859

NAVY DEPARTMENT

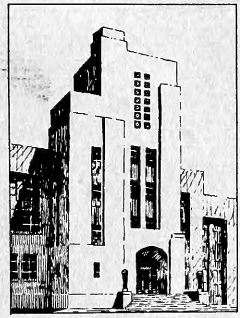
THE DAVID W. TAYLOR MODEL BASIN

WASHINGTON 7, D.C.

AN ELECTRONIC WAVE-HEIGHT MEASURING APPARATUS

by

W.S. Campbell



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Report 859

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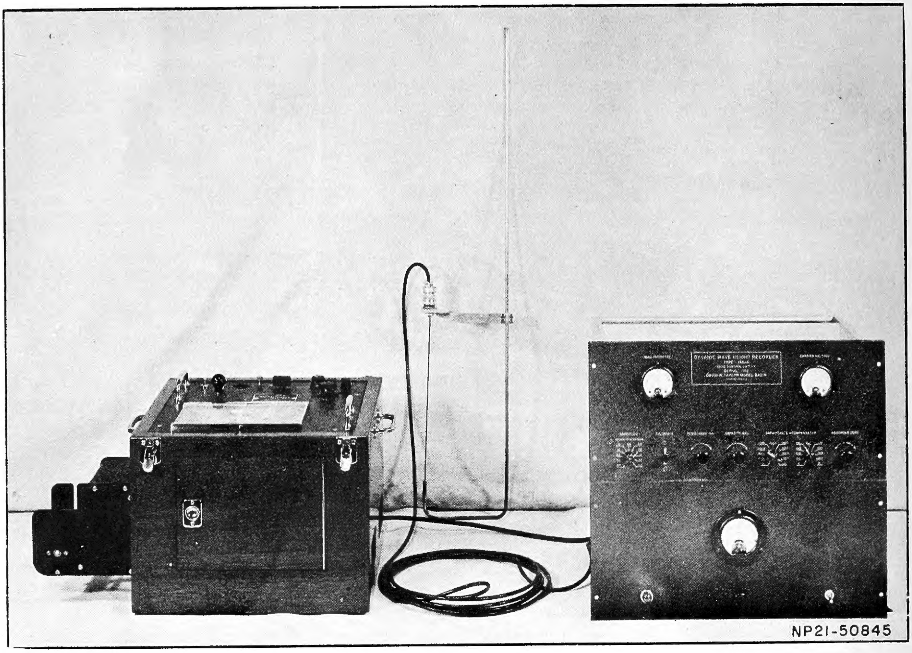

Wave-Height Measuring Apparatus

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ERRATA SHEET

for

DAVID TAYLOR MODEL BASIN REPORT 859

In Figure 4, page 7, the three transformers shown in the carrier amplifier portion of the schematic diagram are identical. Cores should be shown in all three. They are manufactured by the Audio Development Company as their type A-5311.

NOTE: See Figure 4, page 7. In later models of the instrument all the calibrating capacitors shown as 17, 36, 64 .... 114 uufd, were not included. Only one, the 106 uufd capacitor was permanently connected to the calibrating switch, thereby providing an easy means of checking the operation of the instrument. Calibration is accomplished by actually moving the transducer up and then down in the water. The extra switch section which was required for the calibrating capacitors is not used.

In Figure 5, page 8, the rectifier tube is erroneously shown as a type 6AS7; actually, two type 5U4 tubes, each with their plates connected in parallel, are used.

In Figure 5, both output tubes in the amplifier circuit are type 6V6, although only one is so indicated.

ABSTRACT

This report describes briefly the salient features of new instrumentation for measuring and recording the wave amplitudes and wave forms of water waves. This instrumentation was developed by the Electronic Circuit Development Branch* of the Electronic Engineering Division of the David Taylor Model Basin, at the request of the Hydromechanics Laboratory. Because of the increased accuracy and flexibility afforded by the instrumentation described, it has replaced other techniques which were formerly used.

