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A SHIP-BORNE WAVE RECORDER

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S U M M A R Y

The instrument described measures waves from a ship which may be in deep water. It combines measurements of the sea pressure at a point on the ship's hull with the vertical displacement of this point, obtained by double integration of the output of a vertical accelerometer. No equipment has to be put outboard. A brief description of the instrument has previously been published, but the instrument has now proved itself by two years service, during which time approximately 2,500 records have been taken, and it is thought that a more detailed description should now be given, particularly as some of the instrumental techniques are of much wider interest.

Waves have now been recorded with shore-based instruments for some years and considerable advances in our knowledge of the generation and propagation of waves have resulted from study of these measurements. A brief survey of the wave-recorders used in this country has been published by the author (reference 1). It has recently been increasingly apparent, however, that wave measurements in the open ocean are required, particularly for the study of wave attenuation with distance of travel and of the effect on waves of travel through shallow water. A request was also received from the Air Ministry Meteorological Office for a wave recorder for use in the Ocean Weather Ships.

The difficulty of recording waves in the deep ocean arises from the absence of a steady platform on which to mount the recording instrument. A brief description of methods previously tried has been given in the author's previous article on the Shipborne wave recorder (reference 2). As a result of practical experience with some of these methods, the conclusion was reached that no method of wave recording which involves putting equipment outboard of a ship would be satisfactory, since handling such equipment in bad weather is both difficult and dangerous. A wave recorder which is to give satisfactory results under all weather conditions must be simple to operate and must also be reliable, since repair at sea may be difficult or impossible.

The wave recorder described here is contained entirely within the hull of a ship, a record is obtained merely by turning on a switch, and it has proved to be particularly reliable.

The principle of the instrument

In principle, the instrument measures the height of the water surface relative to a point on the ship's hull and adds this to the height of the point relative to an imaginary reference surface. The most satisfactory method of measuring the first of these quantities is to measure the water pressure on the hull, though this method involves some errors which are discussed below. Measurement of the second quantity is more difficult, and it is not practicable to measure the absolute height of the pressure measuring device. Fortunately, for the purposes of wave measurement it is only necessary to measure fluctuations in the height, and this may be achieved by measuring the vertical component of acceleration and integrating this twice. The sum of these two measurements gives the height of the water surface relative to an imaginary reference level (figure 1).

If waves approach the ship on the side containing the measuring device their height may be increased by reflexion, and conversely, if they approach from the opposite side a reduced wave height may be measured. To overcome this effect, a measuring unit is mounted on each side of the ship, the units being accurately opposite one another, and the mean of their outputs is taken. The outputs of the measuring heads are electrical and are brought to a computing circuit situated in a convenient part of the ship.

The ship must, of course, be stationary when the wave recorder is in use. It is apparent that false periods may be recorded if the ship is under way, and it has also been found by experiment that the apparent wave height is reduced.

Hydrodynamic problems

The precise calculation of the response of the wave recorder to waves of different frequencies and approaching from different directions is so difficult that it is probably impracticable. However, an intelligent estimate can be made by looking at the problem physically. The uncertainties involved are not serious for waves with periods of greater than 7 seconds, which includes most of the waves measured in the open ocean, but they are considerable for waves with shorter periods.

It is apparent that long waves, over which the ship will ride, will be measured almost entirely by the vertical accelerometer, whereas short waves, which do not cause the ship to heave appreciably, will be measured by the pressure units. The pressure fluctuations due to waves decrease very rapidly with depth, being reduced to half amplitude at a depth of a ninth of a wavelength, and since the pressure units have to be sufficiently deep to prevent their coming out of the water as the ship rolls, very short waves will not be measured at all.

For wave periods for which it is permissible to assume that the ship does not heave, the response of the pressure units may be calculated from the classical formula for the attenuation of pressure fluctuations with depth in deep water

$$P = P_o \exp(-2\pi h/L)$$
$$= P_o \exp(-4\pi^2 h/gT^2)$$

where P is the pressure amplitude at a depth h
P_o is the surface amplitude
T is the wave period

As the wave period increases and the ship starts heaving, it seems likely that the combined response of the pressure units and accelerometers is not very different to that given by the above formula. We may argue as follows. If the ship were held stationary, the above formula would hold approximately, though the presence of the ship's hull would change the pressure distribution to some extent: the extra changes in pressure as the ship rises and falls are balanced by the integrated signal from the accelerometers and will produce no output. This argument is a great over-simplification, but the attenuation is comparatively small over the critical range of periods (see figure 6) and errors in its calculation are probably not very important.

An extension of this problem arose from the installation in the Ocean Weather Ship "Weather Explorer". In the R.R.S. Discovery II the measuring heads are mounted 10 ft below the waterline amidships where the sides of the ship are almost vertical, but the only possible situation in the "Weather Explorer" was considerably further aft where the hull is V shaped, the sides being at approximately 45° to the vertical. Is the effective depth of the units the true depth of 10 ft, or would it be correct to use the distance round the hull to the nearest free water surface, which is 14 ft? Physical argument leads to the conclusion that the latter would be more correct, and comparison between records from the Discovery II and from the Weather Explorer when in the same vicinity, though not conclusive, also support this view.

The effects of wave reflexion from the sides of the ship represent a further uncertain factor. A short wave approaching from the beam will undergo complete reflexion which doubles its height at the hull of the ship and this doubles the output of the measuring head on that side. However, no output will be obtained from the measuring head on the other side of the ship, so that the average of the two outputs will be correct. The uncertainty arises when reflexion is partial, which occurs when the wavelength is of the order of 10 times the mean draught of the ship, (for a ship of 2000 tons displacement the corresponding wave periods would be about 5 to 6 seconds). The error at the worst wave-period probably does not exceed 10%, and definitely does not exceed 20%. When short waves are approaching from the bow or the stern, their height may be affected by reflexion from the tapering section of the ship's hull, but this effect is likely to be small.

The final hydronamic source of error is the effect of the bilge keels. On the "Weather Explorer" the measuring heads are some feet aft of the after end of the bilge keels, so that the problem does not arise. On the "Discovery II" the measuring heads are amidships and are only about 9 inches from the bilge keels which are, however, only 9 inches wide, so that as the ship rolls the pressure units will be affected by the variations in pressure produced. One unit will experience an increased pressure and one a decreased pressure, and since the mean of the two pressures is measured, the effect on the output will be small.

Ship-borne wave recorders are likely to be used almost entirely in small ships of about 2000 tons or less, that is, in research ships, ocean weather ships and survey vessels. In ships of this size the hydrodynamic uncertainties are only serious for waves with periods of less than about 7 seconds, and for longer period waves the errors involved are almost certainly less than 10%. Since waves in the open ocean rarely have a dominant period of less than 7 seconds, the maximum error due to these effects is taken as 10%.

