HAMBURGISCHE SCHIFFBAU - VERSUCHSANSTALT

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WAVE PROBES FOR MODEL TANKS

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*Commonly referred to as a resistance probe

Author: H. Luft Hamburg, December, 1967

Translated May, 1968, by Lt. W. H. Roth, U.S.C.G.[1] and Dr. S. D. Sharma[2] for the Department of Naval Architecture and Marine Engineering, The University of Michigan, Ann Arbor

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1. The Purpose of the Probe

A probe to measure wave profiles in a towing tank will be described.

The anticipated dimensions of the waves are:

Mean height ± 5 cm., maximum ± 20 cm.
Slope of the wave flank up to a tangent of 0.4
Mean wave length of 2 m.
Basic frequency of about 1 cps., harmonics up to 10 cps.

The towing tank is filled with tap water; the capacity is about 30,000 m^3. The electrical conductivity of the water is quite good. A deliberate modification of the electrical properties of the water, say through the use of additives, is not permitted.

The hydrodynamic properties of ship models are investigated in the tank. The models are exact scale copies of the actual ship. The towing resistance of the model is measured in a resistance test. But also, the wave pattern generated by the model can be analyzed to yield some information on the resistance. The purpose of the probe, then, is to transduce into proportional electrical signals the time dependent wave height and slope generated at the location of the probe by a model passing at a fixed, known transverse distance from the probe. Such measurements may be used as a basis to calculate the optimum form of a bulbous bow.

If it is possible to measure wave height and slope simultaneously at one location with only one probe, then the two signals may be correlated with each other, the effort in conducting measurements is reduced, and mutual electrical interference is avoided.

2. Conductance Probe for Wave Slope

The water surface should be disturbed as little as possible by the probe. It is therefore necessary to use thin wire probes. In order to select an appropriate electrode material for the conductance probe, a few preliminary tests were conducted. The conductance of three wire pairs with three different current loadings was measured over a period of time. The results are shown in Figure 1.

After aging the electrodes for 20 hours with moderate A. C. loading, the high grade silver wires show useable results. The surface becomes coated with a white film of good conductivity. The further increase of current, or calibration factor change, is on the order of 1% per day, which is acceptable for measurements of this sort.

The basic construction of this type of probe is as follows: Three electrodes are suspended in the water in a row with equal lateral spacing of 20 mm. At the upper end, the wires are mechanically connected to, but electrically insulated from, a static calibrating device. Tension is maintained by means of weights suspended from insulators at the lower end of the wires with perlon* lines of 2 m. length. Exact lateral spacing of the electrodes is

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* German trade name for a plastic very similar to nylon

maintained above and below the surface of the water (Figure 2).

The electrodes, in conjunction with the water, comprise one part of a Wheatstone bridge. One leg of the bridge is between the middle and left wires and a second leg is between the middle and right wires.

The immersion depth of the probe is proportional to the conductance. Increasing the immersion depth corresponds to a greater water cross section and an accompanying greater electrical conductance. It is known that conductance and current are proportional. It is a question, therefore, of a current measurement. If one wishes to incur the least possible measuring errors, the internal resistance of the measuring instruments should be negligibly small compared with the total resistance of the measuring transducer circuit. The same is true also for the internal resistance of the source of current, if one is to determine an unknown resistance through current measurement.

The conductance of the probe is about 0.28 milli mhos/cm., which, at a mean immersion depth of 25 cm., corresponds to a resistance of 140 ohms. This essentially predetermines the dimensions (electrical) of the bridge circuit. The two fixed resistors in the upper legs of the bridge were chosen as 0.1% of 140 ohms. The internal resistance of the feeder oscillator is reduced to the same level by means of a transformer. Hence, the resulting total error can not exceed 0.2%, assuming reasonable wave heights are encountered. Furthermore, by means of this transformer, the oscillator input voltage is sufficiently reduced so that the previously required current loading of the electrodes is insured.

In order to set up an economical measuring apparatus, commercially available carrier frequency amplifiers are used for amplification of the measured signal. These instruments also contain the feeder oscillator and are ideally suited for this purpose. The instruments are operated as if used in conjunction with a strain gage bridge.

A transformer in the bridge circuit serves to adjust the resistance. It steps up the voltage of the measured signal, which is only a few microvolts at the transducer, by a factor of about 100. The unsymmetric amplifier input is balanced, and moreover, by means of the transformer, a neat zero potential separation is achieved (further clarified in Section 7).

3. Conductance Probe for Wave Height

It turns out that the probe for determination of wave slope can also be used for measuring wave height. The arithmetic mean value of the slope signal referred to the center electrode is zero, assuming that the value of the slope is constant over the span of the probe. Insertion of two equal resistances in the circuit allows us to determine the mean value. In addition, a compensating branch is necessary, with which the reference potential for the mean wave height (zero point) is set. Figure 4 shows the arrangement of the additional branches. Because of the differences in potential, and to attain resistance compatibility, transformation of voltage, and the balancing of the amplifier input, a transformer is again provided for the wave height circuitry.

4. Combined Probe for Slope and Height

Separate carrier frequency amplifiers are required for amplification of each of the transducer signals (slope and height). For feeding the combined bridge, however, only one oscillator is necessary. Each carrier frequency amplifier has a built-in oscillator, hence one of these can be switched off. In the present case, the oscillator for the slope was merely not connected. Hence the combination probe can also be used without difficulty for measuring wave height alone; usually there is no reason to measure slope alone.

The two carrier frequency amplifiers are connected to the probe as if two separate strain gage bridges were present. The two instruments are synchronized as usual. The balance is achieved at absolutely still water conditions by means of the amplitude and phase controls on the amplifiers. On the probe itself, balancing devices are provided for amplitude and phase. After initial adjustment, however, a change in these controls is not usually necessary. Condensers were connected in parallel with the transformer windings. By this means, excessive phase distortions were avoided which would otherwise cause premature overdriving amplifier. Figure 5 shows the complete bridge circuit.

5. Calibration of the Conductance Probe

The electrodes consist of 50 cm. lengths of high grade silver wire with a diameter of 0.4 mm. Above and below the surface of the water, there are plastic lateral spacer pieces which maintain the wire spacing at exactly 20 mm. The vertical distances from these spacer pieces to the water surface should be as small as possible, but not so small that these pieces are touched by either the wave crests or troughs, lest the water surface be disturbed. By this means (close vertical spacing), the bending of the wires due to hydrodynamic forces is minimized. Any changes in the spacing of the electrodes cause current changes and accompanying undesirable falsifications of the measurements.

Before initial immersion of the probe wires in the water, they should be carefully cleaned and not touched thereafter. The water surface should be as free as possible of contamination. During aging, the entire length of the probe is immersed and at the same time (for the duration of the aging), the carrier frequency amplifier is turned on. After about 20 hours, a surface film has accumulated. The current increases only very slightly thereafter.

The static calibration of the wave height is possible by raising and lowering the probe by means of the lead screw. This lead screw has a pitch of 1 cm., and in the handwheel there is a ratchet spring (pawl) which engages once each revolution. With this arrangement, excellent repeatability of calibration points may be achieved. The travel of the lead screw is 50 cm. At an amplifier setting of 500 μD*, an immersion change of 5 cm. produces full scale deflection. The zero point of the wave slope should not change appreciably while the height is being calibrated. Through careful mounting of the probe one can usually limit the variation to less than 3%. If the variation is too large, it is due to the geometry of the wires and the surface coating. Electrical cross coupling (interaction) between height and slope can be kept to less than 1% of the maximum value (of each individual measurement), which can easily be shown by connecting an ideal dummy probe consisting of known effective resistances.

The static calibration of slope is effected through immersion of one outer wire and simultaneous emersion of the other outer wire. As is shown in Figure 2 (schematic), a cable drive is provided for this purpose. With appropriate gearing, the dial can be

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*This is one of the range settings available on the Hottinger-Baldwin carrier frequency amplifiers which are primarily used for strain gauge transducers (D stands for "Dehnung", or "strain").

made to read directly in tangents (wave slope). It is advisable to calibrate the slope at mean immersion first, then again at the anticipated maximum and minimum wave height.

Typical calibration curves are reproduced in Figure 6 for wave height and Figure 7 for wave slope. In each case, the deflection of a light beam oscillograph (Visicorder) is plotted versus the stepwise incremented wave height and wave slope respectively.

From Figure 6, the excellent linearity of the height probe can be recognized. The two calibration curves were made on the same day without changing the probe setup, one before and one at the conclusion of the test. One can see that the sensitivity has increased by about 1.5% in ten hours.

Figure 7 shows that the slope probe also has a linear response. The calibration curves obtained at three different immersion depths allow a quantitative statement as to the influence of a height change upon the slope response, and one sees a zero drift of about +0.003 and an increase of sensitivity of 0.08% per cm. emersion. On the other hand, there is no influence of a change of slope upon the height response.

