A CURRENT-METER FOR MEASURING TURBULENCE

by :

A.T. DOODSON, F.R.S.

Assistant-Director of the Liverpool Observatory and Tidal Institute, Birkenhead.

1. *INTRODUCTION.*

The measurement of tidal currents presents many difficulties, and many types of apparatus have been designed with special objects in view. It is obvious that apparatus which is self-contained, and which is designed to be left unattended in all kinds of weather, must be of a robust nature and may therefore lack sensitivity; the limitations of size impose limitations on the records, which must be either intermittent or contracted in the time-scale. Some meters are effectively integrating meters and yield the " run " of the current, either at predetermined equal intervals of time or else at unequal intervals of time depending on the speed of the current. Others again integrate the run over a period of 24 or 25 hours so as to average out the tidal variations of current and yield the resultant drift in the period. Comparisons between meters should therefore take into account the purposes of the designer.

Instruments of the " universal " type, capable of recording tidal currents moment by moment, with great accuracy, can be used for the general purposes for which tidal currents are recorded; that is, the records can be made intermittently, if desired. On the whole it appears undesirable to go to the trouble of using a current-meter which does not give the maximum of information. Whenever possible, it is desirable to obtain records of the variation of current, at least hour by hour, so that the tidal currents may be determined, rather than to obtain integrated results only.

For the measurement of turbulence, all types of integrating meters are unsuitable, and it is necessary to be able to obtain frequent readings of velocity and direction of current. Further, the moving parts must be as light as possible to reduce inertia effects, frictional errors must be very small, the apparatus must not be bulky lest its dimensions become comparable with the spatial scale of turbulent motion, and it should not be so heavy that it cannot be managed from a small wooden ship.

The apparatus described in this paper has been specially designed to give records which can be used for the study of turbulence. It is highly sensitive to weak currents, has a scale practically linear with the velocity of current, and it gives records as frequently as at intervals of 15 seconds. If required, velocities only can be registered continuously on a very open time-scale.

2. *PHOTOGRAPHIC AND ELECTRICAL METHODS OF REGISTRATION.*

For records at frequent intervals only two methods of registration appear to be available, the photographic method and the electrical method. These will be briefly compared.

Photographic registration is possible both for positions of the compass (or compass card) and for the indicator of velocity (arm or revolving card) provided that the meter can be made water-tight, so that the clock-work mechanisms and cameras can be operated in air. This would require the use of an elastic diaphragm to record the instantaneous variations of external pressure due to the current. The difficulty of keeping the instrument free from water, the large size of the meter (for records at frequent intervals) in order to include all the apparatus (clockwork, cameras, batteries), the lack of sensitivity and uneven scale resulting from using a pressure plate, are all disadvantages only offset by the advantage of the instrument being self-contained.

Electrical registration is not possible in a self-contained instrument without making it extremely bulky and heavy. It is not then suitable for research work in turbulence. If the apparatus need not be self-contained (that is, if it is always operated from a ship), then the actual recording can take place on board the attendant ship, leading to many simplifications in the design of the meter, which can be made small and easily handled, while the intrusion of water can be avoided by the use of oil in the meter. The disadvantages of a pressure plate can be avoided, but the frictional forces arising from the electrical contacts must be made small. It is necessary to provide means for making the magnet itself to indicate its position by electrical contacts.

3. *THE MAGNET SYSTEM.*

A survey of the current-meters proposed or in use was made and electrical registration was decided upon. Special consideration was given to Witting's meter in which the magnet, or an attached framework, is mechanically moved bodily into contact with a potentiometer, from which electrical indications of direction are recorded on board ship. The contacts are made at intervals depending upon the number of revolutions of a propeller, and therefore at intervals depending inversely on the speed of current. The deflection of the needle of a simple galvanometer indicates the magnetic direction, and the intervals between the deflections are inversely proportional to speed. The whole of the meter is filled with a light petroleum oil to keep out water.