The pressure unit

A simplified drawing of the measuring head is shown in figure 2.

The pressure meter connects with the sea through a half-inch diameter hole drilled in the ship's hull. An oil-filled chamber is separated from the sea water by a soft rubber diaphragm, and the oil takes up the pressure of the sea water and applies it to the outside of a metal bellows whose inside is open to the atmosphere. The resulting deflexion of the bellows is controlled by a spring and is measured by a mechano-electric transducer. The principle of this transducer has already been described (reference 3), but a brief description has been included below for the sake of completeness. The connecting rod is held central by means of spiral diaphragms of beryllium copper, and arrangements are provided for adjusting the initial compression of the spring so that when there are no waves the spiral diaphragms are flat. Following the adjustment, the transducer stator is moved until it is in its correct position relative to the moving coil, as indicated by the output voltage. Neither of these adjustments is critical, and variations of the mean pressure with the loading of the ship are not important.

In the first wave recorder fitted, the half-inch hole in the hull continued straight through the steel pad and then through the stop-cock to the pressure unit. After 6 months use, these holes in both measuring heads were found to be completely blocked by silt, presumably collected while the ship was in harbour. A chamber has now been fitted to collect this silt, and it may be cleared out by means of the drain cock. No trouble has since been experienced from this cause, but arrangements are provided in the electronics to enable each measuring head to be tested separately.

The vertical accelerometer

Measurement of the vertical acceleration on a ship is complicated by the sideways accelerations due to the waves, which resolve with gravity to cause a tilt of the apparent vertical. This means that an accelerometer mounted on a short period pendulum or in gimbals, and which will therefore set itself in the apparent vertical, will not measure the true vertical component of acceleration. It would be necessary to mount the accelerometer on a gyroscope if the true vertical component were required, but his would involve considerable expense, would increase the amount of servicing required, and would reduce the reliability.

Browne (reference 4) has investigated the errors introduced if the acceleration is measured in the direction of the apparent vertical. He was concerned with errors in the measurement of gravity at sea, but his results are directly applicable to the present problem. If the coordinates of the instrument relative to fixed axes are x, y and z (z vertically upwards) and g(t) is the resultant acceleration due to the combination of gravity and the wave accelerations

$$|G(t)| = [(g + \ddot{z})^2 + \ddot{x}^2 + \ddot{y}^2]^{\frac{1}{2}} \qquad (1)$$

giving to the second approximation

$$|G(t)| = g + \ddot{z} + (\ddot{x}^2 + \ddot{y}^2)/2g \qquad (2)$$

The first term on the right hand side represents the constant acceleration of gravity and is balanced out, the second term is the true vertical acceleration, and the third term is the error. Now Browne was only concerned with the long-term mean of the error, but we are concerned with its short-term fluctuations as well. If the horizontal displacement of the ship is $S(t) \cos \omega t$*, where $\omega = 2\pi/T$, T is the period of the motion, and S(t) is its amplitude which varies slowly compared with cos ωt, then to a first approximation

$$(\ddot{x}^2 + \ddot{y}^2)/2g = [\omega^2 S(t)]^2(1 + \cos 2\omega t)/4g \qquad (3)$$

Now $\omega^2 S(t)$, which is the amplitude of the horizontal acceleration, is likely never to exceed 0.3g amidships in an ocean-going ship, and is always of similar magnitude to the amplitude of $\ddot{z}$. The greatest value of $[\omega^2 S(t)]^2/4g$ is thus approximately 0.02g compared with an amplitude of $\ddot{z}$ of 0.3g. The cos 2ωt term represents an output fluctuating with twice the frequency of $\ddot{z}$, and its relative amplitude will therefore be further reduced by a factor of 4 by double integration (see below) and will then be negligible. The right hand side of equation (3) therefore reduces to $[\omega^2 S(t)]^2/4g$, which is a slowly varying quantity and which, being a square, is always positive. If it were truly integrated, it would give an output which increased indefinitely with time, but fortunately perfect integration is not necessary and the electronic integrating circuits can be designed to completely eliminate the steady component and to greatly reduce the effect of the slowly fluctuating component. The way in which this is achieved will be described below.

An estimate of the effect of this term, taking into account the response of the electronic circuits, showed that it might just produce an appreciable output. However, this would be a long slow fluctuation superimposed on the waves and would be readily distinguishable from them, so that it would not cause appreciable errors of measurement.

It was decided, therefore, that it was permissible to mount the accelerometer in gimbals, and this decision has been justified in practice since it has never been possible to distinguish with any certainty any long slow fluctuations under the waves on the record.

The accelerometer, then, is hung in gimbals in a bowl. The bottom of the accelerometer and the inside of the bowl are portions of spherical surfaces centred on the centre of the gimbal system and separated by about 1 mm. The bottom of the bowl contains a pool of silicone oil of 1000 centistokes viscosity, and this slightly more than critically damps the swinging of the accelerometer. Provision is made for rotating the bowl about a fore-and-aft axis, so that it may be set to be upright when the ship is on an even keel. If this were not done, the combined effect of the slope of the hull and the roll of the ship might cause the accelerometer to exceed the permissible angle of swing relative to the bowl. The accelerometer itself consists of a weight hung on a spring and attached to a mechano-electric transducer (see below). This system is prevented from moving sideways or rotating by means of two spiral diaphragms, and the whole device is filled with transformer oil which gives approximately critical damping. The natural frequency of the weight on the spring (including the effect of the inertia of the oil) is about 4 cycles per second, and for wave frequencies the device will therefore measure accelerations. It gives full deflection for an acceleration of between 0.4 and 0.5 g.

To adjust the rest position of the weight, the top of the accelerometer case is removed, the top spiral diaphragm is held flat by means of a simple jig and the transducer zero is adjusted. The top of the accelerometer case is then replaced and the two nuts at the top of the spindle are adjusted until the correct transducer output is restored when the weight and spring system is free.

*A more correct representation of the motion would be $A(t) \cos(\omega t + \delta)$ where δ is a phase angle varying with time in a more-or-less random manner. The omission of δ is not important for the present calculation.

The accelerometer has to be a very refined instrument. Though the maximum acceleration which has to be catered for is 0.3 g, a wave of 24 seconds period (the longest ever met with in the North Atlantic) and with an amplitude of 1 foot only produces about 10^{-3} g. It is apparent that the short-term stability of the accelerometer zero should be considerably better than this. The linearities of the spring and transducer have to be better than 1%, otherwise rectification occurs and a signal fluctuating with the wave envelope is produced. As mentioned above and discussed in more detail below, the sensitivity of an integrator increases as the period decreases, and these slow fluctuations are amplified relative to the wave signal. The electrical power output must also be reasonably high if the subsequent electronics are to be kept simple and reliable.