The gaging element of this system consists of extremely small insulated wire, suspended rigidly upright in the water. The conductor acts as one plate of a capacitor and the water in which the gaging element is partially submerged acts as the other; the insulation material on the wire forms the dielectric of the capacitor. The capacity of this "condenser" (measured between the conductor and water) is directly proportional to the linear length of the submerged portion of the wire. This capacitor is connected in one arm of a resonant-bridge circuit, which may be balanced for the quiescent level of the water. Variations in water height which occur as waves pass the gaging element produce capacitive unbalance of the a-c bridge in each sense, and the direction of unbalance is recovered by a more or less conventional phase sensitive demodulator circuit incorporated in the circuit of the wave-height recorder.

This report includes schematic wiring diagrams of the instrument, its power supply, and a direct-coupled amplifier suitable for driving the recording galvanometer in a Sanborn direct-writing recorder.

INTRODUCTION

For the accurate measurement of small amplitude water waves, it is, of course, desirable to use a gaging element whose presence will least affect the height or form of the wave; ideally, measurement of amplitude should be made at one very small point or along an imaginary vertical line, normal to the still surface of the water. One previously used technique for measuring wave height and profile at the David Taylor Model Basin was to photograph a grid alongside the basin wall. It was found that small imperfections along the wall or even the engraved grid lines created a considerable adverse effect on the shape of the wave. Moreover because of viscosity and surface tension effects in the proximity of the wall, it was found highly desirable to measure wave profile at some distance from the wall. A further disadvantage of the photographic method is the necessity for development of the film, which requires considerable time, and, at best, one obtains only the amplitude and profile of one particular

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*Now the Metric Systems Branch of the Instrumentation Division.

wave. In the adjustment of water-wave generators it is advantageous to be able to observe the effect of various adjustments on a direct-writing recorder which is producing a continuing record of each wave as it passes the measurement point. A still further disadvantage of the photographic method lies in the relative difficulty of moving the measurement point out near the center of the basin or to other points along the length of the basin at which measurements are required.

On 18 January 1952, the Electronics Engineering Division received a request from the Hydromechanics Laboratory to develop reliable instrumentation of this type which preferably should possess none of the disadvantages met in the application of photographic methods then in use. The following performance requirements were stated in lieu of specifications:

The instrumentation should be capable of measuring and recording amplitudes of water waves in the range of 0 to a maximum of 2 ft; the lengths of the waves to be recorded lie within the range of 2 ft to 30 ft, with corresponding periods of 0.564 to 2.43 sec; frequency response should be such as to show no more than ± 1 percent variation in amplitude from 0 to at least 2 cps. A maximum error of $\pm 1/4$ in. in 2 ft of wave height was to be allowable.

A study of various techniques employed at other laboratories engaged in work of the same general nature was made.[1,2] All systems investigated by the author were found unsatisfactory for this particular purpose because of their inability to satisfy the accuracy and frequency-response requirements or their dependence on the chemical composition of the water. Float systems usually fail to respond rapidly enough to "follow" rise and fall of extremely short waves due to the inertia of the float or the friction or mass of the pickup unit attached; moreover it is difficult to design a float which will approach, dimensionally, the requirement for measuring the wave height at a single point. Systems which depend on the variation of electrical resistance between two probes immersed in the water approach the dimensional requirement but suffer from their dependence on the mineral content of the water, corrosion, or oxidation of the probes and cleanliness of the water surface.

The capacitive-wire gage system described herein meets or exceeds all the requirements and avoids the difficulties stated in the preceding paragraph; further advantages which influenced the choice of this system over the many other types of systems in current use included the fact that there are no critical tolerances or spacing adjustments, it has excellent linearity characteristics, is easily cleaned or replaced, and is inexpensive.

MEASUREMENT SYSTEM

The measurement system described in this report is known at the Taylor Model Basin as the type 145-A Dynamic Wave-Height Recorder. For discussion, it may be divided into three major functional parts--the gaging element, the electronic circuitry, and the direct-writing recorder. (See the semi-pictorial sketch, Figure 1). The principle of operation may

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[1]References are listed on page 13.