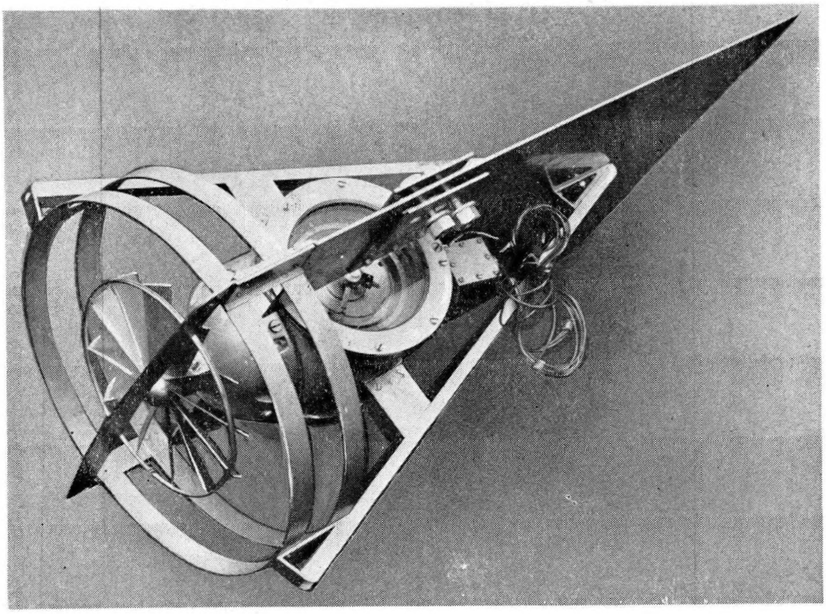

PLATE 1. — PLANCHE 1.
General view of current-meter without swivel.
Vue générale de l'enregistreur de courant sans émerillon.

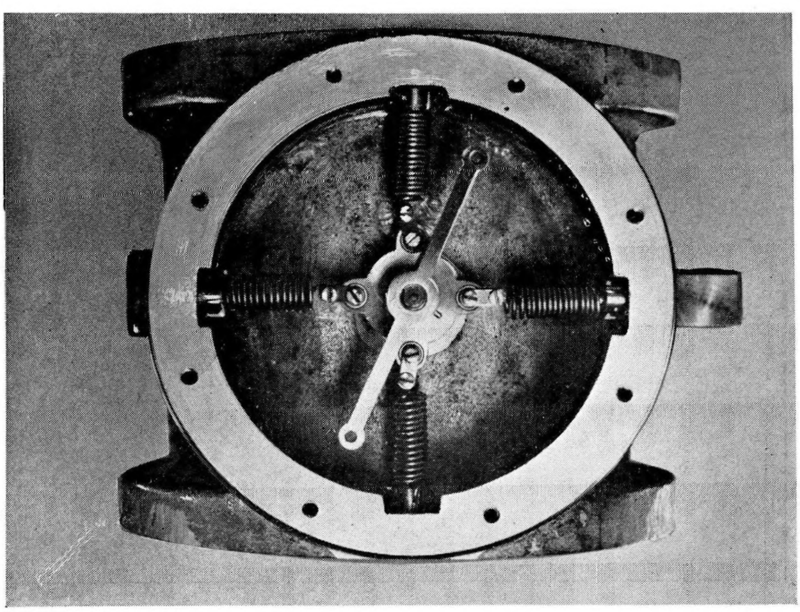

PLATE 2. — PLANCHE 2.
The spring control. — *Commande des ressorts.*

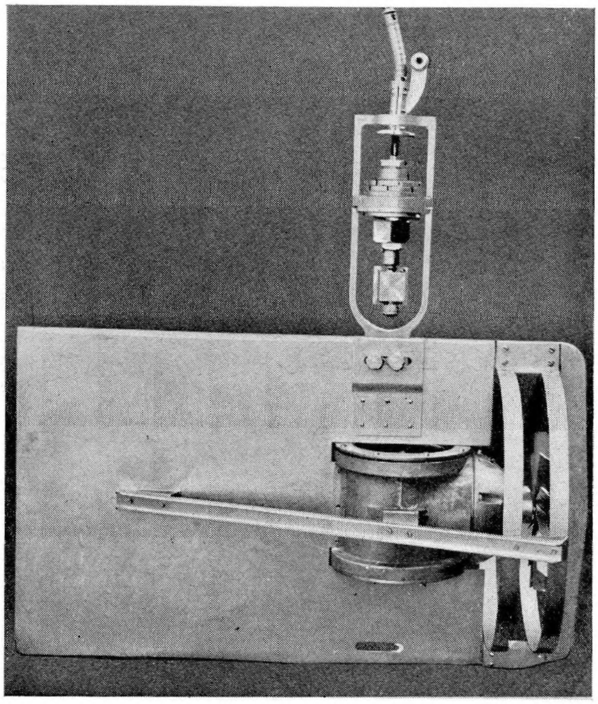

PLATE 3. — PLANCHE 3.
Meter, Swivel and Cable.
Appareil de mesure, émerillon et câble de suspension.