The static calibration just described says nothing about the dynamic behavior of the probe. One needs special investigations in order to find out if the probe produces an accurate and lag free display of response during practical application; i.e., when the transducer signals are varying rapidly with respect to time, and in spite of the disturbances due to hydrodynamic forces. The usual type of dynamic calibration - say, like that used by Pearlman (1963) - by predetermined up and down motion, was out of the question with the present configuration. It was equally impractical to move the water surface in the tank in a precisely controlled way. It was nevertheless possible to obtain by comparison between different probes, a reliable indication as to their dynamic behavior.

First, the new height probe was compared with an existing sonic probe (similar in principle to an airborne echo sounder). The latter is distinguished by the fact that it measures without mechanical contact with the water surface; therefore, it is not disturbed by hydrodynamic forces. The generated wave system of a ship model in uniform motion (in each case) at a constant speed was used for comparison. After the decay of an initial acceleration phase, a steady wave system forms, which can be represented in a coordinate system moving with the model by an equation of form: $z = \zeta(x,y)$; where ζ is an arbitrary function and $0xyz$ is a right handed Cartesian coordinate system with x in the direction of motion and z pointing upwards. In a stationary coordinate system, however, the same wave pattern appears to be time dependent and may be represented by $z = \zeta(x - Vt, y)$; where V is the model speed and t denotes the time. By virtue of the transformation $x = -Vt$, it is therefore possible to interpret the wave profile measured as a function of time by a stationary wave probe, as an x-dependent longitudinal cut through the wave system of the model. Similarly, it is possible to compare, directly with each other, the records of several probes mounted at different locations in the tank (all in a row with the same transverse position, y), with due consideration to their longitudinal spacing. Such comparisons were carried out between the new height probe and the sonic probe on several wave systems and yielded a mean discrepancy of less than 2%. A similar independent check on the slope probe was not possibl due to lack of a corresponding instrument. By the following method however, the height probe could be employed for checking the slope response. In its normal operating position, the slope probe is oriented in the transverse direction and displays the quantity: ζ_y ($= \partial\zeta/\partial y$). Hence, the combined probe records a "wave strip" (ζ,ζ_y) and not just the wave profile ζ. For the purpose of this correlation, the slope probe was turned 90° onto a longitudinal heading and the quantities ζ and ζ_x were recorded as a function of time. On the other hand, by virtue of the previously described property of the ships' wave systems, the quantity ζ_x can also be constructed by differentiating the function ζ with respect to x. Hence, a mutual comparison of the two probes (height and slope components of the combined probe) is possible.

Figure 8 shows a portion of such a record for a model speed $V = 161.6$ cm./sec. From this record, height ζ and slope ζ_x were read off for 200 points at increments of $\Delta t = 0.04$ sec. (corresponding to $\Delta x = 6.46$ cm.). From the digitized ζ-values, $\zeta_x^{(2)}$ was constructed, by numerical differentiation using a nine point interpolation formula, and compared with the direct record of slope $\zeta_x^{(1)}$ (Figure 9). It turned out that the indicated slope $\zeta_x^{(1)}$ was in fact proportional but not equal to the true slope $\zeta_x^{(2)}$. (The mean scatter of about ± 0.004 can be explained by local disturbance of the wave system.) The proportionality factor appears to be a constant for a given setup of the probe. In particular, it is independent of the form of the measured wave profiles. It is however rather sensitive to changes in the probe; on different test days, correlation by the above method yielded values between 0.8 and 1.6. The precise cause for this discrepency between the static and dynamic response of the slope probe could not be determined so far. It is however certain that by reducing the separation between the spacer pieces (see Figure 2) to less than 15 cm., this proportionality factor between $\zeta_x^{(1)}$ and $\zeta_x^{(2)}$ becomes practically 1. It seems likely that the discrepency is caused by hydrodynamic forces changing the wire spacing in a dynamic situation.

6. Capacitance Probe

A capacitance probe was also built following the pattern of the conductance probe. The following assemblies are exactly the same as for the conductance probe: static calibration device, length of the probe wire, mounting of the probe wires, and carrier frequency amplifier. Deviating from the conductance probe are: material of the probe wires and the bridge circuit.

The two outer probe wires are insulated against the water. The core of the wires serves as one electrode; the water as the other electrode. It is important that the dielectric does not absorb water so that the displacement current, or the calibration factor, remains constant. Various types of wires were tested: Teflon insulated wires of various types and polystyrol insulated wire. The measured capacitance values with respect to water are plotted as a function of time in Figure 11. Polystyrol* is the best dielectric for this application out of those tested. The immersed ends may be sealed (watertight) with a synthetic sealant. The wire, with an external diameter of 1.2 mm., has a capacitance of 103 pf/m. ($\mu \mu$ f/m). The center probe wire is not insulated and forms the connection between the bridge circuit and the water.

The basic construction of the bridge circuit corresponds to the circuit of the combined conductance probe. Instead of the

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* German trade name for a san type polystyrene compound manufactured by Badische Anilin-und-Soda-Fabrik AG, U.S. office, Paramus, New Jersey

fixed resistors in the upper part of the bridge, capacitors are used here; likewise in the mean value branch as well as in the compensating branch. The transformers serve for matching the oscillator output and the amplifier input to the bridge circuit. By this means, the amplifier inputs are balanced and the zero potentials are isolated from each other.

An additional R-C-element (4.7 k ohm and 5 nf) corrects the phase shift of the capacitance bridge. The complete circuit is shown in Figure 12.

Because of the small capacitance of the polystyrol insulated wire, it is necessary to have short connecting leads to the bridge circuit. The circuit is enclosed in a brass housing, behind the pulleys, in the immediate vicinity of the probe wires.

By means of a capacitive dummy probe it can be shown that the bridge circuit with two carrier frequency amplifiers yields flawless measurements. The response of the height and slope is linear and mutual interaction is negligible (<1%). The construction of such a dummy probe, with such small capacitance, for a standard of reference, is not easy. However, this problem could be solved with sufficient accuracy by indirect means; namely by detuning a calculated auxiliary oscillating circuit using a frequency meter.

The sensitivity of the probe is: an immersion change of 5 cm., which corresponds to a capacitance change of 5 pf, produces full scale deflection at an amplifier setting of 500 μD.

A slope with a tangent of 0.4 gives full scale deflection at an amplifier setting of 200 μD. This may be simulated, at the selected wire spacing of 2 cm., by raising one probe wire 0.8 cm. (+ 0.8 pf) and lowering the other probe wire 0.8 cm (- 0.8 pf).

Changes of probe wire spacing, for instance as a result of wave impact, generate no output signal at all, as was to be expected and can be easily explained.

However, certain undesirable properties appear. It is true that polystyrol, as claimed in the manufacturer's specifications, does not absorb water at all and hence retains constant capacitance over a long period of time; this was confirmed by the previously mentioned tests. But it is also strongly water repellent, causing non-uniform wetting and necessitating further treatment of the wire surface. Various surface coatings were tried, which improved matters, but still do not represent a satisfactory solution. Only after smearing with a silicon jelly was the desired uniform wetting of the wire surface achieved. But even this is not fully satisfactory; first, because a retardation of the rate of change of the water level results which leads to a phase shift of the measured signal, and moreover, the water washes away the silicon coating (gradually).

If one could discover an insulating material which does not absorb water and at the same time favorably affects the surface tension (which are contradictory requirements), then the capacitance probe would be the ideal measuring device.

The balancing of the null point is effected as in the conductance probe, as if a strain gage bridge were connected to the carrier frequency amplifier.

7. Avoiding disturbances

It is a known fact that the earth resistance between two ground points is greater than 0 ohms, and that in power supply networks which are unsymmetrical with respect to ground, the earth also serves as the return circuit. These ground currents cause a voltage drop between the two ground points.

As an example, consider the following case: The probe (no matter whether conductance or capacitance wave probe) is in direct contact with the tank water, for otherwise a wave measurement would not be possible. The tank water is in direct contact with the saturated reinforced concrete walls and thence with the ground water table. This is the first ground point. A second ground point of the measuring set-up is the earth at the local (model basin's) three phase power transformer, which is required by the power company (i.e. a local transformer ground point is required). The ground wire of the entire local distribution network is also connected to this point. Suppose, for instance, that the distance between the two groundpoints is 150 m. An effective voltage of about 0.2 V was measured between these two groundpoints. It is not sinusoidal, but a triangular form with a high peak; i.e., with a high content of higher harmonics. Moreover, this voltage is subject to variations throughout the day.

Alternatively, one could conceive of this disturbance voltage as a noise generator with V = 0.2 Veff and low internal resistance; namely the resistance of the ground circuit. It is connected at one terminal to the ground lead of the network and at the other terminal to the wires of the conductance probe (or the center wire of the capacitance probe).