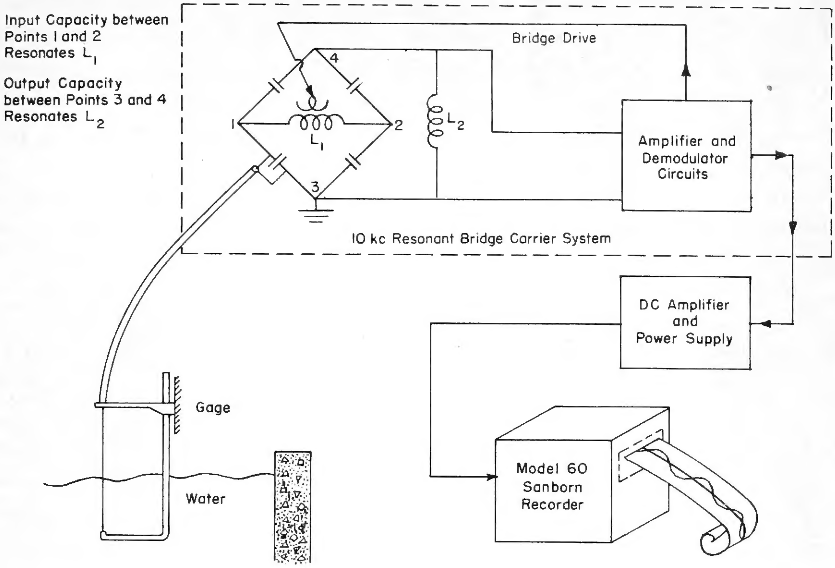

Figure 1 - Functional Block Diagram of Apparatus

be described briefly as follows:

The rise and fall of the water level in which the gaging element has been immersed produces very nearly linear changes of electrical capacitance as measured between the two terminals of the gage; the gage forms a small part of a larger fixed capacitor which is one arm of a resonant a-c bridge. These relatively small capacitance changes produce output voltages from the bridge which are proportional in amplitude and phase, to the degree and sense of the bridge unbalance. These voltages are amplified and demodulated in a linear phase sensitive detector which produces a d-c voltage proportional to the height of the water surface as measured from the water level at which the bridge was first balanced (usually the quiescent water level before waves were generated). This varying d-c voltage is then further amplified and furnishes the driving power required for the direct-writing recorder. Each of the three units so briefly referred to above are described in greater details in the following paragraphs.

GAGING ELEMENT

Probably the most interesting part of the system is the gaging element itself. It consists simply of a length of No. 28 enamel covered copper magnet wire stretched tightly between two support points, one below the water surface and the other located an equal distance above the surface on a vertical line running through the lower point. The distance between

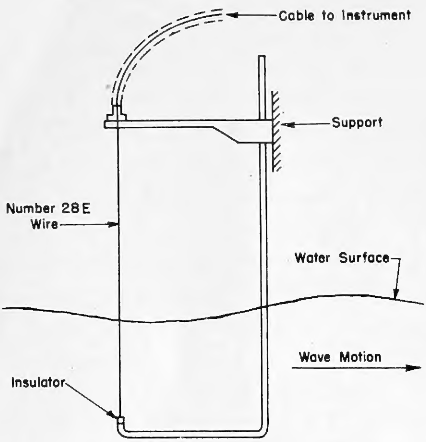

Figure 2 - Sketch of Gage and Support Bracket

these two support points may be about twice the expected double peak amplitude of the largest wave to be measured. This wire is completely insulated from any electrical contact with the water. One type of suitable gage support bracket is shown on the sketch, Figure 2. The J-shaped support bracket is fabricated from a length of 1/4-in. brass rod. The lower end of the gaging wire is fitted with an insulator coupling which plugs into a small bayonet-type socket, an integral part of the lower end of the bent brass rod. The upper end of the wire is fastened, electrically and mechanically, to a 2-pin cable connector mounted on the upper support member. The connecting cable (any reasonable length of high-quality, low-capacity cable such as Amphenol RG-62U) is fitted with a connector in such a manner that the "high" side contacts the conductor in the gage wire and the "low" shield side makes electrical contact with the water through the upper support arm and the J-shaped brass rod. A tensile pull of about 3 pounds has been found sufficient to maintain the wire taut and straight under all conditions encountered in tests so far conducted.