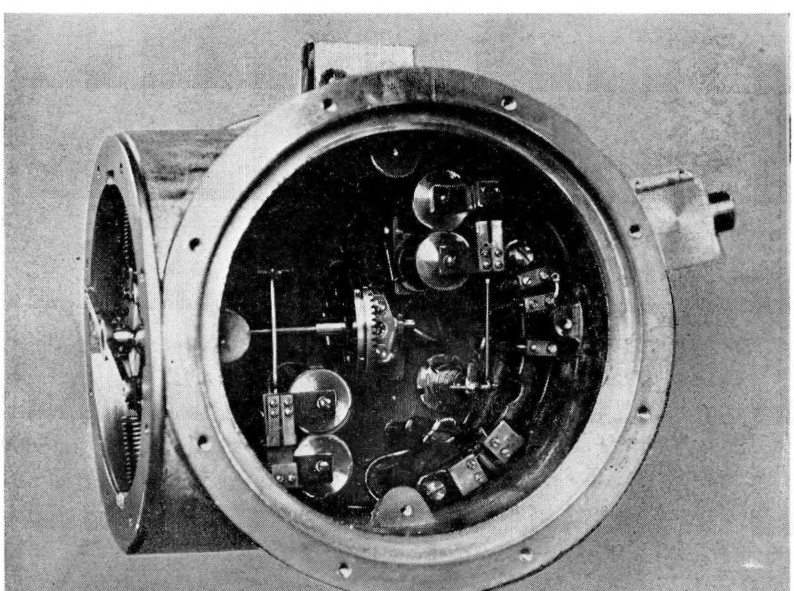

PLATE 4. — PLANCHE 4.
Interior of meter-body showing electromagnets.
Intérieur du corps de l'appareil de mesure montrant les électro-aimants.

The idea of mechanical operation of making electrical contacts, between which the magnet is swinging freely, seemed to be very satisfactory, though the uneven intervals were not regarded as suitable for the purposes in view, while the integration of current due to the use of a propeller is also undesirable for the measurement of turbulence. Contacts at even intervals of time could only be made by enclosed clockwork, with many attendant disadvantages, or by electrical means. Much experimental work on the possibilities of the use of electro-magnets was carried out to ascertain (1) if electro-magnets of small size could give sufficient power to make electrical contacts through an oil film; (2) if the electrical currents involved were such as to allow the use of portable accumulators; (3) if the use of iron cores, or the residual magnetism in them, materially affected the position of the magnet relatively to the earth's field; (4) if the positions of the magnet could be ascertained at intervals of one minute or less.