If one would connect the probe directly to the carrier frequency amplifier, whose electronic circuit is connected to the neutral wire, then a noise current would flow which would have a considerable part of its circuit in common with the measuring circuit; namely the measuring cables, the probe, and the water surrounding the probe (see Figure 14).

This would be catastrophic. Since a part of the higher harmonics of the noise voltage falls within the pass band of the carrier frequency amplifier, a modulation of the 5 kc carrier frequency would occur and the amplifier would be completely overdriven.

These so-called ground circuits must be avoided at all costs. Hence the isolation of the ground potentials by means of transformers, which of course is easily possible at a carrier frequency of 5 kc. These transformers are also required for other reasons described in sections 2 and 6.

Even if no earth circuits are present, disturbances can still distort the recording of measurements somewhat, especially at the more sensitive amplifier settings. Noise pulses could still manage to reach the input of the carrier frequency amplifier through the winding capacitance of the transformers in the bridge circuit. A shielding foil between the windings corrects this by cutting off the last path of noise pulses. One should carefully consider where this shielding is to be connected to the zero potential. Apart from this, the input circuits should have no appreciable capacitance relative to the bridge circuit.

8. Summary

Finally, a few comparisons between wave probes of different types:

For stationary measurement of wave height, we would prefer the conductance probe with high grade silver wires, provided that the following restrictions do not apply: The probe is not in the immediate vicinity of moving displacement bodies, and several probes are not located near each other (because of the possibility of cross coupling).

If the probe is to be employed in motion, i.e., carried along with the model or the towing carriage, and if you are interested only in wave height and not slope, then the ultrasonic echo sounder probe is probably more advantageous, because it avoids surface deformation.

The wave slope is most reliably acquired by the capacitance probe, since changes in the wire spacing have no influence on the measured values; provided the disadvantages mentioned in section 6 are of no consequence or can be diminished by improvement of the wire surfaces.

The conductance probe is the most sensitive to contamination on the water surface. Sonic probes are disturbed in their operation by foam or breaking waves. If the problem of surface tension of the water with respect to plastic could be satisfactorily solved, then the capacitance probe would be the device that could combine various advantages: no aging, moderate sensitivity to dirt, no errors in measurement of slope, displacement of water (laterally) by the presence of a body in the proximity of the probe has no effect on the measurements, and several probes can be operated close to each other simultaneously.

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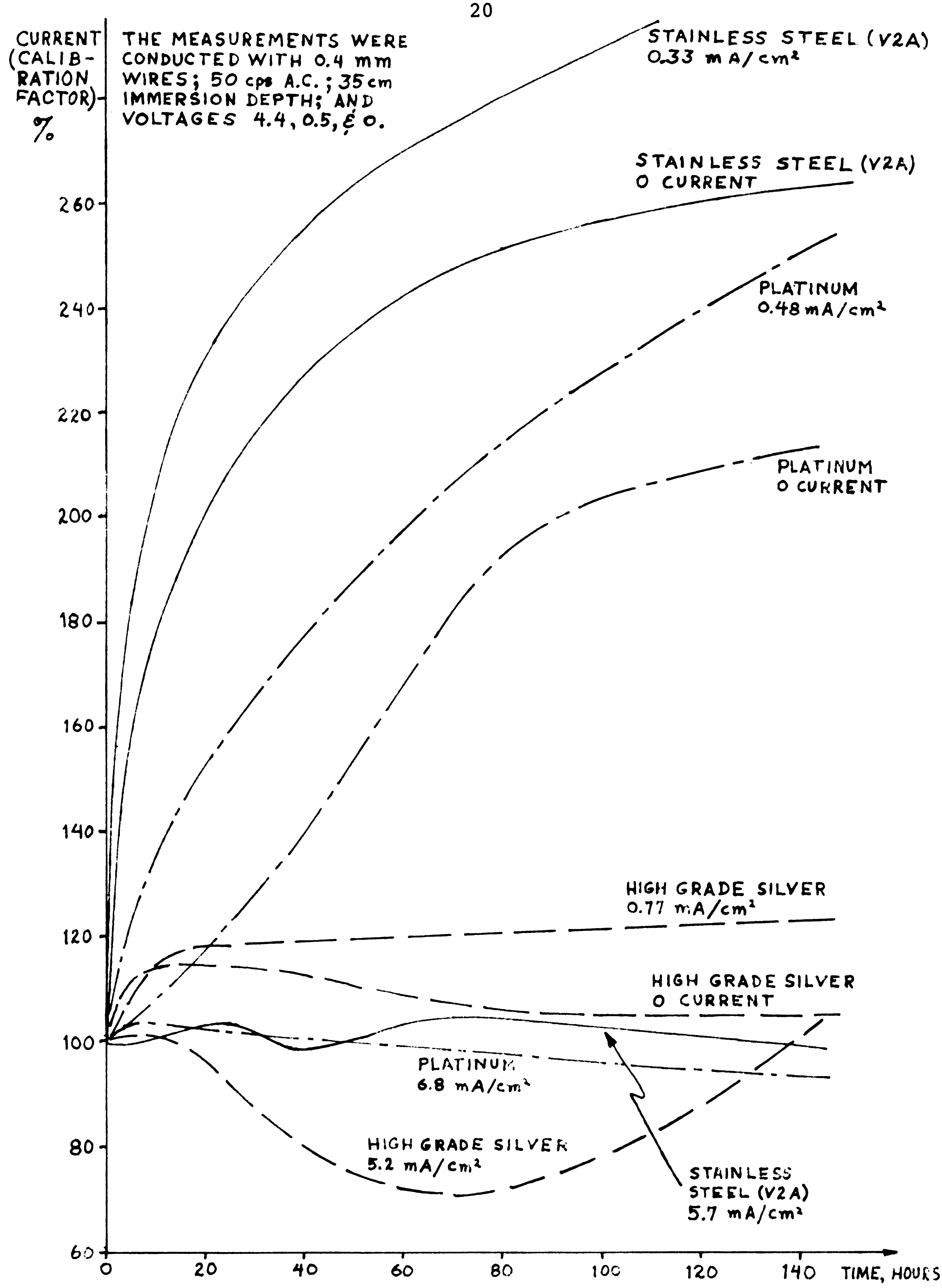