The main difficulties encountered during the development of the accelerometer were as follows:

(1) Initially, two parallel leaf springs were used to support the mass and to constrain it to move along the correct axis. These were found to have a non-linear spring rate, due to the initial deflection caused by supporting the force of gravity on the mass. This effect was overcome by using a helical control spring and two spiral diaphragms to constrain the mass to move along the correct axis.

(2) Trouble was experienced due to toggle action (the "oil-can" effect) in the spiral diaphragms. It was then realised that multistart spiral diaphragms are particularly subject to this trouble if there are any imperfections in manufacture or assembly. Single start spiral diaphragms are much less so, and carefully made single-start diaphragms made from beryllium copper sheet of .004 inch thickness were found to be satisfactory.

(3) Two leads have to be taken from the moving coil of the transducer, and these were originally made of 50 s.w.g. copper wire. A slight instability of the zero was eventually traced to mechanical hysteresis in these, and was eliminated when they were replaced by fine phosphor bronze strip.

<u>The mechano-electric transducer</u>

A transducer for an accelerometer whose output is to be integrated must be very stable and linear to avoid the production of troublesome low frequency signals, any mechanical forces it appies to the moving parts should be small since they will, in general, vary non-linearly with displacement, and a comparatively large voltage output is desirable in order to avoid electronic complications. Fortunately, a transducer fulfilling all these conditions had already been developed by the author for another instrument (reference 3). Its principle of operation is shown in figure 3. A stack of E type transformer laminations has a coil wound round the base of the centre limb and this coil is supplied with 1000 c/s energising voltage. Since the high-permeability laminations form the magnetic equivalent of a short circuit, the whole magneto-motive force appears across the air gap between the centre and outer limbs and produces a uniform field except near the top where end effects become appreciable. A second small coil round the centre limb picks up a voltage which is proportional to the number of alternating lines of force threading it and which therefore varies linearly with displacement along the limb. The voltage picked up by this coil in its central position may be balanced by connecting it in series - opposition with a small fixed coil wound over the main energising coil, but in the present instrument it simplifies the electronic circuit if balancing is done after rectification.

The transducers in the ship-borne wave recorder use a 1/4 inch stack of stampings of 0.004 inch thickness and with overall width and height of 1 inch. The output voltage varies linearly with displacement to within 1% over a displacement range of 1/4 inch, corresponding to a voltage range of 6.4 to 13.6 volts. The output impedance is about 85 ohms, but varies slightly with displacement, so that it is not permissible to use a load impedance of less than 500 ohms if the 1% linearity is to be retained. The electromagnetic reaction forces on the coil vary with the electrical loading, but are of the order of a few milligrams with the load circuit used in the wave recorder. The zero is stable to about 10^{-4}cm (long term) if the steady voltage is balanced by using a third coil, but is not quite as good as this with the balancing arrangements used in the present circuit.

Electronic Integration

Though the problem of electronic integration will be discussed with particular reference to the Ship-borne Wave Recorder, the principles involved are quite general.

Sea waves may conveniently be regarded as being composed of a series of sinusoidal wave trains, and over a period of time P we may represent the vertical acceleration A (t) by

$$A(t) = \sum a_n \cos(\omega_n t + \theta_n) \qquad (4)$$

where $\omega_n = 2\pi/T_n$

T_n is the period of the component wave train. *

The vertical velocity $V(t) = \int A(t)\,dt + C$ where C is a constant of integration

Thus $V(t) = \int \sum a_n \cos(\omega_n t + \theta_n)\,dt + C$

$= \sum (a_n/\omega_n) \sin(\omega_n t + \theta_n) + C$

Similarly, a second integration to convert the velocity to the displacement S(t), will give

$$S(t) = \sum (-a_n/\omega_n^2) \cos(\omega_n t + \theta_n) + Ct + D \qquad (5)$$

The term Ct + D is dependent on the initial state of the integrators when the equipment is switched on. It would be important in a perfect integrator, but in the present application it represents a transient whose effect disappears when the instrument has settled down. Thus a device performing double integration has an amplitude response inversely proportional to the square of the frequency, and produces a phase shift of 180° for all frequencies.

The greatly increased response to low frequencies is extremely inconvenient in practice, since small low frequency voltages can be introduced into the input of the integrating circuits in several ways, such as by non-linearity of the transducer or rectifier, by instability of the transducer zero, or by small changes in the characteristics of the rectifiers. Changes in power supply voltage can often also introduce low frequency voltages into a critical part of the circuit, and it has been pointed out above that in the present application the effect of mounting the accelerometer in gimbals is to introduce a low frequency component derived from the wave envelope. These small voltages may be amplified and produce large drifts in the output. Obviously all possible precautions must be taken to avoid the introduction of low frequency voltages into the early stages of the circuit, but it is also possible to minimise their effects by making the integrators only just good enough for the job in hand. The circuit will integrate accurately if the frequency response and phase-shift characteristics are correct for those frequencies present in the input signal: the response to other frequencies is unimportant and may be made to fall off as quickly as possible for frequencies below the lowest present in the input. The lowest frequency component we have ever detected in the North Atlantic had a period of 24 seconds, and the response of the integrators must therefore be correct down to this limit.

The simplest form of electrical integrator is a capacitor fed through a resistor (figure 4). If the voltage E_0 across the capacitor C is kept small, the current i through the resistor R is E_1/R and

$$E_0 = (1/C)\int i\,dt = (1/RC)\int E_1\,dt$$

The simplest way of examining accurately the response of this circuit is to transform it to the equivalent circuit shown in figure 5. The equivalence is exact, and may be proved by comparing the differential equation or the circuit responses using the j operator. It will now be seen that the problem has been reduced to designing the R C coupling to pass the lowest frequency present in the input, and this is a problem familiar to electronic engineers.

* This is a Fourier series, and is a mathematically rigorous representation if the summation extends for all integral values of n from 0 to infinity. a_n and θ_n may be found from the equations

$$a_n \cos\theta_n = (2/P)\int_0^P A(t) \cos\omega_n t\,dt$$

$$a_n \sin\theta_n = (2/P)\int_0^P A(t) \sin\omega_n t\,dt$$

In the present case an integrating time constant (the product of C and R) of 8.8 seconds is used, giving, for one integrator stage, approximately 92% response to a wave of 24 seconds period. A separate series-capacitance shunt-resistance coupling with the same time constant is also included in the circuit, so that the overall amplitude response is down to 77% at 24 seconds period. When combined with the effect due to the depth of the pressure units, this gives a frequency response which is reasonably constant over the most important range of periods, that is, between 8 and 20 seconds (figure 6). It has been assumed in calculating these curves that the response of the circuit to a voltage fed into the pressure unit inputs has the same errors as the response to the acceleration signal, whereas it actually has the errors corresponding to 2 R C couplings instead of to 3. The difference will be small for the short periods contained in the pressure signal, and will produce less than 1% error in the response curve. The nominal sensitivity is arranged to be correct for the range of periods over which the curve is sensibly flat, and for other periods a small correction may be applied.