Electrically, the conductor of the gaging element and the water in which it is immersed form two plates of a coaxial capacitor. Measurements made with the General Radio precision capacitance bridge indicate that the capacity of this unique condenser varies linearly with the length of submerged portion of the gage wire. This is not surprising since the wire diameter is very closely controlled by the manufacturer and the thickness of the enamel insulation is very nearly uniform. The power factor of the gage in the water is exceptionally good especially if at least 4 in. of the wire are always wetted. No appreciable difficulty has been observed from meniscus or flowback effects, and static peak-to-peak calibrations obtained by physically moving the gage element up and down in the water hold equally well for dynamic conditions.

The choice of gaging wire size was made by use of experimental methods to determine the degree of error encountered under dynamic conditions; the use of very large wire, rod, or tubing, which might seem desirable from the support problem viewpoint, is precluded by surface tension and slow flowback effects when the water recedes. The No. 28 enameled copper wire appeared to be about the optimum since the capacity changes follow wave-height variations up to at least 4 cps with negligible phase error, and yet it can be put under sufficient tension to avoid bending by the advancing waves.

ELECTRONIC SYSTEM

The electronic apparatus is required to transform the changes in capacitance which appear in the gaging element into proportional current or voltage variations to drive the recorder. The equipment as designed provides a sensitivity range of 0.60 to 25.0 in. (trough to crest wave amplitude) for full-scale (30-mm) recorder deflection. A precision attenuator is built in which allows selection of 10 fixed sensitivity positions--0.60, 1.0, 1.5, 2.5, 4.0, 6.0, 10, 15, 25, and 40-in. peak-to-peak amplitude for full-scale recorder deflection. Calibration is accomplished by switching the calibrating condensors which are chosen by the setting of the attenuator first to one side of the bridge and then to the other. This simulates equal incremental variations in water level about the zero reference point, i.e., the water level at which the bridge was initially balanced by the operator.

The circuits employed are a modification and adaptation of those employed in the resonant-bridge carrier system which has been used for some time for the measurement of extremely small changes in capacitance.[3] The system consists of a doubly resonant capacitance bridge which is driven by the output of a 10-kc oscillator-amplifier circuit, an attenuator, a 2-stage voltage amplifier and a dual demodulator, the output of which is a d-c voltage whose magnitude and polarity are proportional to height of the water surface from any arbitrary zero point chosen by the operator (usually, but not necessarily, the quiescent water level in the absence of waves). A block diagram of the complete system is shown in Figure 3. The 10-kc oscillator-amplifier circuit (block 1) supplies the excitation to the resonant bridge (block 2) which incorporates provision for manually balancing out the resistive and reactive components