WAVE PROBES — COMPARATIVE MEASUREMENTS

FIG. 1

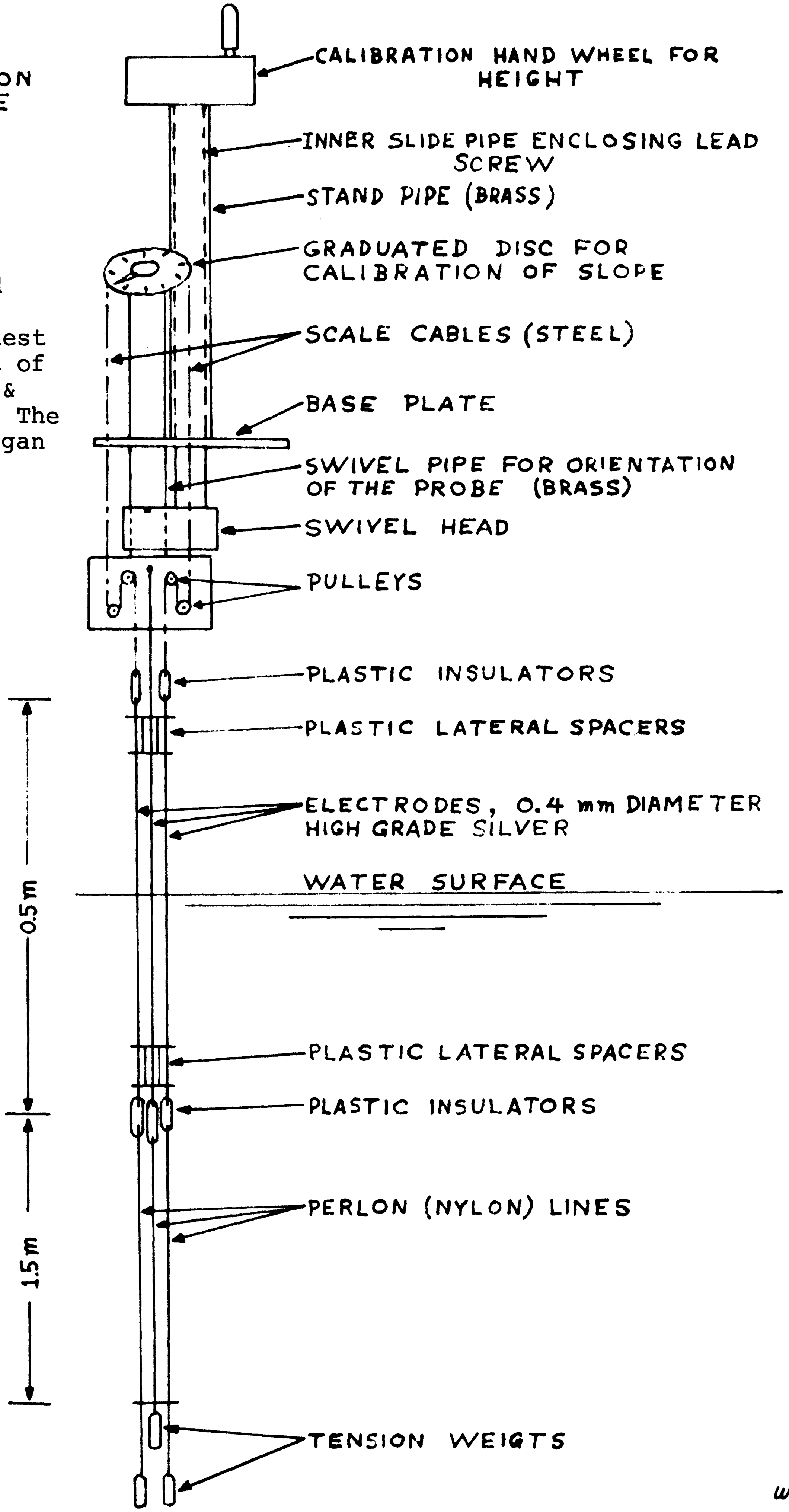
WHR

FIG. 2

CONSTRUCTION OF THE PROBE

SCHEMATIC

Detailed translated assembly drawing available upon request from the Department of Naval Architecture & Marine Engineering, The University of Michigan



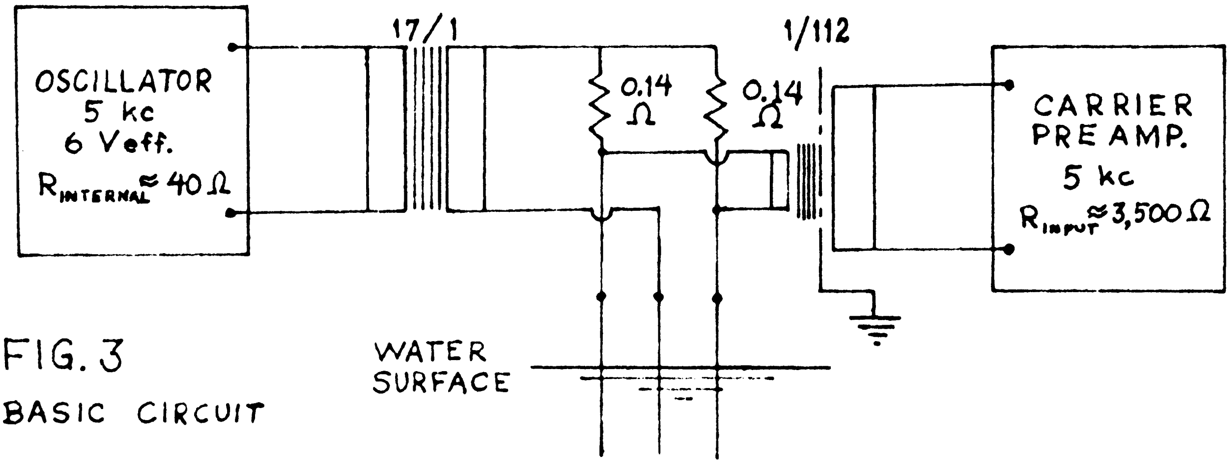
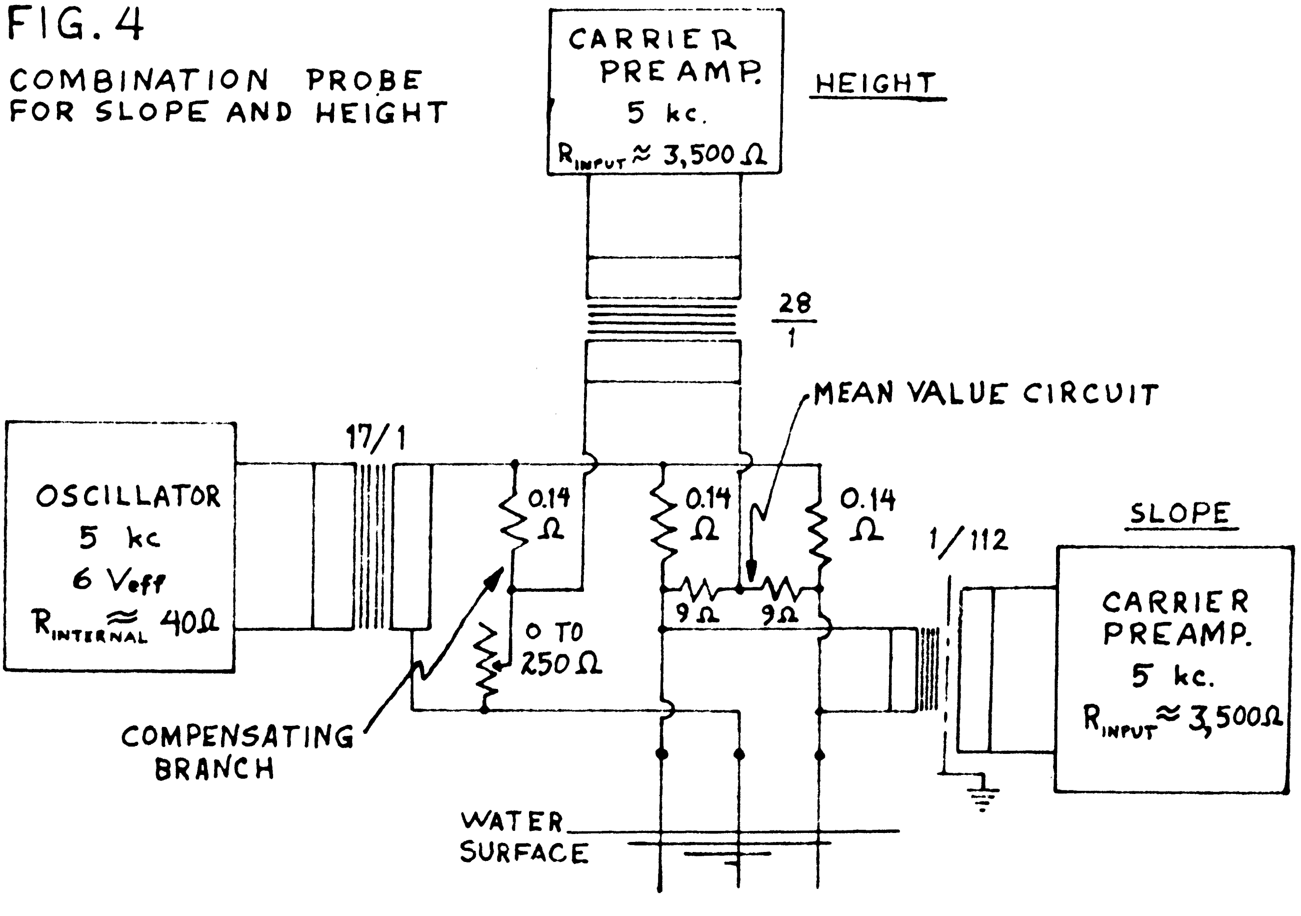
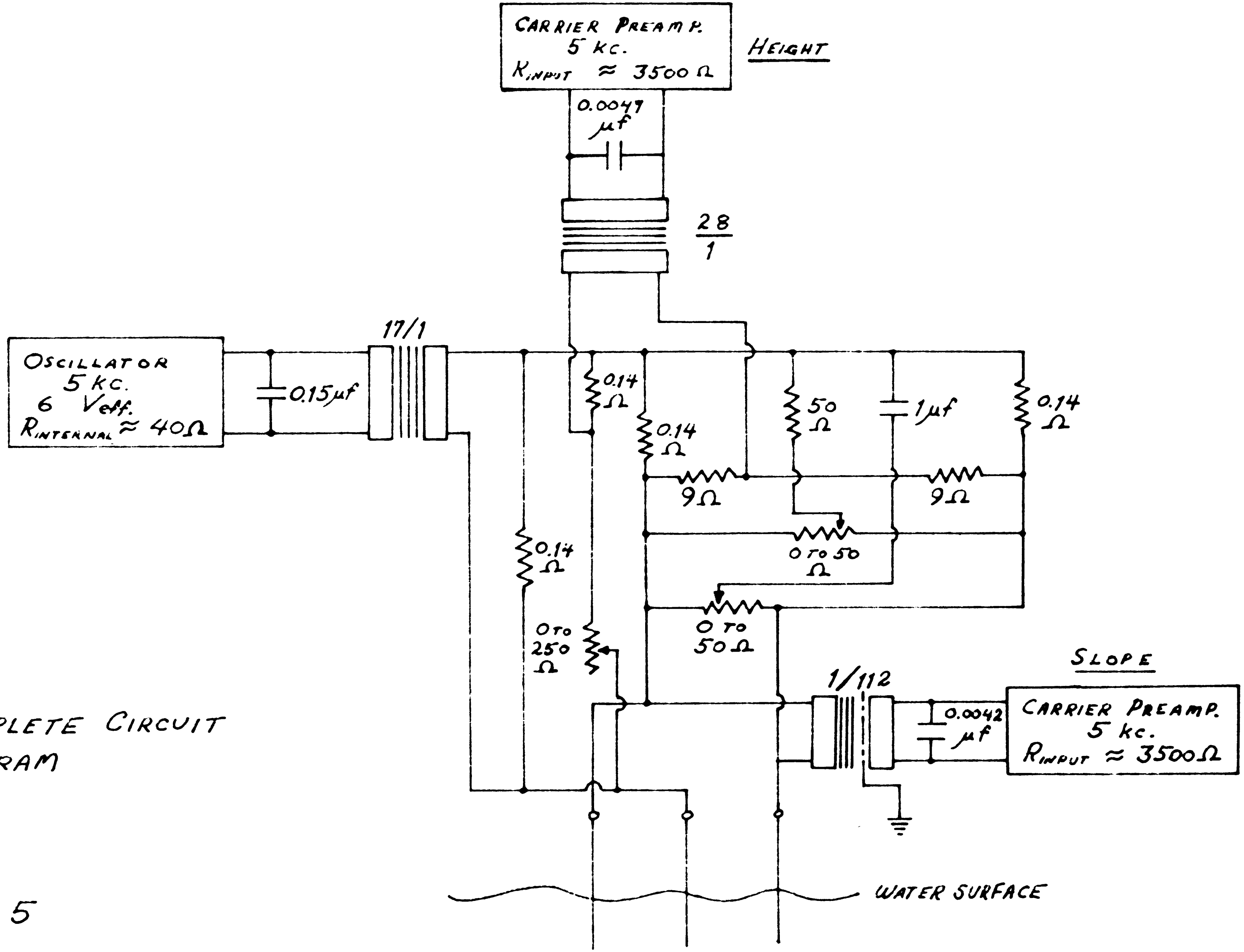