The falling-off in response for long period waves is, of course, undesirable, but even with the comparatively low time-constant used, the response of the amplifiers to very low frequency input voltages rises to about 12 times the response to voltages of 10 seconds period (figure 7) and the time-constant used appear to be the best compromise.

<u>The electronic computer circuit</u>

The complete circuit is shown in figure 8. The 1000 c/s output of the port accelerometer (which varies about a mean of 10 volts r.m.s.) is transformed up in voltage by 1 : 8 and is then half-wave rectified in diode V 1 B. A voltage in the opposite sense derived directly from the 1000 c/s supply is balanced against this, and the output is then taken through a preset potentiometer P2 to the first integrator R3 and C1. P1 adjusts the balance and P2 adjusts the sensitivity of this circuit (see under "Calibration"). It is important to connect T1 so that both diodes are conducting simultaneously. If they conduct on alternate half cycles, the sensitivity is reduced by about 20% since diode V1B will then have R2 in series with it during conduction and similarly V1A will have R1 in series. The sense of connection is checked by measuring the A.C. voltage on T P 1. The D.C. sensitivity on the input of P2 is between 30 and 40 volts/g. A simple R C integrator is used in preference to a feedback ("Miller") integrator, since the required time constant can be achieved with standard components of reasonable values, though the 8 μ F capacitor, which has to be of good quality, is bulky. It is the author's experience that circuits in instrument electronics should be as straightforward as possible, since the more complicated the principle of operation of a circuit, the more is the chance of unexpected side effects and the greater is the difficulty of fault-finding. The output resistance of the rectifier and sensitivity control P2 depends to some extent on the setting of the latter, but will be about 100 K ohms. This value, added to the value of R3, gives an effective time constant of 8.8 seconds.

The starboard accelerometer rectifier is similar in principle, but is opposite in sense to the port accelerometer rectifier. The two integrated voltages are fed in push-pull to the grids of a double triode which gives a voltage gain of about 20. The second integrator (port side) comprises R 17 and C3. The port pressure signal is fed into the earthy side of C3 and comes from an impedance sufficiently low not to affect the integration. The pressure-unit rectifiers are similar in principle to the accelerometer rectifiers, except that the signal from the measuring head is rectified direct, and the balancing signal is transformed down from the 1000 c/s supply. From the point of view of the port pressure signal, C3 and R17 form an R C coupling which brings the signal to the correct D.C. level. R18 and C4 form the smoothing circuit of the port pressure-unit rectifier, and have to be this side of C3 in order to avoid an appreciable impedance in the integrator circuit. The operation of the starboard circuit is similar, except that the rectifier is in the opposite sense.

The signals, which are now proportional to the water height on each side of the ship, are fed to the grids of a double-triode. Since the port rectifiers are in opposite senses to the starboard rectifiers, the difference in the voltages is proportional to the sum of the heights, which is the quantity required. V5 is therefore connected as a differential amplifier which feeds through an R C coupling to a balanced cathode-follower output stage with an output impedance of approximately 1050 ohms.

There is a D.C. path from the accelerometers to V5, and the meter M therefore checks the balance of the accelerometer rectifiers and of the amplifiers V2 and V5. To adjust the balance controls, switches S1, S2, S3 and S4 are switched off; P3 is adjusted till M shows no current, S1 is switched on and P1 is adjusted, and finally S2 is switched on and P5 adjusted. This process is rather slow, since the signals have to come through the integrators. The D.C. voltage on TP5 should be between 75 and 110 volts relative to H T -.

The gain of a triode amplifier is comparatively stable, and a certain amount of negative feedback is also introduced by the cathode resistors of V2 and V5. All important resistors are high stability carbon, and the sensitivity of the computing circuit should therefore be constant within narrow limits.

A recalibration of one of these wave recorders after a year's service in an Ocean Weather Ship showed an overall change in calibration of 6% on the port accelerometer, 1% on the starboard accelerometer and 3% on the pressure units. These are within the estimated accuracies of calibration, which is 6% for both the accelerometers and the pressure units.

It is interesting to note that owing to the circuit being balanced all the way through, the deterioration or failure of any valve except V4 and V6 will show up as an unbalance on M or in the output, and the same holds for the majority of the components. The circuit, besides being a fundamentally reliable design, is therefore unlikely to develop a fault without warning the operator.

The switches S1 to S4 allow the operator to make sure that each measuring unit is working.

The 1000 c/s oscillator and power unit

The sensitivity of the wave recorder is proportional to the 1000 c/s voltage energising the measuring heads, and it is therefore desirable to keep this voltage within about 1% of the correct value. The transducers also require a low impedance supply if they are to be linear and if interaction is to be avoided. The total power required is just under 3 watts. It was therefore decided to use a bridge-stabilised oscillator followed by a power amplifier with heavy negative feedback.

The circuit of the oscillator is shown in figure 9. The bridge-stabilised oscillator (V1 and V2) was developed from that described by Clifford (reference 5). This is followed by a power amplifier whose whole output is fed back negatively to the input. This, of course, involves difficulties with stability, but the problem is eased by using a tuned air-gap transformer in the output. The network R 12, C 13 and C 14 and the capacitors C 10 and C 11 do not appreciably affect the response at 1000 c/s but reduce the loop gain at high frequencies without their combined phase-shifts reaching 90° at any frequency.

The output impedance is 7 ohms, the stabilisation ratio against mains voltage is approximately 80 : 1, and the long-term stability is about 1%.

The power unit, which is unstabilised, is of conventional design and no circuit diagram is therefore given.

Calibration

The pressure measuring heads are calibrated by measuring the A.C. output voltage for various applied pressures. This gives a sensitivity in Volts/foot. The voltage gain of the amplifier from the pressure unit inputs is measured by connecting to each in turn a 1000 c/s voltage which is switched suddenly from 10 volts to another suitable voltage. The instantaneous change in output voltage is measured using a fairly fast graphic recorder and allowance is made for the slight delay in response. It is usually possible to choose the port and starboard pressure measuring heads so that the overall sensitivity (output volts/ft pressure change) is the same for both to the required accuracy, but if this cannot be done, the sensitivity of the more sensitive unit is reduced to that of the other by using either R 15 and R 16 or R 28 and R 29 as a potential divider. The basic sensitivity of the wave recorder is TWICE the overall sensitivity of the individual pressure channels, since normally both channels work at the same time.