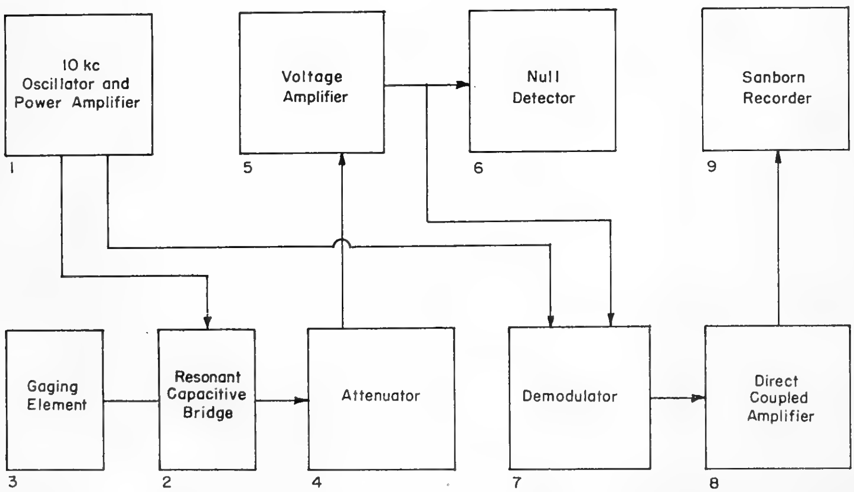

Figure 3 - Block Diagram of the Type 145-A Dynamic Wave-Height Recording System

of gaging-element impedance which is connected in parallel with one arm of the bridge. Drive voltage is applied to the bridge from a balanced source, which permits grounding (earthing) of one of the bridge terminals which is also connected through a cable (RG-62U) to the ground side of the gaging element, (see Figure 2). This is a necessary condition since the body of water in which the gaging element is to be submerged is used as the ground reference potential point for the entire system. Unbalance voltages arising at the opposite terminal of this bridge, which is initially manually balanced for still-water conditions, are applied to the attenuator (block 4) and thence to the voltage amplifier and demodulator circuits (blocks 5 and 7). The null indicator (block 6) is employed in order to ascertain when bridge balance has been achieved. The output of the demodulator circuit is a d-c voltage which varies from 0 to 2 volts in either polarity as a linear function of water height. The output impedance at this point is quite high and should not be loaded heavily in the interest of linearity. Since very little power can be drawn from this circuit, a direct-coupled power amplifier (block 8) is designed to match the particular recorder chosen (block 9). Any desired recorder could, of course, be used provided that a suitable power-amplifier circuit is substituted.

Copies of the final schematic wiring diagrams of the gage control unit and the power supply-amplifier unit are included as Figure 4 and Figure 5, respectively.

RECORDER

The instrument described in this report is designed particularly for use with the Sanborn* Model 60 direct-writing electromagnetic recorder. (This model is a two-channel unit, which is used in those measurements where waves are to be measured at two points simultaneously.) This recorder is equipped with heated stylii and records on heat-sensitive paper. Frequency response is uniform to about 40 cps, which is far more than adequate for this application. The galvanometers (pen motors) are rugged and reliable, and, except for some slight mechanical hysterisis which amounts to approximately 0.25 mm on the record, the recorder is quite satisfactory. With the amplifier shown in the schematic diagram, Figure 5, full-scale deflections of ± 2 cm from the center can be obtained with good linearity. One great advantage realized by use of this recorder is the rectilinear recording feature which facilitates analysis of recorded wave forms. A wide range of paper speeds is made available by changing gears in the chart drive mechanism; in addition a quick shift ratio of 10 to 1 may be accomplished by a small lever located on the control panel.

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*Manufactured by the Sanborn Company, Cambridge 39, Mass.