FIG. 3
BASIC CIRCUIT

FIG. 4
COMBINATION PROBE FOR SLOPE AND HEIGHT



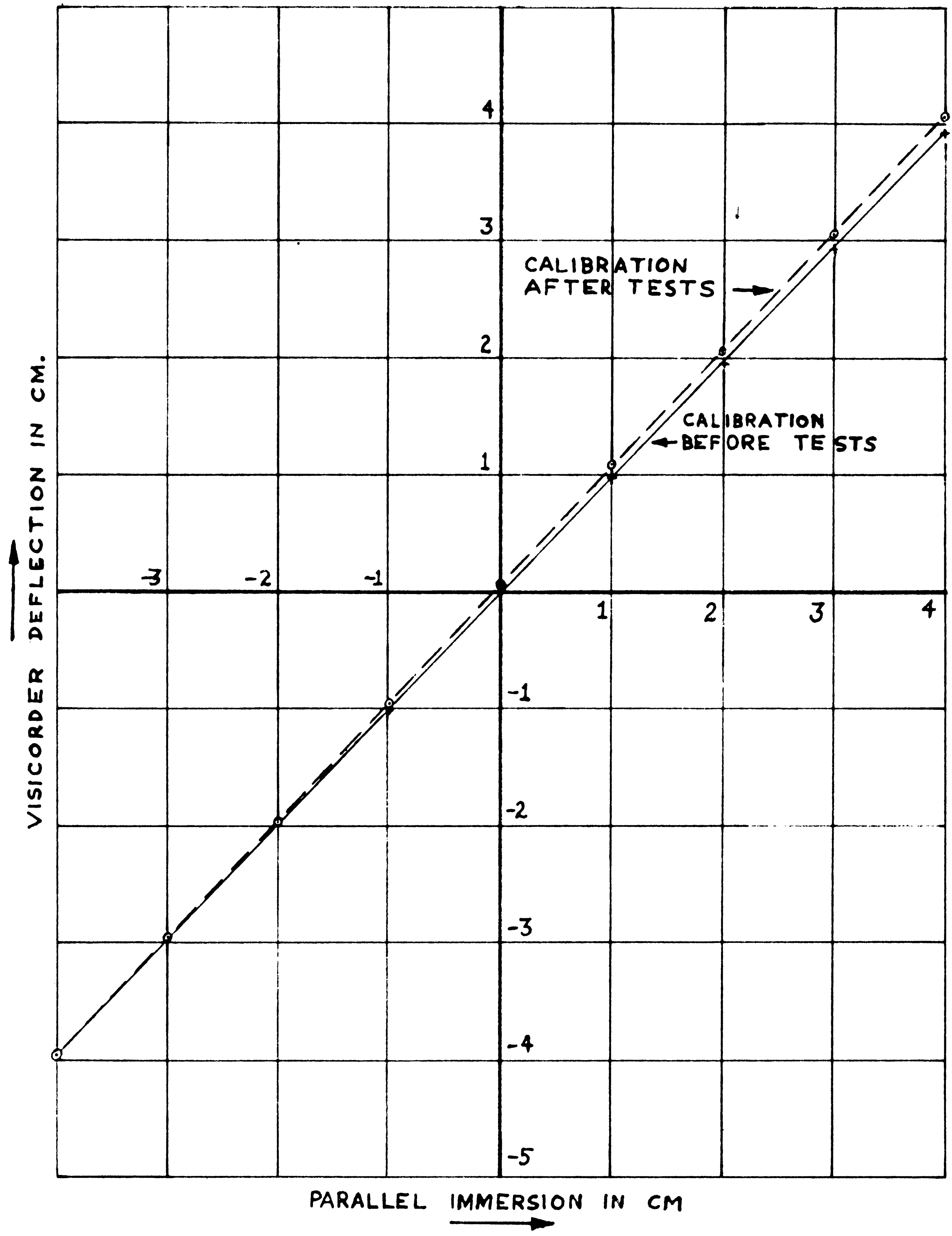
WHR



COMPLETE CIRCUIT
DIAGRAM

FIG. 5

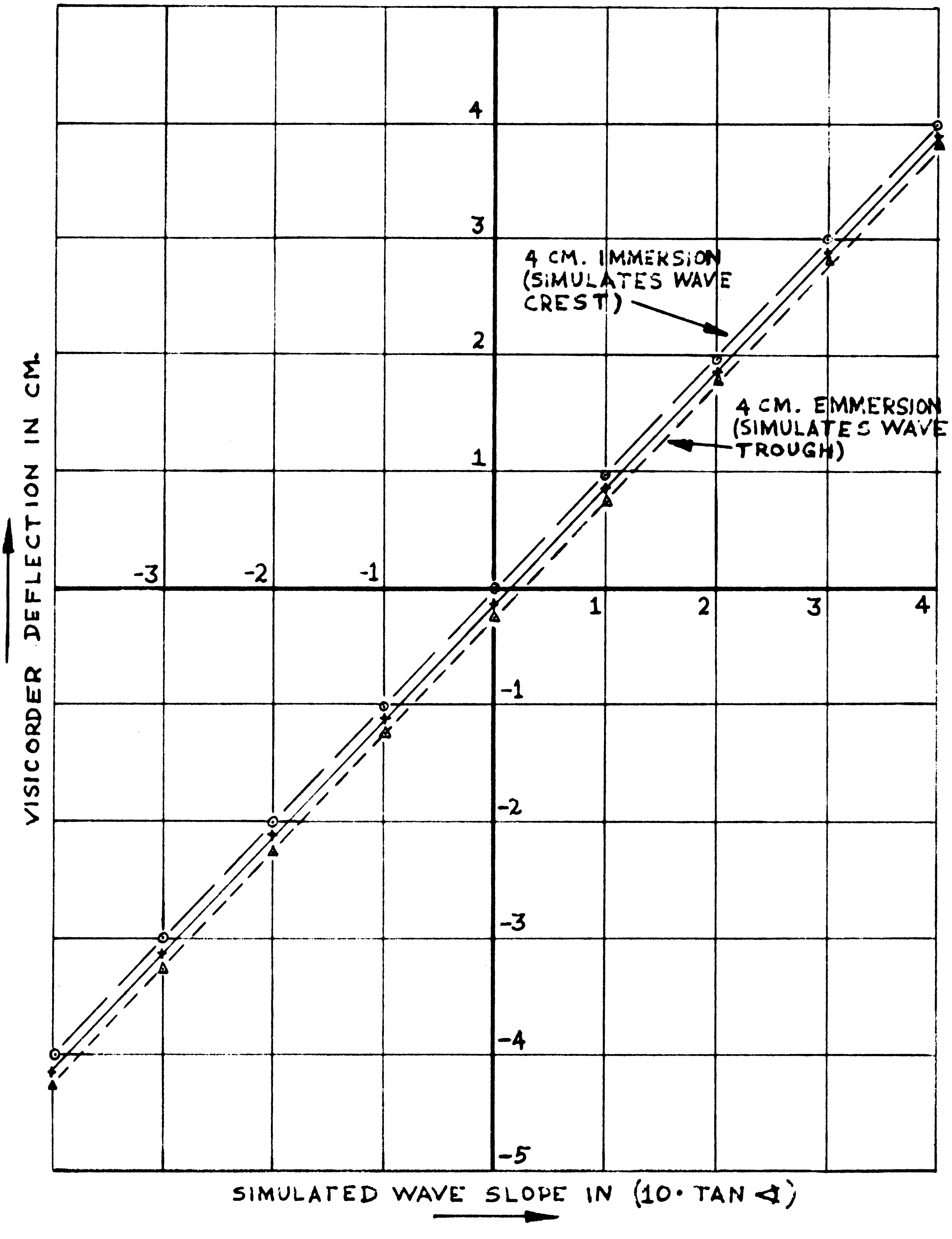
WHR



STATIC CALIBRATION OF THE PROBE FOR HEIGHT