The port accelerometer is now mounted in gimbals on an arm of 18 inches radius rotating in a vertical plane, and is connected to the corresponding input of the computing circuit. A sensitive graphic recorder measures the circuit output voltage. The arm is now rotated with a period of, say, 10 seconds and the sensitivity is set using P2 until the peak-to-peak output voltage is correct for a wave height of 1.5 feet (since only one accelerometer is connected), using the basic sensitivity with a small correction for the attenuation of the integrators at the period of rotation used (see figure 6). The output is checked at other rates of rotation. The sensitivity of the starboard circuit is set in a similar way.

The basic sensitivity obtained in this way corresponds to the level I in figure 6, and the nominal sensitivity is therefore this value divided by 1.2.

The output voltage measured is always the intrinsic voltage, that is, the voltage that would be developed on open circuit. The current flowing through the graphic recorder is the intrinsic voltage divided by the total circuit resistance, which includes the output resistance (approximately 1050 ohms) of the computer circuit. In practice, the recorder is calibrated in terms of intrinsic voltage by connecting a battery in series with it through a reversing switch, and measuring the voltage on the battery terminals and the deflection of the recorder when the reversing switch is thrown.

The other necessary precaution is to use a fast recorder chart speed during calibration in order to minimise the effects of pen friction.

Conclusion

The author would like to express his thanks to Mr. F.E. Pierce who was responsible for the mechanical design of the instrument, and whose able co-operation contributed greatly to its success.

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Figure Captions

Figure 1
The principle of operation of the instrument.

Figure 2
The measuring head (simplified drawing).

Figure 3
The principle of operation of the transducer.

Figure 4
The simplest electrical integrator.

Figure 5
A circuit exactly equivalent to that shown in figure 4

Figure 6
The frequency and phase response of the wave recorder, assuming the measuring heads are mounted 10 feet below the waterline on a vertical section of the hull. The dotted line shows the attenuation due to the depth of the measuring head, the chain-dotted line shows the error due to the electronics, and the solid line is the combined response.

Figure 7
The frequency response of the computing circuit to a voltage fed into the first integrator. The dotted line is the response of a perfect double integrator.

Figure 8
The computer circuit. For the components schedule, see below.

Figure 9
The 1000 c/s 3 watt bridge-stabilised oscillator which energises the transducers. For the components schedule, see below.

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Components schedule for the computer circuit (figure 8)

C 1, C 2, C 3, C 8, C 9, C 10, 8 microfarads high quality paper dielectric.

C 4, C 5, C 6, C 7, 0.1 microfarad.

Resistor values in K ohms. Resistors marked (1) are $\frac{1}{2}$ Watt, Grade 1 $\pm$ 5%; those marked (2) are $\frac{1}{2}$ Watt, Grade 2, $\pm$ 20% and those marked (225) are $2\frac{1}{2}$ Watt, Grade 2, $\pm$ 5%.

R 1	100	(1)
R 2	100	(1)
R 3	1,000	(1)
R 4	47	(1)
R 5	220	(1)
R 6	220	
R 7	4.7	(1)
R 8	4.7	(1)
R 9	1,000	(1)
R 10	100	(1)
R 11	100	(1)
R 12	1.0	(2)
R 13	4.7	(1)
R 14	4.7	(1)
R 15	Initially short circuit	
R 16	Initially open circuit	
R 17	1,000	(1)
R 18	100	(2)
R 19	100	(1)
R 20	100	(1)
R 21	10	(1)
R 22	10	(1)
R 23	0.47	(1)
R 24	0.47	(1)
R 25	68	(2)
R 26	100	(2)
R 27	1,000	(1)
R 28	Initially short circuit	
R 29	Initially open circuit	
R 30	4.7	(1)
R 31	4.7	(1)
R 32	1,000	(1)
R 33	1,000	(1)
R 34	100	(1)
R 35	47	(1)
R 36	15	(225)
R 37	15	(225)
R 38	4.7	(1)
R 39	4.7	(1)

Potentiometer values in K ohms

P 1	10
P 2	500
P 3	100
P 4	500
P 5	10

Meter M 250-0-250 μA 500 ohms resistance

V 1	CV 140	(6 AL 5)
V 2	CV 455	(12 AT 7)
V 3	CV 140	(6 AL 5)
V 4	CV 140	(6 AL 5)
V 5	CV 491	(12 AU 7)
V 6	CV 140	(6 AL 5)
V 7	CV 491	(12 AU 7)

....

Components schedule for the 1000 c/s bridge-stabilised oscillator (figure 9).

Capacitor values in microfarads

C 1	0.01	C 9	0.1
C 2	----	C 10	0.000,1
C 3	0.0015	C 11	0.000,33
C 4	0.0015	C 12	0.01
C 5	2.0	C 13	0.000,047
C 6	0.1	C 14	0.000,47
C 7	2.0	C 15	0.02
C 8	0.1		

If the amplifier oscillates at high frequency, this can probably be stopped by interchanging C 10 and C 11

Resistor values in K ohms. Resistors marked (1) are ½ Watt, Grade 1 ± 5%; those marked (2) are ½ Watt, Grade 2 ± 20%, and those marked (22) are 2½ Watt, Grade 2 ± 20%

R 1	100	(2)	R 13	2.5	(2)
R 2	2.2	(2)	R 14	150	(2)
R 3	0.33	(2)	R 15	22	(2)
R 4	2.5	Eureka wire-wound	R 16	150	(2)
R 5	1,000	(2)	R 17	330	(2)
R 6	0.15	(2)	R 18	0.47	(22)
R 7	100	(2)	R 19	1.0	(2)
R 8	(100	(1) (Vary this to tune oscillator	R 20	4.7	(2)
R 9	(100	(1)	R 21 x	0.1	(2)
R 10	10	(2)	R 22 x	0.1	(2)
R 11	470	(2)	R 23	330	(2)
R 12	100	(2)			

x Connect R 21 and R 22 direct to valve holder tags

P 1 1 K ohm (adjusts amplitude of oscillation)

V 1	CV 133	(6C 4)	V 4	CV 2136
V 2	CV 138		V 5	CV 2136
V 3	CV 455	(12 A T 7)		

T 1 T K 6 A (special air-gap transformer)
Primary 1,500 turns centre tapped.
Secondary 600 turns tapped at 400 and 500.

T 2 "Wearite" type 212

T 3 T K 6 A

L P X 964208 (nominal 230 Volts 12 Wt) leads to be soldered direct to lamp base.