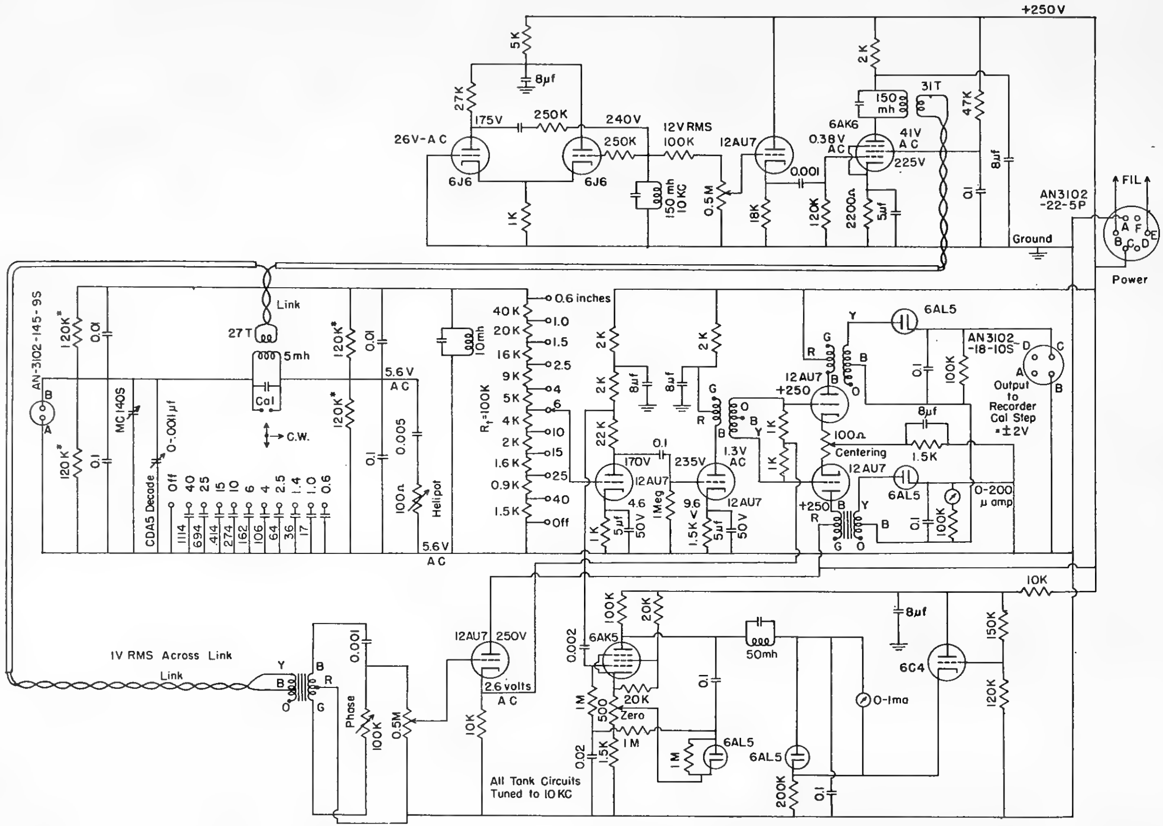


Figure 4 - Schematic Wiring Diagram of the Gage Control Unit of the Type 145-A Dynamic Wave-Height Recorder

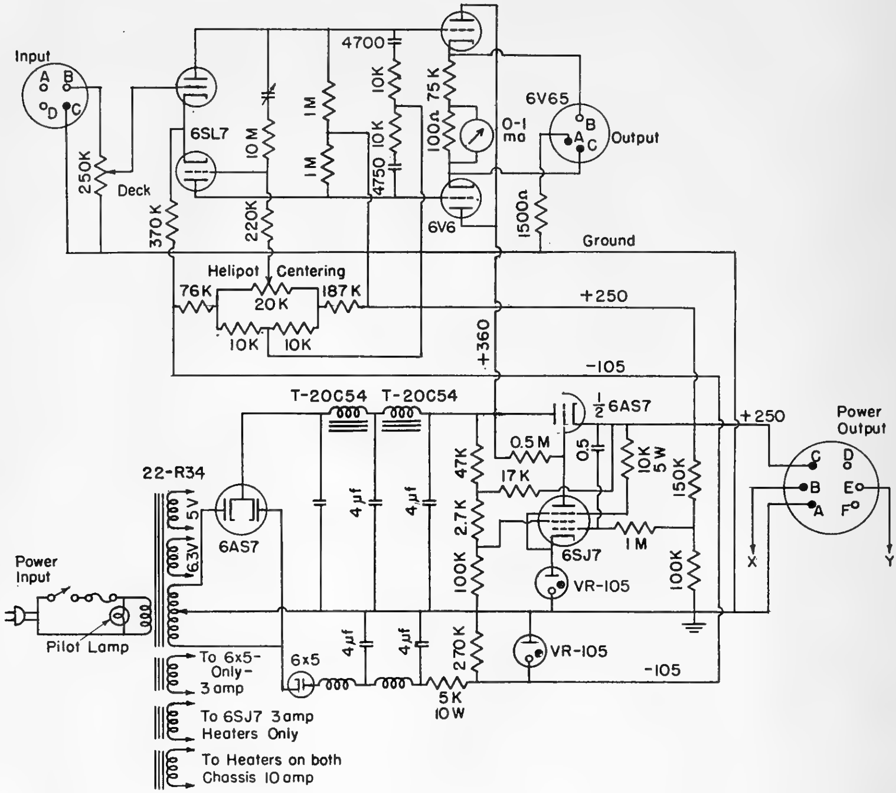


Figure 5 - Schematic Wiring Diagram of the Power Supply-Amplifier Unit
of the Type 145-A Dynamic Wave-Height Recorder

OPERATION

For operation the instrument may be powered from any source of 115-volt, 60-cycle, single-phase voltage capable of furnishing at least 300 watts of power. The gaging element should be mounted on a rigid support in such a manner that approximately half the length of the insulated wire is submerged. One such support designed for use at the Model Basin is equipped with a fine screw adjustment by which the gaging element can be raised or lowered in the water. This permits a simple and direct means of calibrating the entire system. After the instrument has been turned on for about five minutes or more and the gaging wire has been placed at the desired point, the operator may proceed to balance the bridge by means of the controls provided for this purpose. Bridge balance is obtained in the usual manner prescribed for balancing a-c bridges, utilizing the null indicator meter deflections as a guide. Maximum deflection of this meter obtainable by adjustment of the decade capacitor and resistance balance controls indicates that the bridge is balanced. If difficulty in arriving at balance is encountered with a high-sensitivity setting of the attenuator, this control may be rotated toward the 25-in. position until a position is reached where the null indicator meter responds to adjustment of the balance controls.