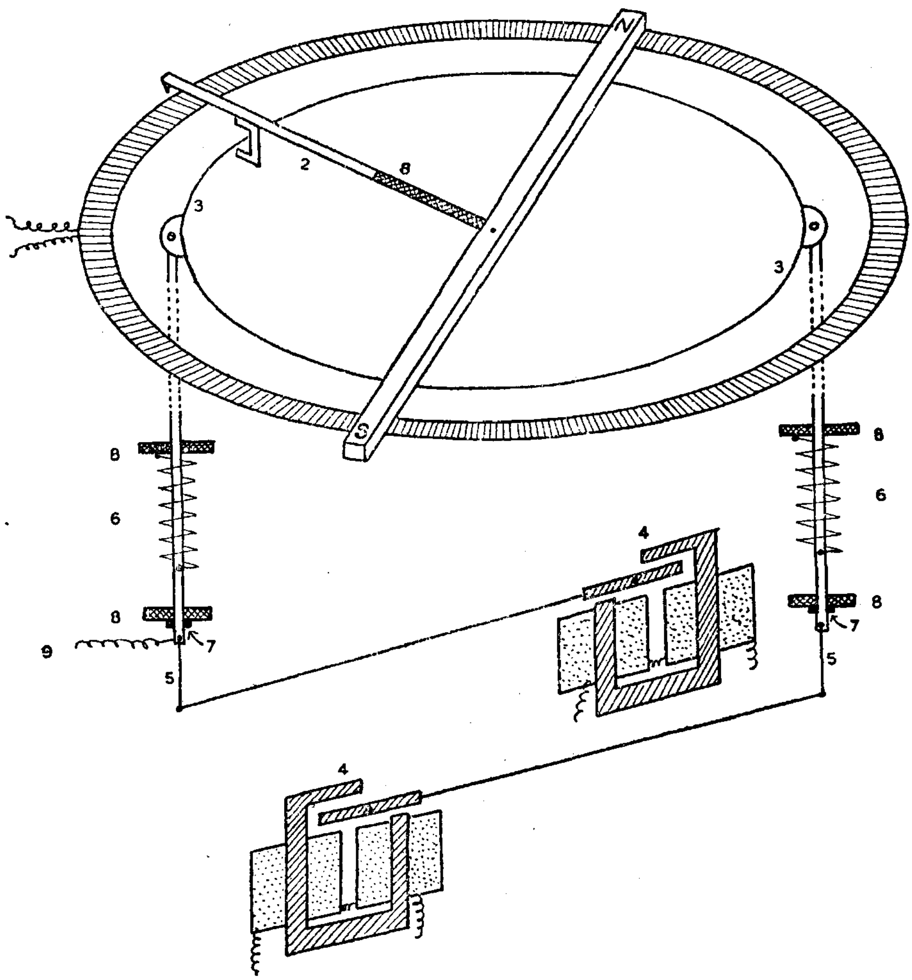

FIG. 1.

1. Potentiometer.
2. Contactor Arm.
3. Contactor Ring.
4. Electromagnets.
5. Swivels.
6. Light springs.
7. Stops.
8. Ebonite rod and rings.
9. To galvanometer.

Satisfaction having been obtained on all these points, the magnetic system was ultimately designed as indicated in Fig. 1. It was deemed inadvisable to use the end of the magnet itself to make contacts on account of the loss of magnetism due to frequent bumps, and accordingly a contactor arm at right angles to the magnet was used. This arm carries a small strip of metal in which there is an aperture on one side. The magnet swings on a needle in a central split cone mounting, and the magnet mounting contains an agate cup for engaging the needle. Thus the magnet swings very freely. In the centre of the aperture in the vertical strip carried by the contactor arm is a ring of very thin metal, bent into an L section, each part of the L being about 2 mm. This ring is light but rigid and it is carried by two prongs which pass through the base of the magnet compartment, these prongs being made of thin brass tubing. When the ring is depressed it engages the contactor arm, the end of which is drawn firmly into contact with a potentiometer. The clearance between the ring and the contactor slot is about 2 mm. on each side of the ring, with 3 or 4 mm. clearance between the end of the contactor arm and the potentiometer windings. This clearance is ample, and allows for a reasonable amount of tilting of the meter under the influence of turbulent motion. We have no reason to suppose that such tilting does take place, but if the magnet swings at all then the motion is stopped by the ring, which is quite smooth. Any bumping of the contactor arm in the ring takes place rapidly as the natural period of swinging of the magnet is very small, so that there is no effectual hindrance to the free movement of the magnet in between the periodical movements of the contactor ring.

It is a point of some importance to note that there are no electrical circuits energised during the periods of free swinging of the magnet so that there is no distortion of the earth's magnetic field by the presence of electrical currents.

4. *THE ELECTROMAGNETS.*

The electromagnets (Plate 4) operating the contactor ring have been placed as far away as possible from the magnets, as close to one another as possible, with the minimum of iron in the cores, and with small air gaps, so as to reduce the effects on the external field. The downward movements of the rings were designed to be a possible 10 mm. so that levers were necessary. The magnets were specially designed so that the armatures were pivoted (the common form of electromagnet in which the armature is carried by a strong spring is most unsuitable as it requires large electrical currents to operate it). Light brass tubes were screwed into the armatures and their ends coupled by swivels to the prongs of the contactor ring. The weight of the ring, its prongs, swivels and the two rods connecting it with the armatures, is about 20 grams and this weight was balanced by two long springs, whose lengths could be adjusted *in situ* so that the contactor arm gently but definitely returned to its null position. Adjustable stops were also provided. These electromagnets have thus been specially designed to avoid having to do unnecessary work, and the main part of the available electrical energy is used in ensuring good electrical contact between the contactor arm and the potentiometer.