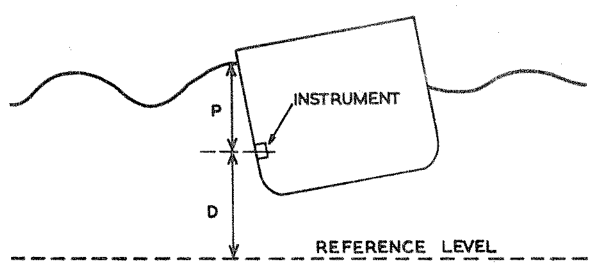

FIGURE 1

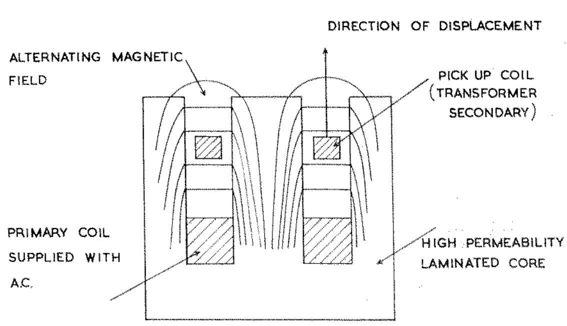

FIGURE 3

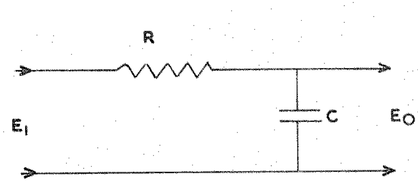

FIGURE 4

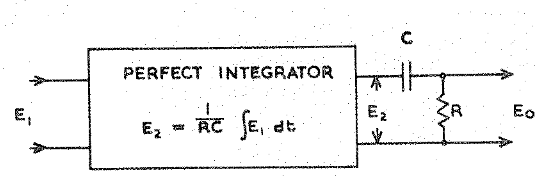

FIGURE 5

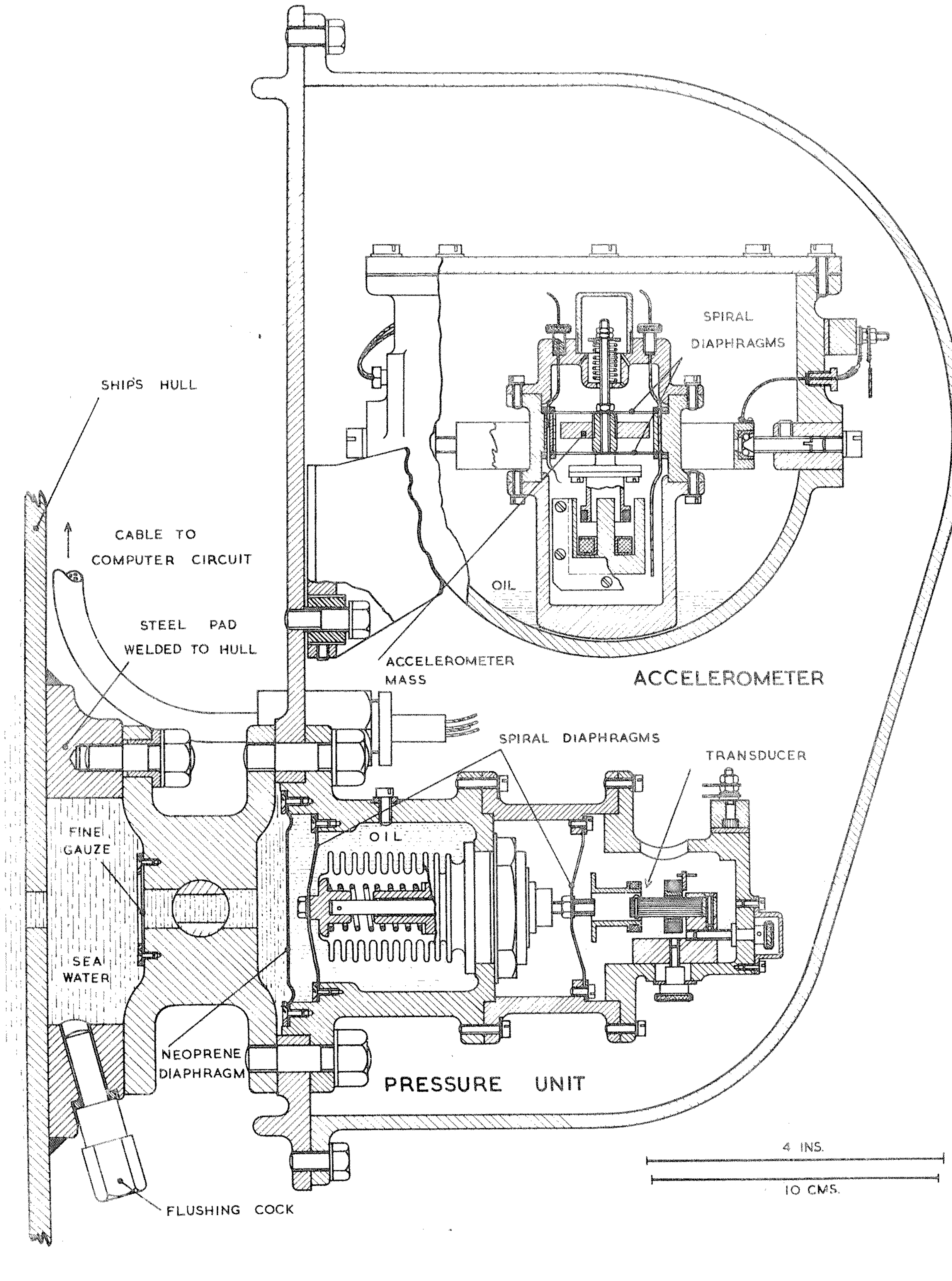
SPIRAL
DIAPHRAGMS
SHIPS HULL
CABLE TO
COMPUTER CIRCUIT
OIL
STEEL PAD
WELDED TO HULL
ACCELEROMETER
MASS
ACCELEROMETER
SPIRAL DIAPHRAGMS
TRANSDUCER
OIL
FINE
GAUZE
SEA
WATER
NEOPRENE
DIAPHRAGM
PRESSURE UNIT
4 INS.
10 CMS.
FLUSHING COCK