After the bridge has been balanced, the operator should select the attenuator position whose marking most nearly approximates the peak-to-peak amplitude of the expected waves to be recorded. At this time, calibration may be performed by raising and lowering the gage element through an accurately measured distance and recording the corresponding deflections of the recording pen.

PERFORMANCE

A complete wave-height recording system of the type described in this report was installed in the miniature model basin in late March 1952. After an initial period devoted to calibration, testing, and minor adjustments to suit the selected operating conditions, the performance characteristics were verified to be as follows:

1. Maximum usable sensitivity was 0.6 in. (double peak amplitude) of wave height which produced 3 cm deflection of the recording stylus; (the built-in sensitivity control provides attenuation in 10 fixed steps covering the range from 0.6 to 40 in. of wave height).

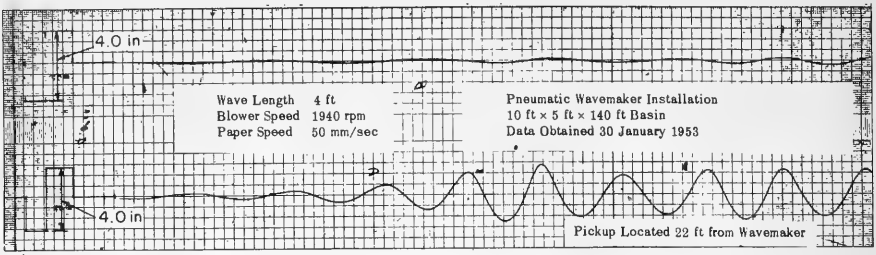
2. Linearity of the gaging element and the electronic system is approximately 1 percent of full scale on any sensitivity range selected. The recorder itself was found accurate to approximately 2 percent of full scale.

3. Resolution (on the record) on the most sensitive step of the sensitivity control is of the order of 0.010 in. of change in water level.

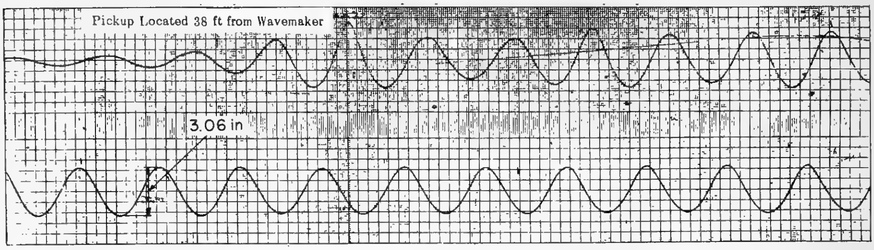
4. Frequency response of the system was measured by mounting the gage and its supporting bracket on a cam-driven vertical oscillator whose frequency of vibration was adjustable from 0 to about 5 cps. Response was found to be uniform up to the upper frequency limit of the mechanical oscillator. There is no reason to believe that the range of uniform response does not extend considerably above 5 cps, since no measurable amplitude distortion was evident at this frequency.

Figure 6 is a photographic copy of one continuous record taken in the 140-ft towing basin by personnel of the Hydromechanics Laboratory using the instrumentation system described. The upper trace on each strip shows the record obtained from a gage placed 38 ft from the wavemaker and the lower trace shows the record from another gage located 22 ft from the wavemaker.

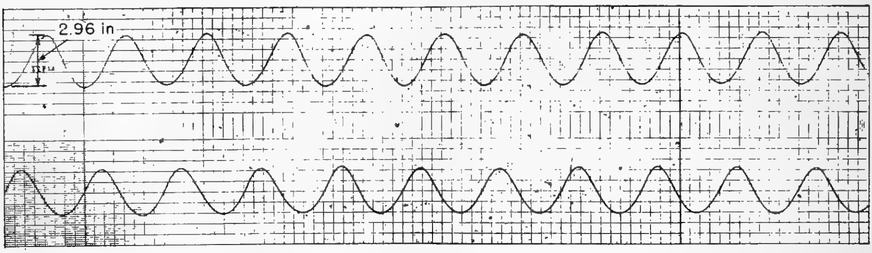
Early in October 1952, an exact duplicate of this system was constructed and placed in use along with the original pilot model. The performance characteristics of this system were found to be identical to the first one, and no adjustments or modifications were required.