5. *SPRING CONTROL OF THE PRESSURE ELEMENT.*

The instantaneous measurement of velocity can only be effected by measuring the associated pressure, and a very serious disadvantage of this is that the pressure varies as the square of the velocity. If the meter is to be sensitive to small currents some means of obtaining linearity of relation between velocity and meter indications must be found. In some meters the pressure is registered by means of a plate, hanging under gravity, but this alone is not sufficient control as any variation in the tilt of the meter will affect the zero reading of the instrument. A plate controlled by a simple spiral spring will have all the disadvantages of the square law. While it would be possible to design a potentiometer, or even to design mechanical coupling between plate and potentiometer, which would give linearity, a simpler method of compensation seemed to be desirable. It was found that a very satisfactory solution of the problem was to use the blades of a propeller as the pressure element and to control rotation by means of springs as in Fig. 2. If C is the axle of the propeller, B a fixed point, CA an arm rigidly attached to the axle, BA a spring, angle BCA = θ, CAB = ψ, then as the axle is rotated from the initial position CA'B (θ = O), we have two effects : (1) increase in tension of the spring and (2) increase in the moment of the tension.

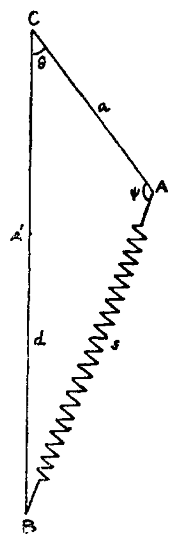

FIG. 2. — The spring control.

We shall denote by

- s the length of the spring BA,
- u the unstretched length of spring,
- d the distance CB,
- a the length of the arm CA.

Then

$$T \text{ varies as } (s - u)$$

$$\sin \psi = \frac{d}{s} \sin \theta$$

and the couple on the shaft varies as Ta sin ψ But the couple also varies as v^2 so that we have

$$v^2 \text{ varies as } da \frac{(s-u)}{s} \sin \theta$$

Also we have

$$s^2 = d^2 + a^2 - 2\,ad \cos \theta = (d-a)^2 + ad\theta^2 \quad \text{if } \theta \text{ is small}$$

whence $s = (d-a)\left[1 + \frac{ad}{2\,(a-d)^2}\theta^2\right]$

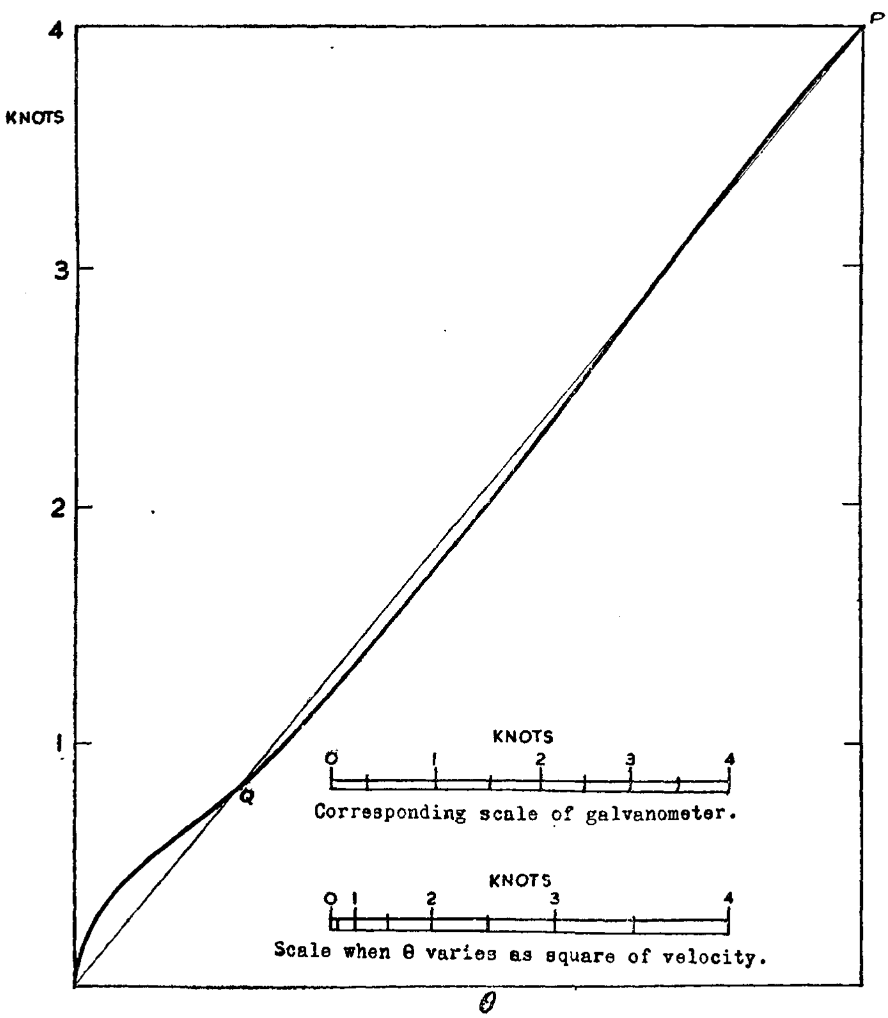

FIG. 3. — Calibration curve for velocity.

