Chapter 14

A CAPACITANCE-WIRE RECORDER FOR SMALL WAVES

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For some years there has been an increasingly urgent requirement for a satisfactory device for the measurement of small waves such as those in harbour models and wave tanks. Many earlier instruments developed for this purpose used floats, but these suffer from certain practical disadvantages. In particular a large arm is necessary to transmit the motion of the float to the measuring device, which must be well clear of the water surface, and this arm introduces inertia and hence lag into the system. To reduce this lag the float has to be fairly large, and it cannot be regarded as measuring the wave height at a point on the surface. The device described below, in which the capacitance between an insulated copper wire and the surrounding water is measured (figure 1), does effectively measure the height at a point on the surface and has given satisfactory results in several applications.

Instruments working on this principle are used in many hydraulics laboratories, and a description of those used at the Laboratoire Dauphinois d'Hydraulique has been given by Boudan in "La Houille Blanche", Vol. 8, p. 526 (Aug.-Sept. 1953). The National Institute of Oceanography demonstrated one of these wave recorders at the Conversazione of the Institution of Civil Engineers in June 1952, and it was briefly reported in the July 1952 issue of "The Dock and Harbour Authority". The instrument described below appears to be simpler than others at present in use, and the authors feel that a description of it will be of general interest.

THE MEASURING HEAD

The measuring head consists of an insulated wire stretched vertically through the water surface between two supports. In practice it is convenient, where it is permissible, to loop the wire round the bottom support and bring it back up to the top support, since this avoids the necessity of insulating the lower end (figure 2). The wire we have mostly used up to the present time is 24 s.w.g. copper wire insulated with medium thickness 'Lewmex' enamel giving a capacitance of about 15 $\mu\mu$F per cm. So far none of our measured curves of the capacitance of the measuring head against water height for a head made with this wire has deviated from the best straight line by more than 1% of the maximum capacitance (a rapid calibration of a previously dry wire must be made - see below). Some of the other types of wire we have tested have not been satisfactory in this respect. If the wire is handled carefully during construction of the head, it is unusual for a test at 250V D.C. to reveal faulty insulation. A major disadvantage of this type of insulation is

COPPER CONDUCTOR.

WIRE INSULATION
ACTING AS
CONDENSER
DIELECTRIC

CIRCUIT   MEASURING
CAPACITY   BETWEEN
CENTRE   WIRE
  AND   EARTH

RECORDER

SEA ACTING
AS OUTER
PLATE OF
CONDENSER

EARTH
CONNECTION
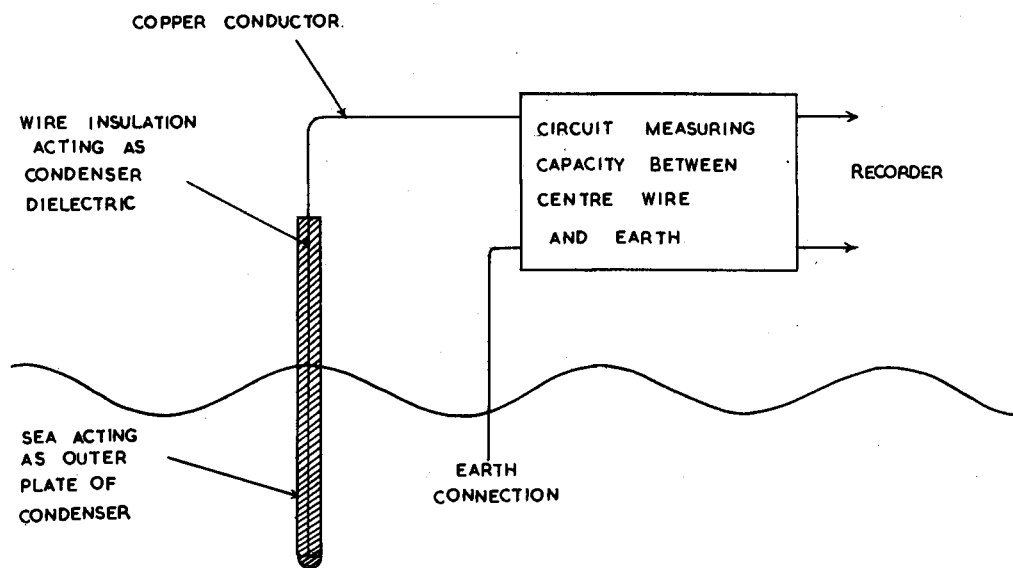
Fig. 1.   The principle of operation of the instrument.

