELS TESTED.

Designation.	Monoplane	Biplane No. 1.	Biplane No. 2.	Biplane No. 3.	Biplane No. 4.	Biplane No. 5.	Biplane No. 1A.	Biplane No. 2A.	Biplane No. 3A.	Reverse Curve Wings.
Gap	—	C	C	C	C	C	C	C	C	C
Stagger	—	0	0·50 C	0·50 C	0·50 C	0·50 C	0	0·50 C	0·50 C	0
Upper Chord	C	C	C	C	C	C	C	C	C	C
Lower Chord	C	C	C	C	C	C	0·83 C	0·83 C	0·83 C	C
Decalage ... ... deg.	—	0·0	0·0	1·0	2·5	4·0	0·0	0·0	2·1	0·0
Max. $\frac{k_y}{k_x}$	1·15	1·00	1·00	0·95	0·95	0·87	1·04	1·04	0·96	0·86
Max. k_y	1·16	1·00	1.06	1·03	1·03	1·04	1·04	1·04	1·03	0·83
$\frac{k_y}{k_x}$ where $k_y = 0{\cdot}0005$	0·90	1·00	1·00	1·00	1·00	0·90	0·09	1·03	0·96	1·21
$\frac{k_y}{k_x}$ where $k_y = 0{\cdot}0018$	1·24	1·00	1·02	1·01	1·02	0·99	1·05	1·08	1·05	0·88
Range of flat burble-point in degs.	2	2	2	6	4	4	4	12	12	2
Remarks	U	U	U	N	S	S	U	U	S	S

S = stable. N = neutral. U = unstable. C = chord length (upper).

so modified in comparison with the original section. These test results apply only to a monoplane. The biplane effect found by us from tests on biplane No. 1 and monoplane R.A.F. 6 was applied as a percentage to the published results on the modified R.A.F. 6.

It appears that for the reversed-curve wings the maximum lift is 17 per cent. less, and the maximum lift/drift ratio 14 per cent. less, than for our biplane No. 1. This is a serious price to pay for stability. However, for very low values of lift coefficient the reversed-curve biplane offers over 20 per cent. less resistance. For a racing machine, when a high landing speed may be tolerated, this type of wing might be employed with advantage. For general purposes, the loss of maximum lift is too serious to be outweighed by its low drift at great speeds.

15. *Conclusions.*—The relative merits of the various wing combinations are brought out in the subjoined Table II. Coefficients are there expressed in terms of the coefficients for the orthogonal biplane (No. 1) taken as unity. It is to be noted that the stability of biplane No. 4 is gained at the expense of but 4 per cent. of maximum lift-drift ratio, while a gain is obtained in all other properties.

Biplane No. 3A is stable, and likewise loses but 4 per cent. on maximum lift/drift ratio. This arrangement, moreover, has a lift curve which remains at its maximum over a range of 12 deg.

If longitudinal stability be assured by a tail, biplane No. 2A is the most effective arrangement. It is superior by from 4 to 8 per cent. in all aerodynamic properties to biplane No. 1. Furthermore, it has a lift curve which remains flat for a range of 12 deg. over the burble-point, while this range is but 2 deg. for biplane No. 1.

It is believed that the present investigation should permit a designer by interpolation to form an estimate of the characteristics of other combinations than those here tested, at least with sufficient precision to satisfy him that no fantastic results are to be expected, and that, as in all engineering work, his problem is a compromise. Excellence in one characteristic is likely to involve some sacrifice in others.