(a) Lower trace shows build-up of wave at the 22-ft station.



(b) Upper trace shows build-up of wave at the 38-ft station.



(c) Steady-state conditions at both measurement stations.

Figure 6 - Record of Wave in the 140-ft Basin

Photographic copy of one continuous record taken in the 140-ft towing basin. The upper trace on each strip shows the record obtained from a gage placed 38 ft from the wavemaker; the lower trace shows the record obtained from another gage placed 22 ft from the wavemaker.

Since October 1952, both of these measurement systems have been in continual use on one or another of the various research programs currently being conducted at the Model Basin. It is felt that this instrumentation, although simple in principle and design, represents a forward step in the technique of recording small wave heights and wave forms.

PERSONNEL AND ACKNOWLEDGMENTS

The conception and design of the wave-height measuring system described herein was the work of the author. The pilot model of this instrument was constructed by other members of the Instrumentation Division who contributed many valuable suggestions and constructional "know-how." Messrs. Howard Reese and Paul Golovato of the Hydrodynamics Division performed calibration, linearity, and frequency response tests, the results of which are included as a part of the verified quantitative performance characteristic data in this report.

APPENDIX

A. GAGE FACTOR OF WIRE GAGE

The increment in capacitance ΔC produced by a change in water height Δh may be computed from the formula,

$$\frac{\Delta C}{\Delta h} = 0.555 \frac{k}{\ln \frac{r_2}{r_1}} \ \mu\mu\text{f per cm} \qquad [1]$$

where k is the specific inductive capacity of the dielectric (enamel),

ln is the natural logarithm,

r_2 is the outer radius of dielectric,

r_1 is radius of the conductor in the same units as r_2, and

h is the change in water height in cm.

The total capacitance presented by the gaging element is of secondary interest only, as this capacitance may be considered as a part of the fixed capacitor in the bridge arm in which the gage is connected.

Formula [1], although exact, should be used to obtain approximate values only, owing to the difficulty of accurately measuring the thickness of the insulation on the wire and determining the dielectric constant k of the insulating material. For example, computed values for ΔC ($\mu\mu$f per in.) of the No. 28 enameled wire used was 53.5 $\mu\mu$f per in., while the average experimental value obtained by direct measurement was 56.0 $\mu\mu$f per in. (This value was used as a basis for selecting the internal calibrating condensers.)

B. LINEARITY CONSIDERATIONS

The degree of linearity obtainable from a conventional four-arm bridge is a function of the ratio of the maximum change in impedance which will occur in the active bridge arm and the impedance of the same arm at balance.

The expression for the open circuit output voltage for a capacitive bridge with one active (variable) arm is

$$e_0 = \frac{e\alpha}{4} \cdot \frac{2}{2+\alpha} \text{ volts} \qquad [2]$$

where e is the bridge driving voltage and α is the ratio of the change in capacitance of the active arm to the capacitance of the arm at balance, i.e., $\frac{\Delta C}{C}$.

For example, in order to realize a linearity of one percent of full scale, the error factor $\frac{2}{2+\alpha}$ in Equation [2] must not be numerically less than 0.99. Or stated otherwise, the ratio $\frac{\Delta C}{C}$ must not exceed 0.02.

The range of the instrument described extends to 20 in. of water (single peak amplitude). The ratio $\frac{\Delta C}{C}$ for this largest amplitude is approximately 0.012 so that the bridge nonlinearity does not exceed 0.6 percent of full scale on this sensitivity setting and is considerably less for the measurement of smaller wave amplitudes.

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2. Chinn, A.J., "Progress Report on Wave Measurements at Apra Harbor, Guam," University of California Department of Engineering Report No. HE-152-2, 5 July 1949.

3. Cook, G.W., "A Resonant-Bridge Carrier System for the Measurement of Minute Changes in Capacitance," TMB Report 626, February 1951.

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2. Measuring instruments
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