TO MEASURING CIRCUIT

INSULATING
SUPPORT

MEASURING
WIRE

METAL SUPPORT
(ALSO EARTH
 CONNECTION)
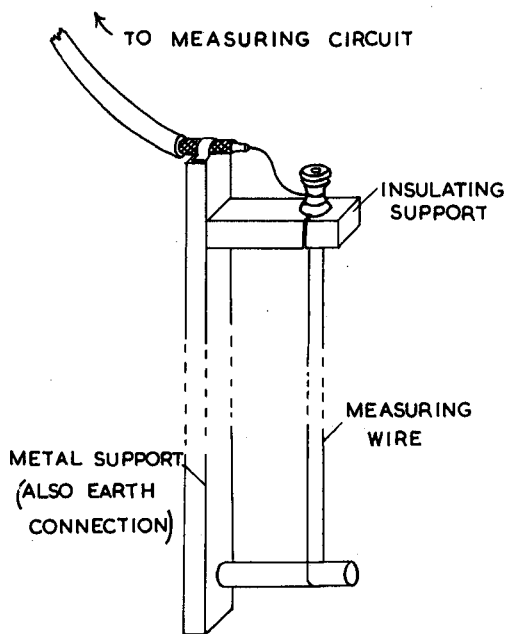
Fig. 2.   The measuring head.
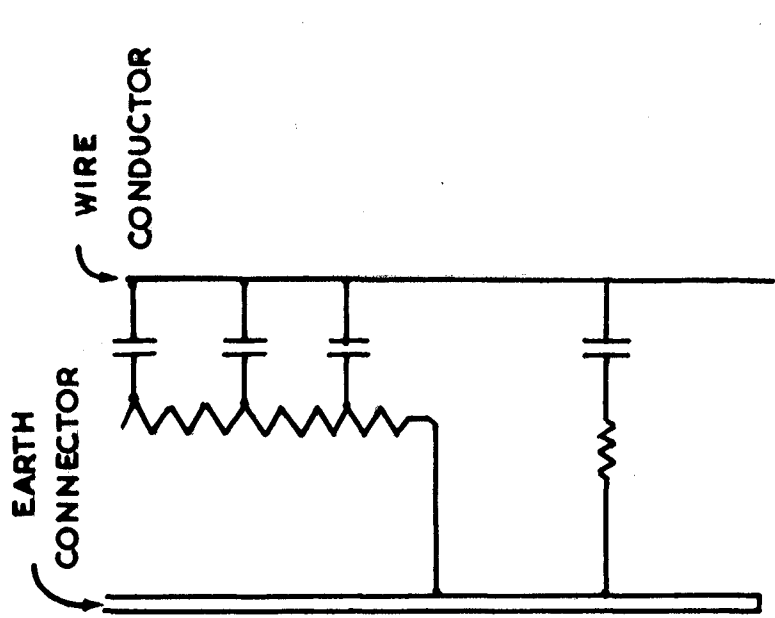
Fig. 4. The approximate equivalent circuit of the measuring head. The upper set of resistors and capacitors represent the film of water round the wire just above the water surface. Below is represented the capacitance of the wire in series with the resistance of the path in the main body of the water.
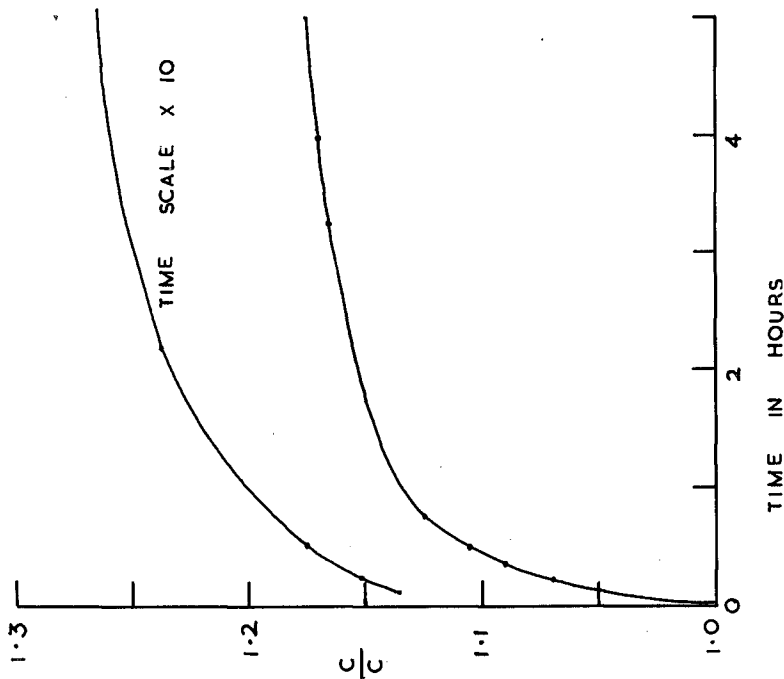
Fig. 3. The increase with time of the capacitance of a 24 s.w.g. copper wire insulated with "Lewmex H.F." enamel and completely immersed in water.