If the unstretched length of the spring is nearly equal to (d — a), then v^2 approximately varies as

$$\frac{da}{(d-a)}\left[(d-a-u)\,\theta + \frac{ad}{2\,(a-d)^2}\,\theta^3\right]$$

It is possible to make $u = d - a$, in which case v^2 varies as θ^3 only.

Compared with the linear relation (v varying as θ) this law of variation would give a much more open scale for small velocities and a somewhat contracted scale for large velocities. The only disadvantage of this law of variation would be that the zero position of the velocity contactor would be indefinite. In practice an attempt was made to give precision to the zero position, and otherwise to adjust the value of u so that the greater part of the scale (say from one tenth of the full scale upwards) should be as nearly uniform as possible. If we write $\theta/\alpha = \varphi$, where α is the maximum value of θ , and

$$v^2 = A\,\varphi + B\,\varphi^3$$

so that $v^2 = A + B$ when $\varphi = 1$, then the curve expressing v in terms of φ is cut by the line

$$v = \sqrt{(A+B)}\,\varphi$$

in the points given by

$$A\,\varphi + B\,\varphi^3 = (A+B)\,\varphi^2$$

which are $\varphi = 0$, $\varphi = 1$, and $\varphi = A/B$.

In practice it was found, agreeable to this computation, that an initial stretch of 2% of the unstretched spring would give practically a linear law of variation over nine-tenths of the range. The calibration curve is shown in Fig. 3. The inset scales show the improvement in galvanometer readings as compared with the readings if the scale varies as the square of the velocity.

6. *PRESSURE ELEMENT.*

The pressure of the moving fluid is transmitted to the axle of the spring control by means of the vanes of a pressure plate designed on the same lines as a propeller. A consideration of the law of action of the control springs shows that there is nothing to be gained by allowing the pressure wheel more than 60° of angular movement. The inertia effects are made very small by restricting the movement of the pressure wheel to this amount.

The pressure of the water, resisted by the spring control, results in the tilting of the mcter in the same direction as the rotatory movement of the pressure wheel. If the meter lacks sufficient weight, the result is a tilting which will affect the free movement of the magnet. The effect can be measured by suspneding the meter in air and hanging weights on the periphery of the pressure wheel until the maximum rotation is obtained. Such a test yielded a result of about 0°.5 of tilt of meter body. This could be counteracted if necessary by permanent fins on the body of the meter.

It is necessary to balance the pressure wheel and all other moving parts so that gravitational effects are eliminated and the spring controls alone need to be considered.

The pressure on the wheel has been tested in an artificial tank by courtesy of Professor ABELL, Professor of Naval Architecture of the University of Liverpool. A speed of about 1.25 knots could be attained.

The pressure on the wheel will vary with the type of support, so that in all the tests which have been made the pressure wheel has been on its axle and the whole meter has been submerged. In order to facilitate tests and calibration the pressure wheel was constructed with a groove round its periphery, to take a fine string. In testing the meter, the pressure of the known currents was counterbalanced by an accurate spring balance. For all later tests (e.g. at sea, or if fresh springs are fitted) all that is required is to apply a known pull on the periphery. This facility of testing and calibration is a valuable feature of the instrument.

A large wheel was used in order to measure the pressures of water at known rates (less than 1.25 knots) and it was verified that within measurable limits the pressure of water, as registered by the meter in turbulent water, varies as the square of the mean velocity. This test, valuable in itself, also proved the suitability of the design of the meter body.

7. *DESCRIPTION OF GEARING FOR VELOCITY ARM.*

The pressure wheel is fixed on the end of its axle by means of a short length of metal rod made of stainless steel, which is fixed in slots in the wheel and axle. The first bearing for the axle, where it enters the meter, is a double race of phosphor-bronze balls (Fig. 4). Just inside the meter is a "baffle-plate" (Fig. 5), which has two functions, one of which is in relation to water entering the meter (see paragraph 8), and the other is that of acting as a stop. The more delicate parts of the transmission are thus protected by the baffle-plate limiting the amount of movement of the pressure wheel. The rear end of the axle is carried by a strong brass plate separating the first and second compartments (Fig. 4), and the bearing consists of a ball race, using phosphor-bronze balls. This also acts as a thrust-bearing.