FIG 2

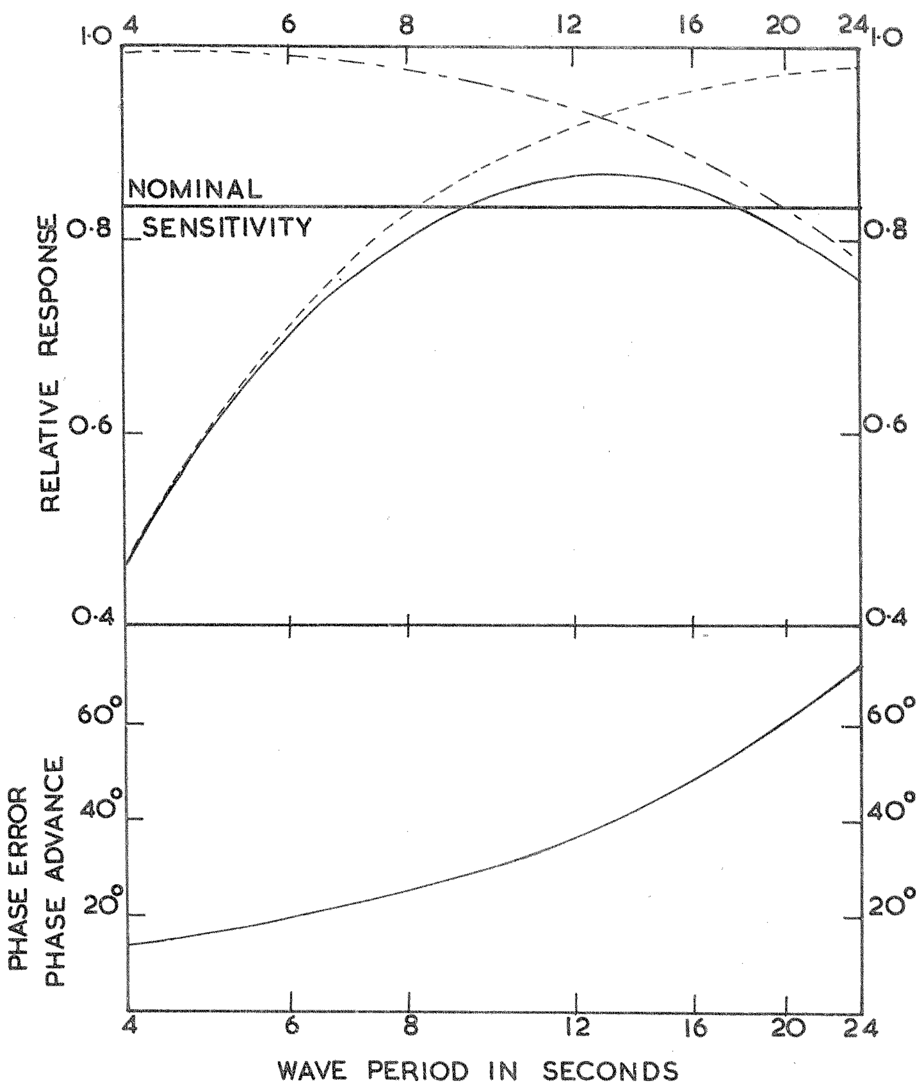

FIGURE 6

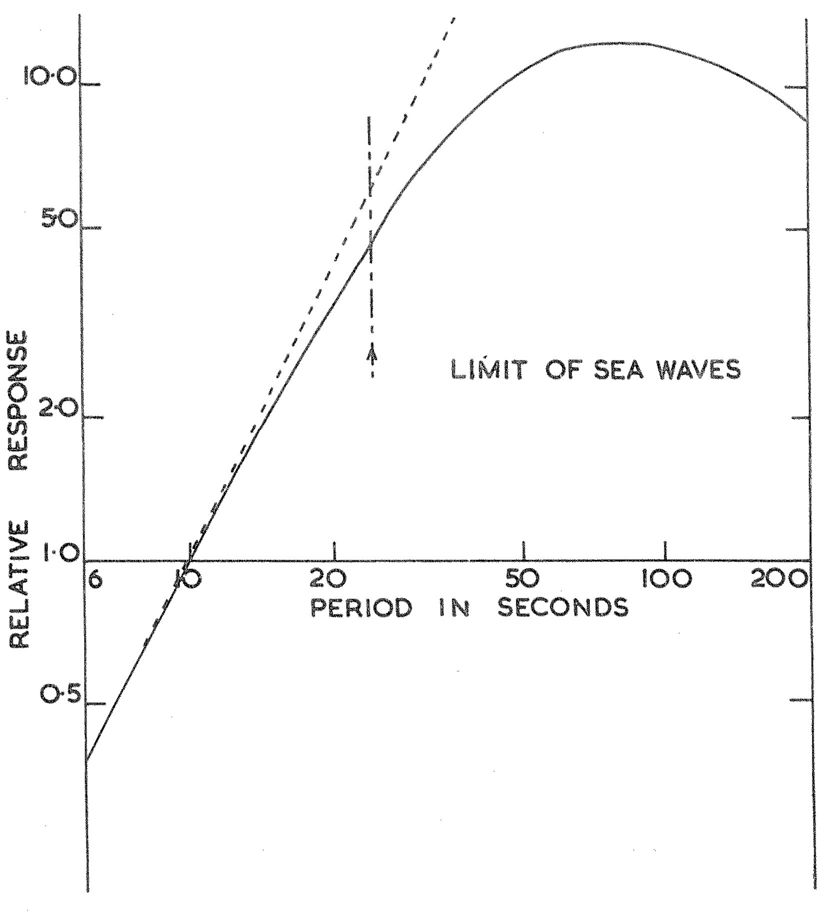

FIGURE 7

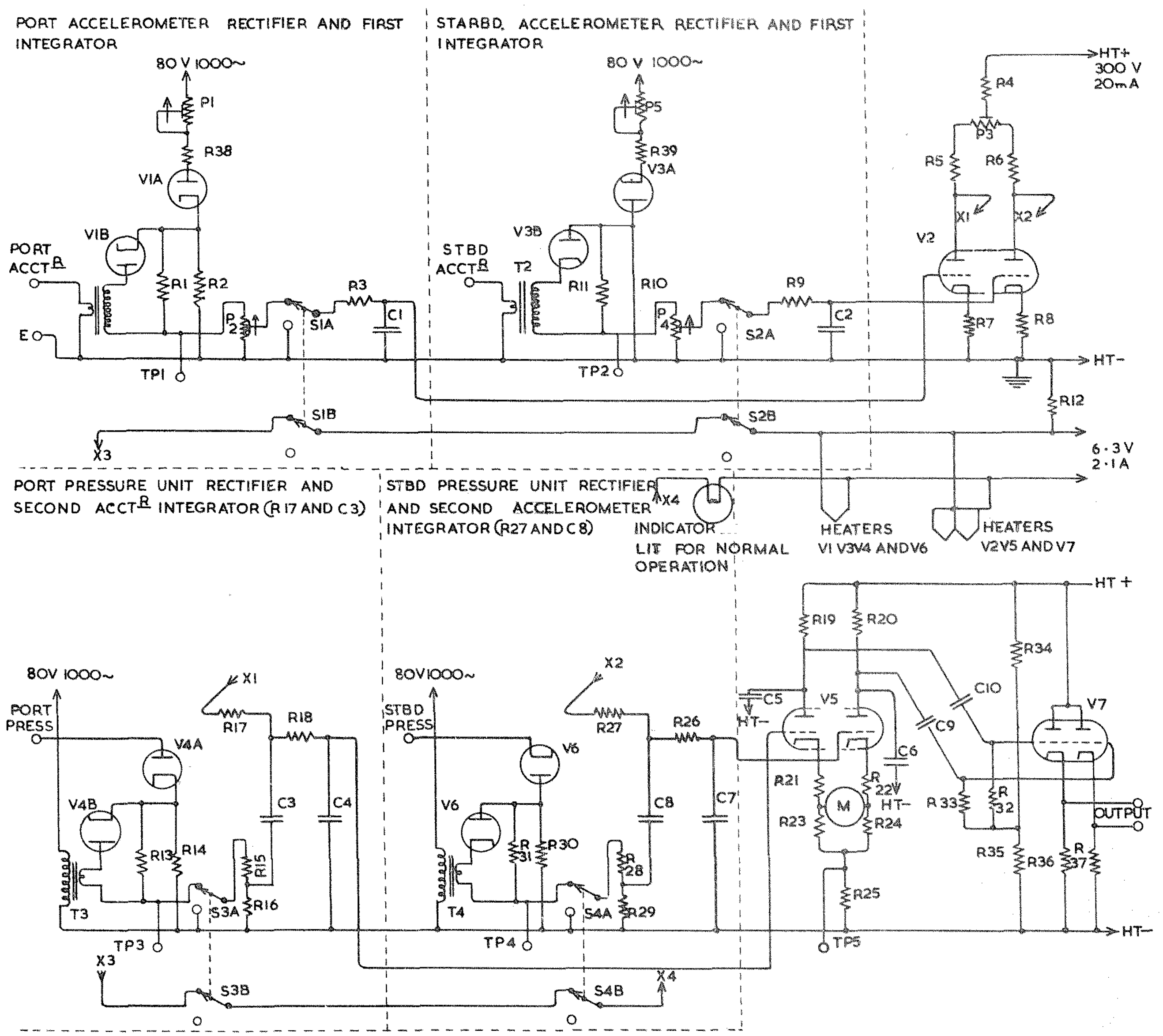
PORT ACCELEROMETER RECTIFIER AND FIRST INTEGRATOR
STARBD. ACCELEROMETER RECTIFIER AND FIRST INTEGRATOR
PORT PRESSURE UNIT RECTIFIER AND SECOND ACCT^R INTEGRATOR (R17 AND C3)
STBD PRESSURE UNIT RECTIFIER AND SECOND ACCELEROMETER INTEGRATOR (R27 AND C8)