its property of slowly absorbing water and increasing its dielectric
constant, causing an increase in the capacitance of the wire (figure 3).
The effect is serious for accurate work, but for many purposes can be
overcome by keeping the wire out of the water except during the actual
periods of measurement.   It is also advisable to calibrate the wire at
regular intervals.   If the wire is left permanently in position, the
sensitivity of the underwater part of the wire increases and a non-linear
characteristic results.   Water absorption can be avoided by using wire
insulated with polythene, whose water absorption is negligible, but the
only suitable wire of this type which the authors have been able to
obtain (20 s.w.g. copper with 0.024 in. radial thickness of polythene)
has comparatively thick insulation and gives a capacitance of approxi-
mately 2 $\mu\mu$F per cm.   This, unfortunately, is too low for the authors'
most important application, which is measuring waves on a reservoir where
the measuring head has to be at the end of up to about 100 metres of
coaxial cable with a total capacitance of about 0.01 μF.   However, it is
satisfactory for use with up to 10 metres of coaxial cable, which is
adequate for most model work.

Surface tension produces a meniscus which rises about 0.5 mm up the
Lewmex wire and about 1 mm up the polythene wire, but the static value of
this height will be more or less constant when the wire is in use and the
static errors introduced will not be large.   If the water level drops
rapidly a thin film of water may be left round the wire, acting as a con-
ducting sheath giving a spurious increase in capacitance.   This problem
is not so serious as might at first appear, since we have found experi-
mentally that it is not possible to wet the thin wires used for measuring
small waves.   However, viscosity will prevent the water leaving the wire
instantaneously as the level falls, and the thicker wires which have to
be used to measure large waves may be permanently wetted.   Now most
methods of measuring a capacitance use a sinusoidal oscillating voltage,
and the effect of the water film round the wire can be minimised by
choosing the correct frequency for this voltage.   If we consider the
capacitor formed by an upper part of the film of water, the current
through this capacitor has to pass through the lower part of the film
before reaching the main body of the water.   The equivalent circuit is
of the type shown in figure 4.   If the resistance is sufficiently high
compared with the impedance (the A.C. equivalent of resistance) of the
capacitor, this will be effectively isolated and will not be measured.
The impedance of a capacitor decreases as the frequency increases, so
that the resistances become comparatively larger and the effect of the
film decreases.   The upper limit of frequency is reached when the
effective resistance R of the main body of water which is in series with
the capacitance C of the underwater part of the wire becomes appreciable.
It can be shown that for the part of the wire below the surface