FIG. 6

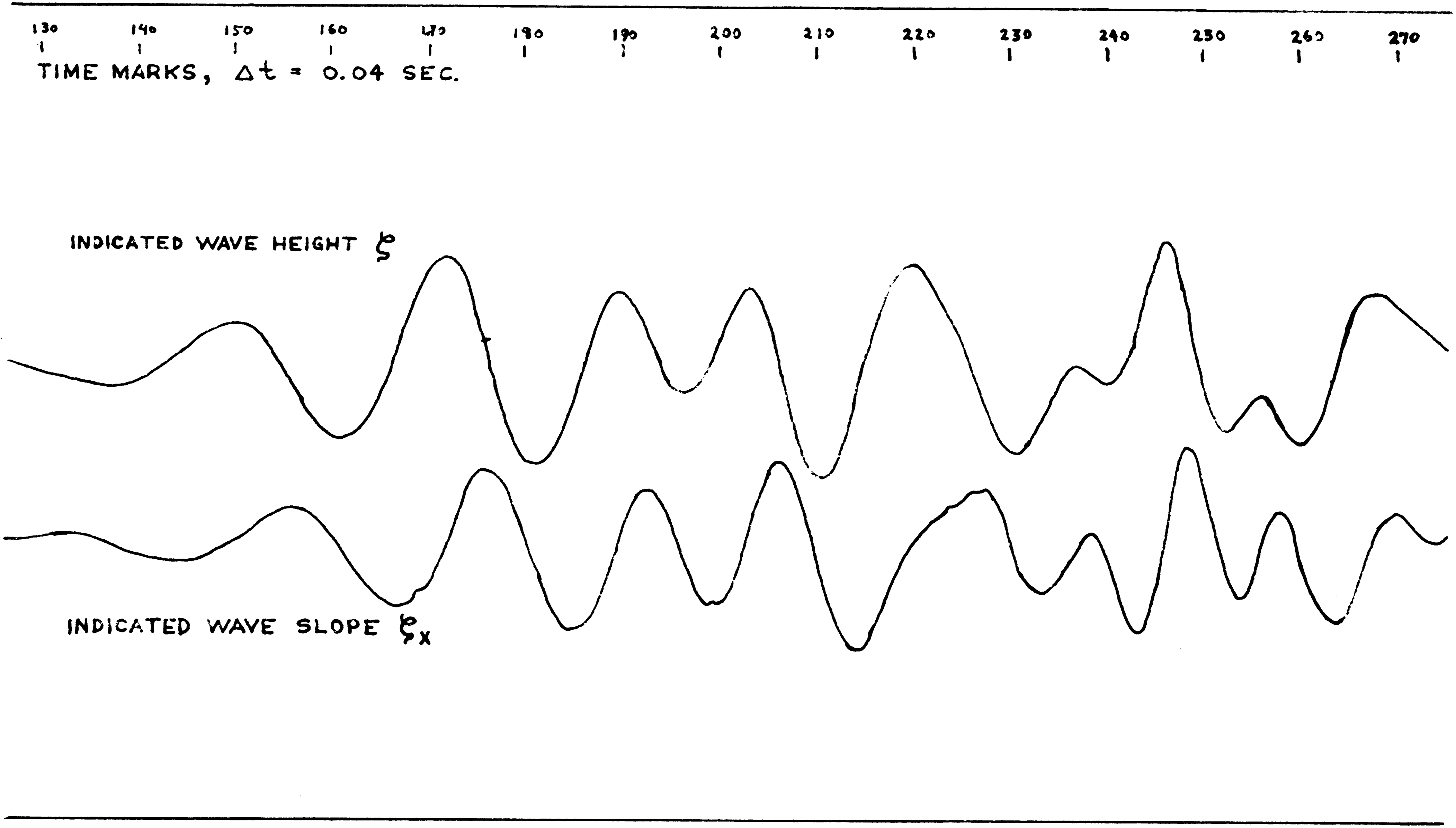
WHR



STATIC CALIBRATION OF THE PROBE FOR SLOPE

FIG. 7

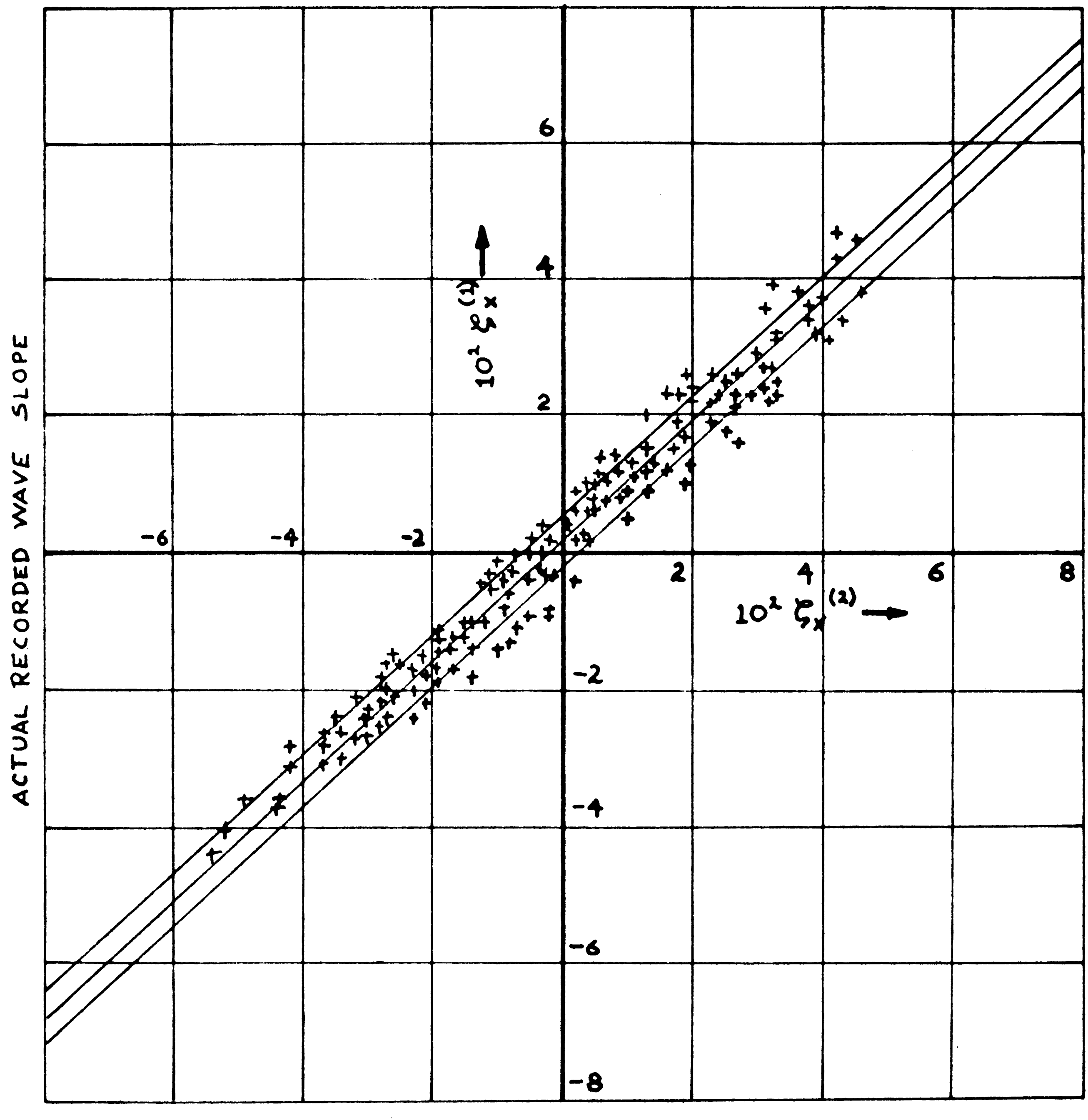
WHR



SECTION OF AN ACTUAL RECORD
(MODEL SPEED : $V = 161.6$ CM./SEC.)