INDICATOR LIT FOR NORMAL OPERATION
HEATERS V1 V3 V4 AND V6
HEATERS V2 V5 AND V7
HT+ 300 V 20mA
6·3 V 2·1 A
OUTPUT

FIGURE 8

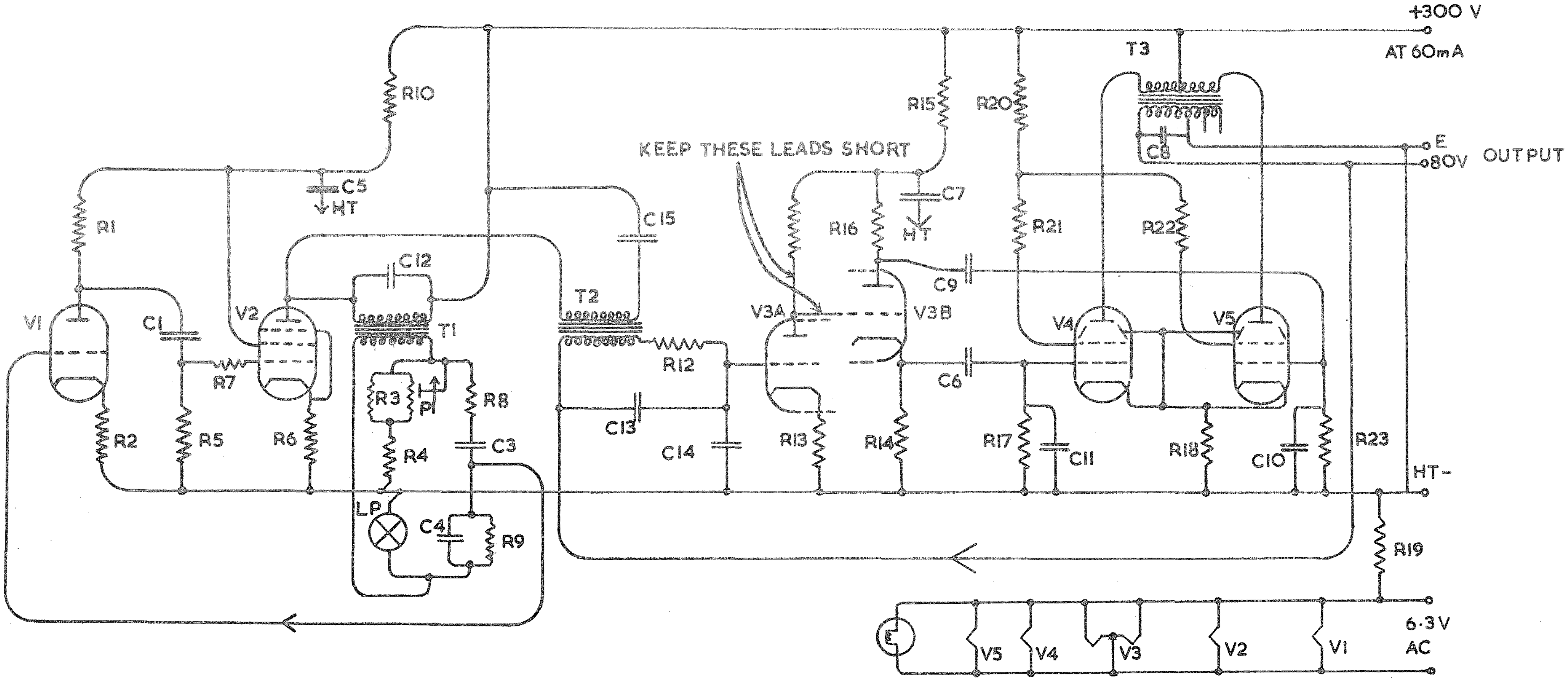
+300 V
AT 60mA
T3
R10
R15
R20
KEEP THESE LEADS SHORT
E
80V OUTPUT
C8
C5
HT
C7
HT
C15
R1
R16
R21
R22
C12
T2
C9
V3A
V3B
V1
C1
V2
T1
V4
V5
R12
R3
P1
R8
C6
R7
C13
R2
R5
R6
R4
C3
C14
R13
R14
R17
C11
R18
C10
R23
HT-
LP
C4
R9
R19
6·3V
AC
V5
V4
V3
V2
V1

FIGURE 9