$$R/Z = 10^{-12} \rho K f \left[\log_e (2S/D_2) \right] \Big/ 1.8 \log_e (D_2/D_1)$$

where $Z = 1/\omega C$ is the impedance of the capacitance of the wire

 ρ is the restivity of the water

 K is the dielectric constant of the wire insulation

 f is the frequency

 D_1 is the diameter of the conductor

 D_2 is the overall diameter of the wire

 S is a distance which may be termed the effective distance of the wire from the earth conductor.   If the wire continued to the bottom of the tank, assumed to be an insulator, and the earth electrode was a cylinder also extending from the surface to the bottom, S would be the radius of this cylinder.

Substituting values of K, D_1 and D_2 corresponding to 24 s.w.g. 'Lewmex H.F.' wire, and typical values for ρ and S,

 ρ = 1000 ohm cm (corresponding to about 0.1% NaCl)

 K = 3.6

 D_1 = 0.056 cm

 D_2 = 0.062 cm

 S = 10.0 cm

giving R/Z = 1.12 x 10^{-7} f.

For a typical polythene-insulated wire

 K = 2.3

 D_1 = 0.091 cm

 D_2 = 0.21 cm

and R/Z = 6.7 x 10^{-9} f.

The maximum permissible value of R/Z depends to some extent on the type of measuring circuit used, but is probably of the order of 0.1, which would give a maximum frequency of about 1 Mc/s for the Lewmex-coated wire and about 20 Mc/s for the polythene-coated wire.   However, the value of ρ varies greatly and might in certain cases reach 10 times the value used above, so that a large factor of safety has to be allowed.

A further limitation to the maximum frequency is the length of the cable connecting the measuring head to the electronic circuit. The electromagnetic wavelength in the cable corresponding to the frequency used must be long compared with the length of cable if resonance effects are to be avoided. Even with the maximum length of cable specified below, which is only about 1/30 of a wavelength, an appreciable increase in sensitivity occurs and the head must be calibrated with its cable connected in circuit. It is also desirable that the frequency used should not correspond with that of a widely used radio programme, though the amount of power radiated will be extremely small. Taking these factors into account, a frequency of 60 kc/s was chosen for use with the Lewmex-insulated wires (maximum cable length 100 metres) and 600 kc/s for use with the polythene-insulated wires (maximum cable length 10 metres).

THE ELECTRONIC CIRCUITS

The two commonly used methods of detecting a small change in capacitance are to cause it to unbalance a bridge, or to cause it to change the frequency of an oscillator and then to detect this change in frequency. Though at first sight the bridge method appears to be the more straightforward approach, in practice it involves considerable complication since it requires an oscillator, amplifier, phase-sensitive detector and output stage. The second, or frequency-modulation method is simpler, requiring an oscillator, frequency-deviation detector and output stage. It is interesting to note that a bridge-type circuit developed by the David Taylor Model Basin (unpublished report) uses seven active valve elements, i.e., triodes or pentodes, up to the point corresponding to the grid of our output stage, whereas we have only one active valve up to this point.

Figure 5 shows a battery-operated circuit suitable for use with a Lewmex-insulated wire measuring head at the end of up to 100 metres of cable, and figure 6 shows a mains-operated circuit suitable for use with a polythene-insulated wire measuring head at the end of up to 10 metres of cable. Both circuits are similar in principle. The changes in capacitance of the measuring head alter the resonant frequency of a valve-maintained inductance-capacitance tuned circuit. A voltage from this circuit is fed to a frequency discriminator similar in principle to that used in most F.M. radio receivers, and this is followed by a simple D.C. amplifier output stage.