FIG. 8

WHR

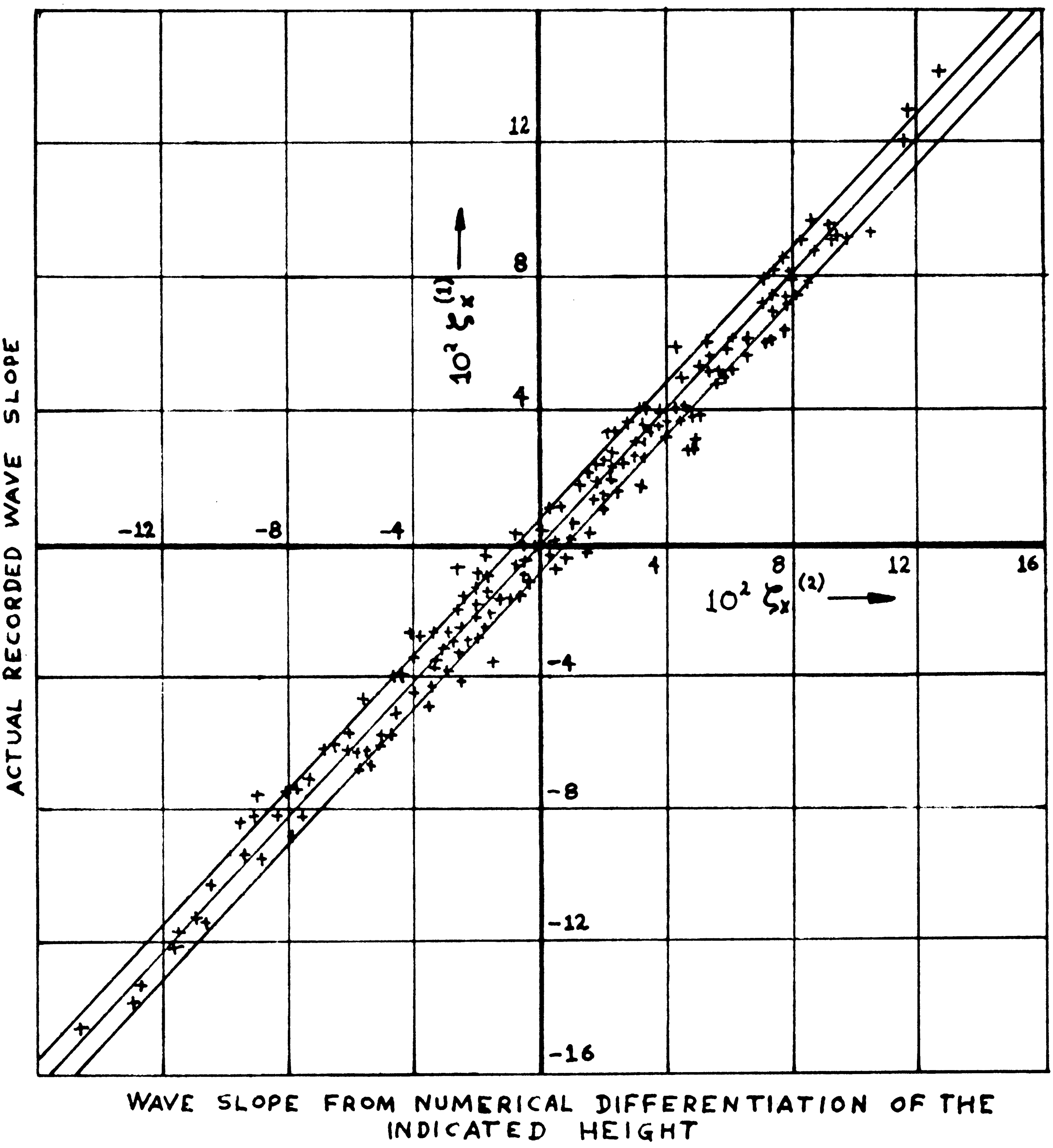


MEAN CORRELATION: $\zeta_x^{(1)} = [0.874\, \zeta_x^{(2)} + 0.002] \pm 0.004$

DYNAMIC CALIBRATION OF THE SLOPE PROBE WITH 25 CM. SEPARATION BETWEEN THE LATERAL SPACERS (SEE FIG. 2)

FIG. 9

WHR

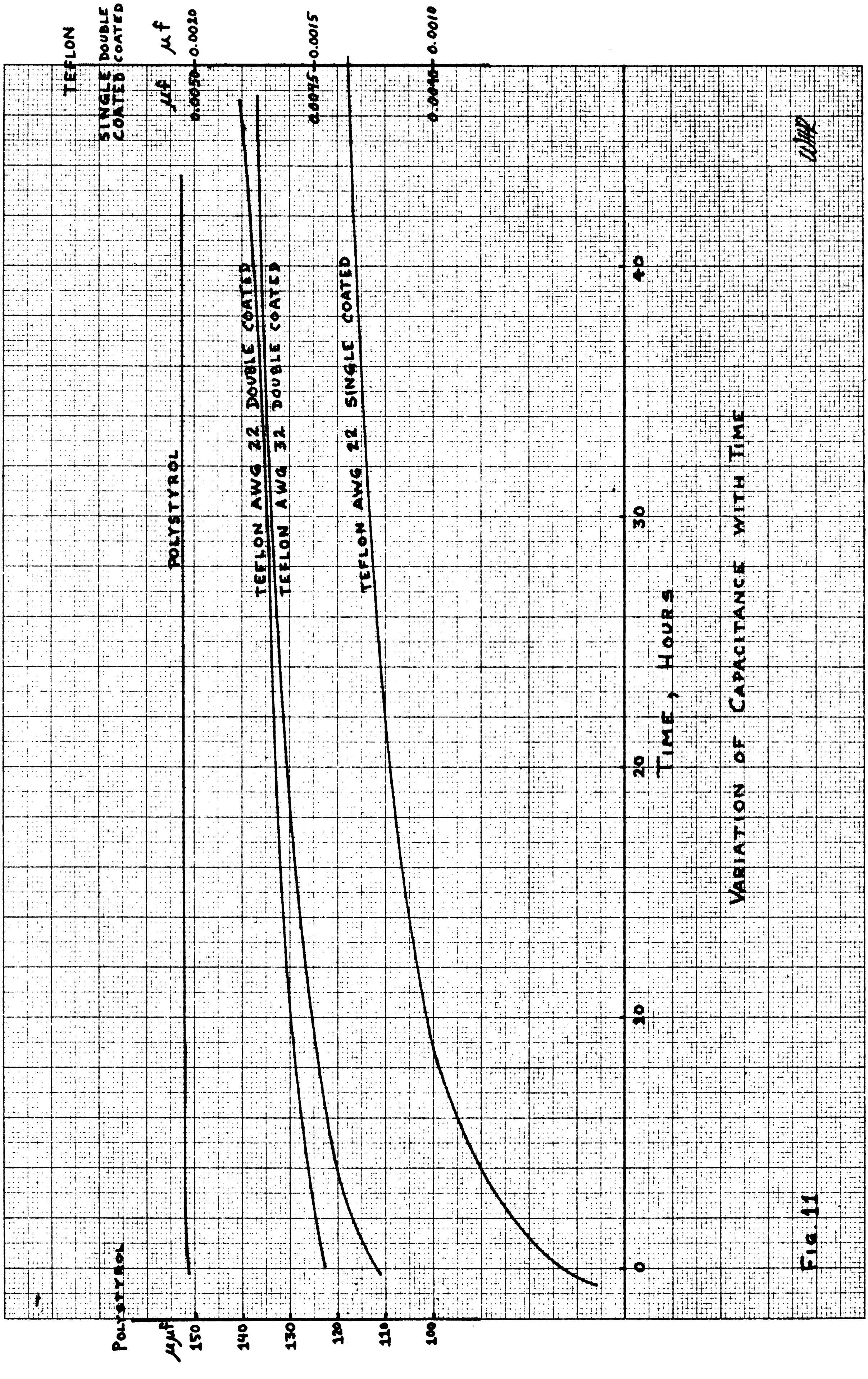


MEAN CORRELATION: $\zeta_x^{(1)} = [1.013\,\zeta_x^{(2)} - 0.002] \pm 0.008$

DYNAMIC CALIBRATION OF THE SLOPE PROBE WITH 15 CM. SEPARATION BETWEEN THE LATERAL SPACERS (SEE FIG. 2)