The second part of the transmission is in the third compartment of the main body of the meter, and consists of two bevel gearings with a ratio of 6 : 1. These convert the angular movement of 60° in a vertical plane into one of 360° in a horizontal plane. The horizontal axle carrying the larger gear passes from the second compartment into the third compartment and is carried by ball races at each end. The vertical axle carrying the smaller gear passes through a detachable horizontal plate into the lower compartment

The arm of the potentiometer is insulated from the spindle, and electrical contact is made by means of a flat spiral spring to an insulated terminal. The contactor end is plit and the two parts bent, one under the other, so that a double contact is made in the same radius on the potentiometer. This double contact enables very light spring contacts to be made, so greatly reducing the frictional forces.

Returning to the second compartment, the end of the axle passing into the main compartment of the meter holds a brass plate which carries 4 sets of small ball races (Plate 2) in which are engaged the ends of the links to the 4 springs controlling the movement. The other ends of the springs are attached to the meter body by screwing the springs on to suitably threaded studs. The springs were specially made from non-magnetic stainless steel. All the ball races used in the second and third compartments of the meter are of high precision, of a type which has only recently been available to instrument makers. They are known as the R.M.B. Miniature Ball Bearings, made in Switzerland and marketed by Miniature Bearings, Ltd., London.

The two axles are coupled by means of two long arms. The first one is attached to the axle in the first or " nose " compartment, and at its end is a short rod which passes through a slot in the plate separating the first and second compartments. This rod slides into a hole in the arm coming from the second axle. The object of this coupling is to be able to remove the nose of the meter intact, and to replace it with precision.

8. *INSULATION OF ELECTRICAL CIRCUITS AGAINST WATER.*

The electrical circuits have to be safeguarded from all possibility of sea-water coming into contact with them. At a depth of 25 fathoms the pressure of the water is five times that of atmospheric pressure so that if the meter were air-filled the air filling the meter at the surface of the sea would be reduced in volume to one sixth of the volume of the meter when submerged to the depth of 25 fathoms. Such great pressures would cause leakages at the joints unless they were exceptionally strong. If, however the meter can be filled with oil the reduction of volume under the pressure of 6 atmospheres is only a few cubic centimetres. Experiments were therefore made with a view to using an oil which would be a good insulator for the electric circuits but would not hinder the free movement of the magnet or the electrical contacts at the two potentiometers. The last two criteria obviously demand a light oil. Ultimately, a light switch-gear oil was found to have ideal properties in all respects. Provision, of course, has been made for suitable orifices for filling the meter with oil.

The main compartment, that containing all the electrically operated parts of the meter, is protected by two thick glass plates at the top and bottom; and soft rubber rings about 3/8 inch thickness are placed round them. Two flange rings are placed over the rubber rings and screwed to the main body of the meter. These force the rubber seals into close contact with the meter and the glass plates, without very great force being needed.