It is desirable to have an oscillator whose amplitude is as stable as possible against changes in the damping of the tuned circuit, since the frequency discriminator imposes a considerable load which varies with the frequency deviation, and the insulation resistance of the measuring head is not always very high. A bridge-stabilized oscillator
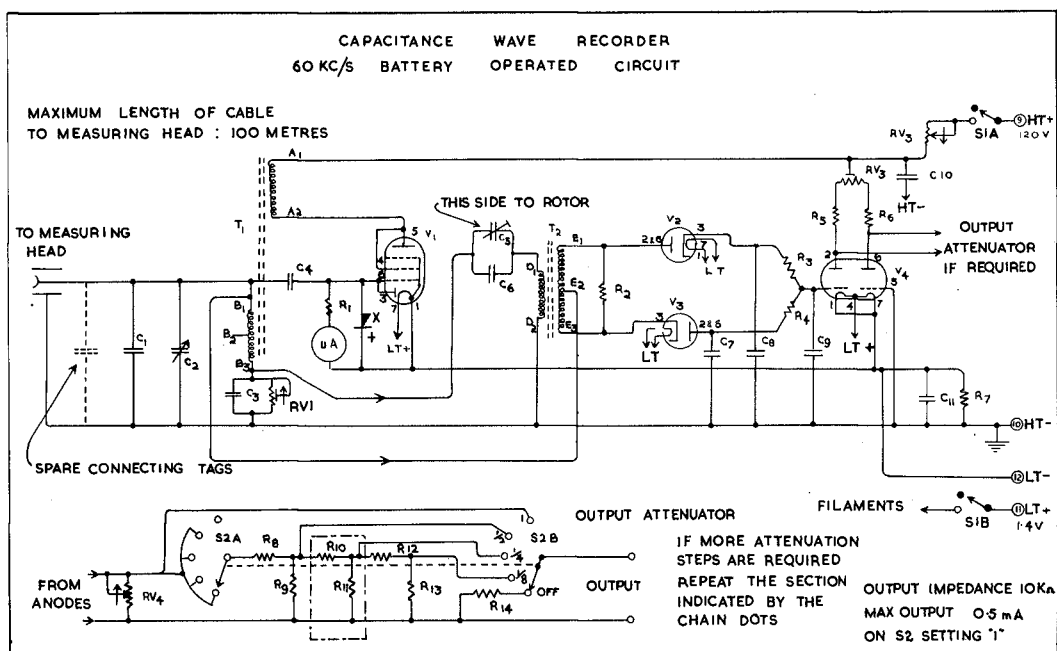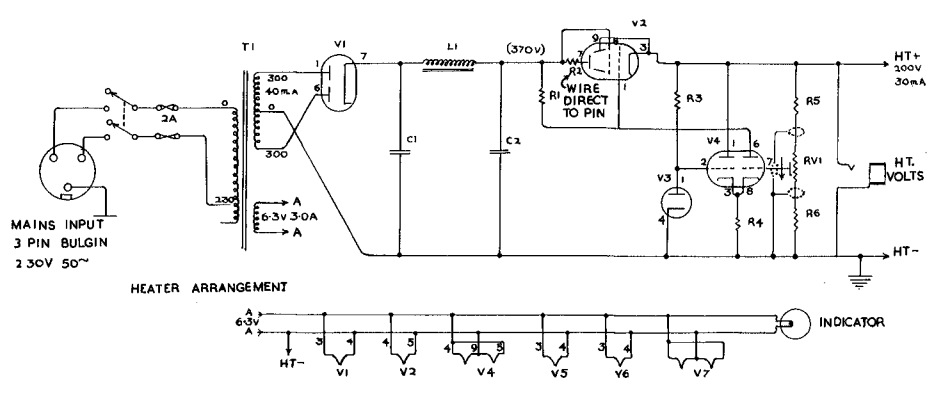
Fig. 5.   60-kc/s battery-operated circuit. (For components, see below).

Component schedule for Figure 5.