FIG. 10

WHR

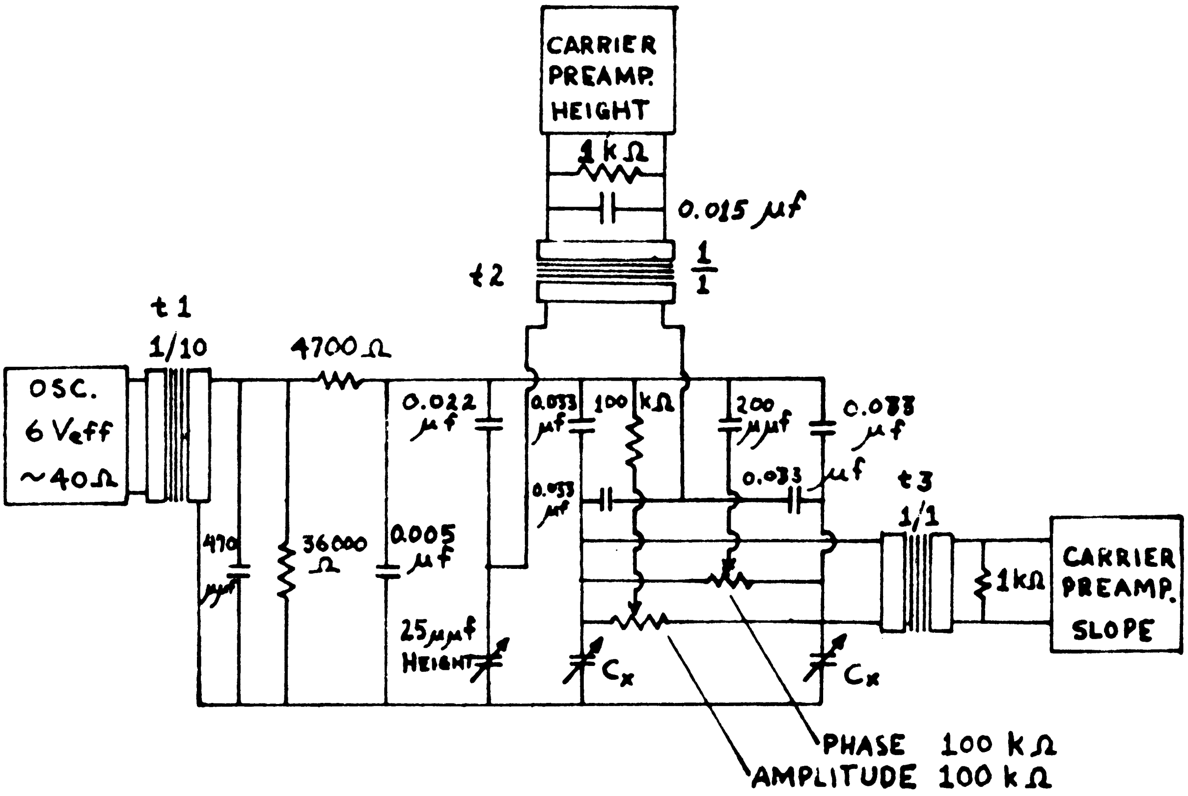


VARIATION OF CAPACITANCE WITH TIME

FIG. 11

FIG. 12 CAPACITANCE WAVE PROBE

Values Applicable To Polystyrol Coated Probe



Transformer Data:				Measured:
t1	1:10	p85 wd	0.3 mm. wire	30 mH Q130 (1 kc)
		s850 wd	0.12 mm. wire	2.6 mH Q200 F_{res} 12 kc
t2	1:1	p86 wd	0.3 mm. wire	31.6 mH 1.05 Ω
		s86 wd	0.3 mm. wire	30.7 mH 1.21 Ω
t3	1:1	p86 wd	0.3 mm. wire	35 mH 1.05 Ω
		s86 wd	0.3 mm. wire	35 mH 1.25 Ω

All wire is enameled copper; all cores are Siemens & Halske Siferrit type T26 without air gap, A_L = 4900 (inductance factor in nH or 10^{-9}H), Diam. 26 mm.

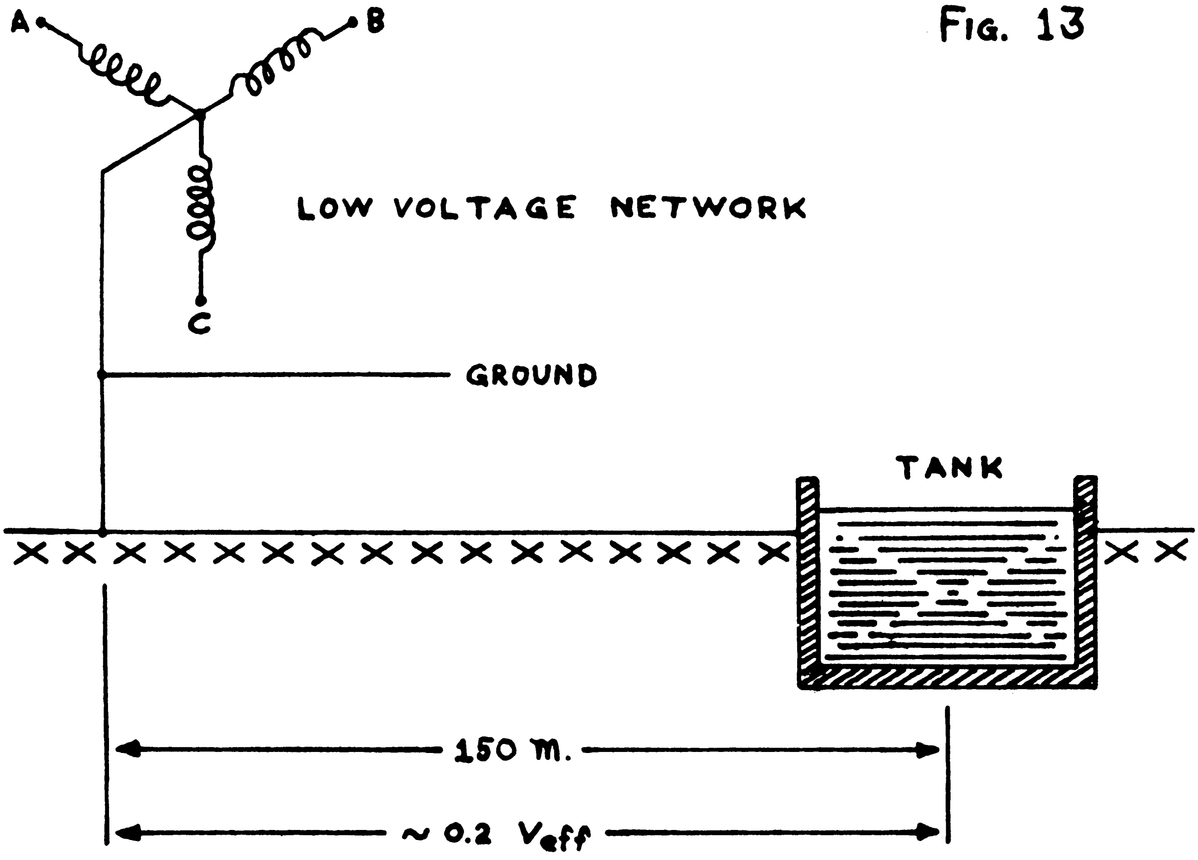


Fig. 13

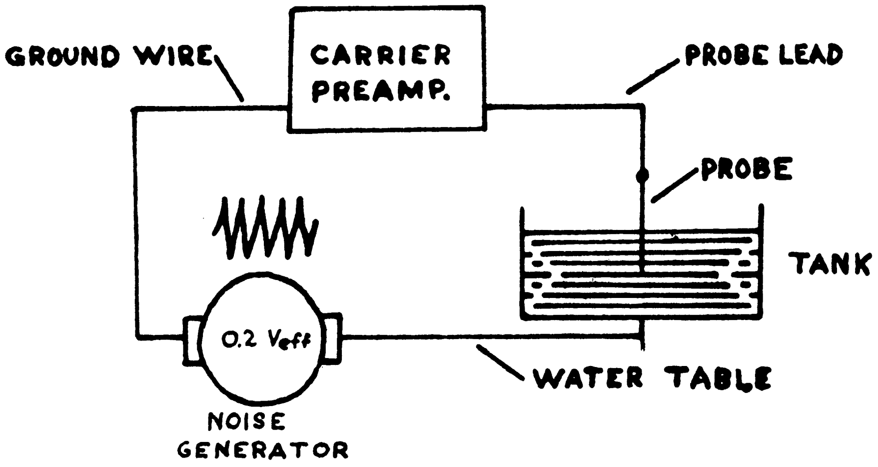


Fig. 14

WHR