μF		K ohms	
C1	0.02 Mica (To be adjusted as necessary to compensate for the capacitance of the lead to the measuring head)		
C2	0.001 (Zero Control)	RV1	1 (Phase-correction resistor)
C3	0.1	RV2	10
C4	0.005	RV3	10 (For adjusting H.T. voltage)
C5	0.0001	RV4	100 (This is adjusted till the amplifier output impedance is 10 K ohms)
C6	0.0015		
C7	0.01		
C8	0.01	T1	Core: Gecalloy C56V dust core
C9	0.01		Primary: (A₁, A₂) 500 turns 38 s.w.g. 'Lewmex H.F.' (35 mH)
C10	0.1		Secondary: (B₁, B₂, B₃) 60 turns centre tapped 26 s.w.g. 'Lewmex H.F.'
C11	0.1		
		T2	Core: Gecalloy C56V dust core
	K ohms		Primary: (D₁, D₂) 200 turns 34 s.w.g. 'Lewmex H.F.'
R1	10		Secondary: (E₁, E₂, E₃) 400 turns centre tapped 38 s.w.g. 'Lewmex H.F.'
R2	33		
R3	150	V1	CV 784 (1S5)
R4	150	V2	CV 753 (1A3)
R5	10	± 5% ¼W Grade 1	V3	CV 753 (1A3)
R6	10	V4	CV 808 (3A5)
R7	0.22		
R8	10	X	GEX 45/1 Germanium Diode
R9	60	μA	500 μA F.S.D.
R10	15		
R11	30	± 1% ¼W Grade 1	
R12	15		
R13	15		
R14	10		

NB.   WIRES CARRYING 600 KC/S SHOULD
      BE AS SHORT AND RIGID AS POSSIBLE

      CABLE TO MEASURING HEAD MUST NOT
   BE LONGER THAN 10 METRES
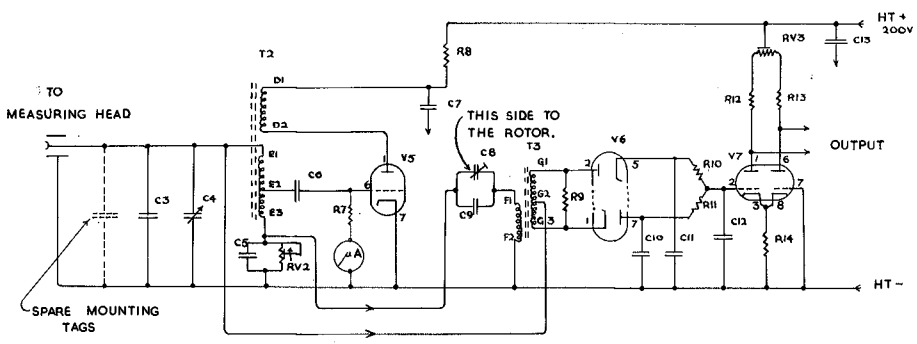
Fig. 6.   600-kc/s mains-operated curcuit.   The upper circuit
is the stabilized power supply. (For components schedule, see
below).

Component schedule for Figure 6.

C1	8 μF 400V D.C. Working	
C2	8 μF " " "	
C3	0.002 μF, Mica (To be adjusted as necessary to compensate for the capacitance of the lead to the measuring head)	
C4	100 μμF (Zero Control)	
C5	0.01 μF	
C6	470 μμF	
C7	0.1 μF	
C8	20 μμF	
C9	70 μμF	
C10	0.01 μF	
C11	0.01 μF	
C12	0.01 μF	
C13	0.1 μF	
L	9 Henry 50 mA	

K ohms

R	value	spec
R1	150	± 5% ¼W Grade 1
R2	0.1	±20% ½W Grade 2
R3	26	± 1% Composite Grade 1
R4	47	± 5% ¼W Grade 1
R5	150	" " "
R6	100	" " "
R7	33	" " "
R8	2.2	±20% 1W Grade 2
R9	220	± 5% ¼W Grade 1
R10	150	" " "
R11	150	" " "
R12	3.3	± 5% ¼W
R13	3.3	" " "
R14	0.33	" ¼W "

K ohms
RV1   25
RV2   1
RV3   5

T1   Gardner's Radio R173 or other suitable transformer

T2   Core: Gecalloy C56V dust core
     Primary: (D₁, D₂) 50 turns 26 s.w.g. 'Lewmex H.F.'
     Secondary: (E₁, E₂, E₃) 16 turns centre tapped 24 s.w.g.
                                              'Lewmex H.F.'

T3   Core: Gecalloy C56V dust core
     Primary: (F₁, F₂) 60 turns 26 s.w.g. 'Lewmex H.F.'
     Secondary: (G₁, G₂, G₃) 120 turns centre tapped 30 s.w.g.
                                              'Lewmex H.F.'

V1   CV 493 (6X4)
V2   CV 2136
V3   CV 449 (85A2)
V4   CV 492 (12AX7)
V5   CV 133 (6C4)
V6   CV 140 (6AL5)
V7   CV 491 (12AU7)

μA   500 μA F.S.D.

would be best in this respect, but has the disadvantage of being comparatively complicated and of consuming more H.T. and L.T. power than simple oscillators - an important point in the battery-operated circuit. The best simple oscillator uses a triode maintaining valve with grid bias obtained by rectifying the oscillator voltage, and this also has the minor advantage that the amplitude of oscillation may be monitored simply by connecting a D.C. meter in series with the grid-leak resistor.   The bias is obtained by grid rectification in the mains-operated circuit, but in the battery circuit a germanium diode is used since the grid of a 1S5, even when connected to the diode unit, will not rectify efficiently with the low-value grid-leak resistor made necessary by the meter.

The frequency discriminator works by first converting the frequency deviation into a phase shift.   This is achieved by means of a series tuned circuit driven from a low impedance: the voltage across the inductance is 90° out of phase with the driving voltage at resonance, and this phase shift increases at lower frequencies and decreases at higher frequencies.   In figure 6 this circuit is formed by C8 and C9 and the primary of T3.   Owing to the effect of stray capacitances and inductances, the phase on the secondary of T3 at resonance is not quite the theoretical value, and has to be corrected empirically using RV2.   (In practice this resistance is adjusted till the overall calibration curve is symmetrical about zero output.)   The voltages appearing on the secondary of T3 are shown in figure 7.   The voltage at G1 is rectified positively, that at G3 is rectified negatively, and half the sum of the rectified voltages appears on the grid of the output stage.   It will be seen that a D.C. voltage is produced which is proportional over a limited range to the deviation of the oscillator frequency from the resonant frequency of the discriminator.

An interesting phenomenon occurs owing to the coupling of the two resonant circuits.   The impedance of a series resonant circuit is purely resistive at the resonant frequency, but above resonance it has an inductive component and below resonance a capacitative component.   Thus, if an increase in the capacitance of the measuring head lowers the oscillator frequency, the discriminator resonant circuit will effectively connect a further capacitor across the oscillator circuit, and will further lower the frequency.   If the coupling and Q of the discriminator circuit are high enough, this process can become unstable and the oscillator frequency will give a sudden large jump for a minute change in the capacitance of the measuring head.   For this reason the coupling must be kept low.

In the battery circuit it is necessary to compensate for slow changes in the battery voltages, which would otherwise alter the sensitivity.   It is particularly important to keep the amplitude of oscillation constant, and this is achieved by varying the H.T. voltage using RV3 (figure 5).   This adjustment will also greatly reduce variations in the gain of the output stage.
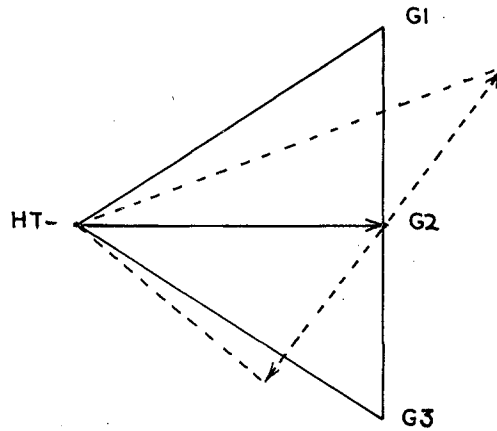
Fig. 7.   The voltage relationships in the
frequency discriminator. (Refer to Fig. 6.)

The full lines show the voltages at re-
sonance; the broken lines show the voltages
when there is a frequency deviation.
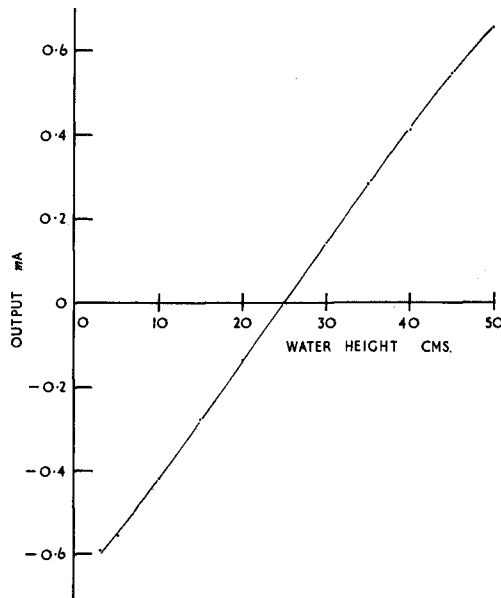
Fig. 8.   Typical overall calibration curve using
the circuit of Fig. 5 and a measuring head of
24 s.w.g. "Lewmex H.F." insulated wire.   The curve
was obtained by keeping the wire immersed for some
days and then reducing the water level in stages.
The output was measured with a 500-ohm meter con-
nected directly between the output anodes.

An attempt was made to replace the thermionic diodes in the battery circuit by germanium-crystal diodes, but these were found to be extremely noisy.   Very small selenium rectifiers were then tried, which reduced the noise by a factor of about 10 but introduced a large amount of drift. Copper oxide rectifiers have too large a capacitance to be used at these frequencies, and silicon diodes have a ratio of backwards to forwards resistance which is too low to give efficient and stable rectification.

In an instrument built to the circuit of figure 5, the drift in output zero corresponded to a change in the capacitance of the measuring head of about 15 $\mu\mu$F during the first 10 minutes after switching on, and subsequent drift over a period of two hours was equivalent to less than 5 $\mu\mu$F.

METHODS OF RECORDING

The frequency of the waves which these instruments will be used to measure is usually too high for the ordinary graphic pen recorders.   We normally use fast mirror galvanometers recording on photographic paper, and our circuits are designed to drive such a system.   Some users may prefer a fast pen recorder, of which there are several types now on the market, and these are usually provided with a special driving amplifier which may be coupled directly to the output of the frequency discriminator.

ACCURACY

The main limitation to the accuracy of the instrument is probably the lag caused by viscosity.   If the water level is raised and lowered rapidly the shape of the meniscus can be seen to change, but the authors have been able to think of no satisfactory way of measuring the effect on the capacitance of the measuring head.   In practice, it will probably result mainly in a time lag and is unlikely to produce an error in amplitude of more than about 2 mm.

The rapid fluctuations in the output produced by the circuit itself have an r.m.s. amplitude corresponding to a change in capacitance of about 0.5 $\mu\mu$F in the circuit shown in figure 5, and corresponding to a change in capacitance of about 0.01 $\mu\mu$F in the circuit of figure 6 (recorded with a 7-c/s galvanometer critically damped).   The slow drift may be a nuisance, but will not produce errors in the measurement of wave height.   The non-linearity of the calibration curve (figure 8) may be allowed for, if necessary, when measuring the records.

ACKNOWLEDGMENT

ENREGISTREUR A FIL A CAPACITE POUR LES ONDES

DE FAIBLE AMPLITUDE

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RESUME

    Un dispositif est décrit pour la mesure des
variations de hauteur du niveau de l'eau le long d'un
mince fil vertical.   Il convient pour la mesure d'ondes
dans les modèles de ports et dans les réservoirs à houle
et a été utilisé pour mesurer des ondes depuis quelques
mm à 50 cm de crête à creux.   Le fil est en cuivre
isolé et l'on mesure la capacité entre le conducteur en
cuivre et l'eau environnante, l'isolant constituant le
diélectrique: l'eau agit comme bon conducteur dans
cette application.   Cette capacité et la réponse de
l'appareil varient linéairement avec le niveau de l'eau.