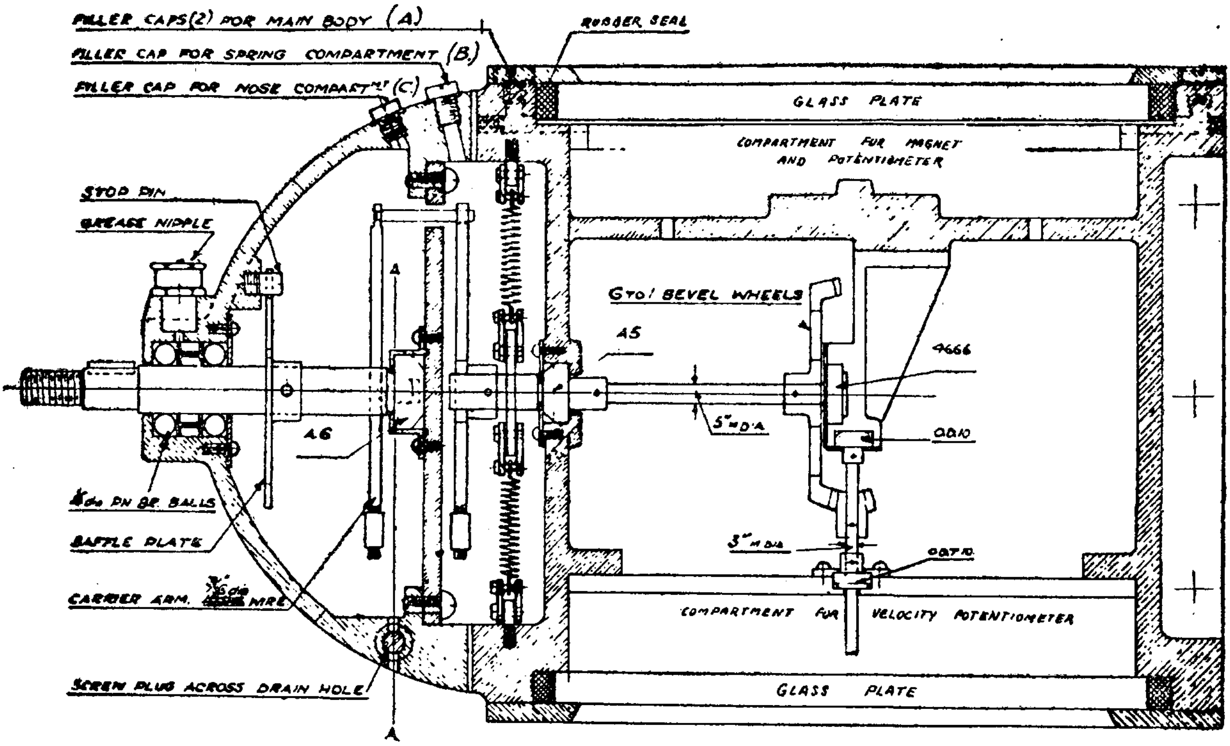

FIG. 4. — Section of meter body.

of the meter, and to its free end is attached an arm which serves to indicate velocity and which makes contact with a potentiometer. The vertical axle is carried by ball races of a suitable design.

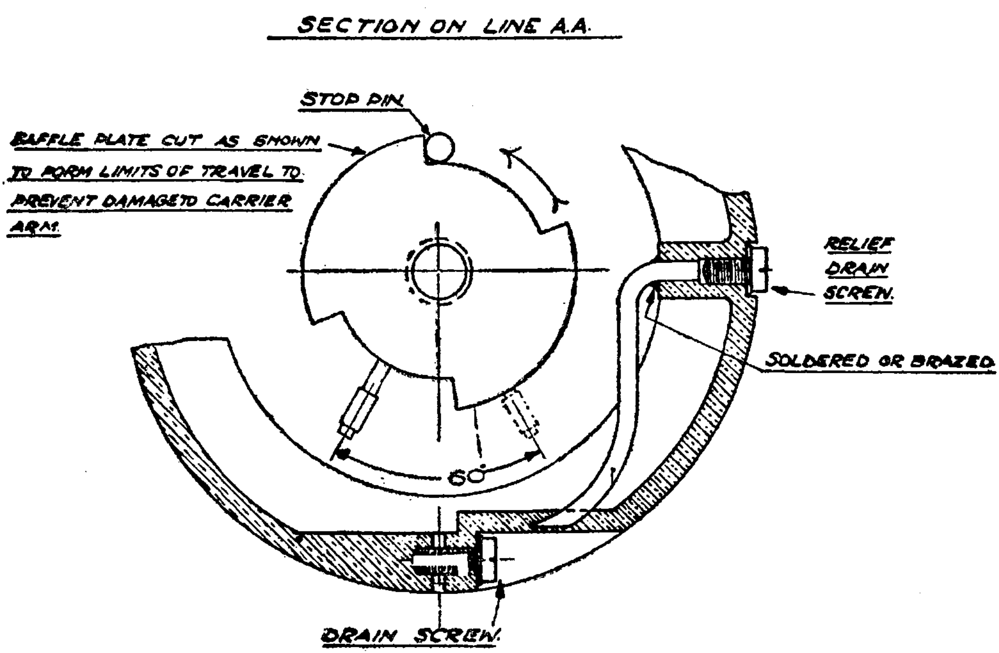

FIG. 5. — Baffle plate and drain pipe.

The nose and the main body of the meter are separated by a ring of flat rubber which serves as an efficient seal and the division between the first and second compartments is also sealed by a packing ring and by the use of lead washers to the screws.

The junction boxes for the connections to the electrical cable have also been efficiently sealed by rubber and lead washers where the boxes screw onto the meter body. The leads passing into the meter are joined inside the boxes to the flexible leads from the cable; originally the junctions were made by bare connectors set in ebonite, and the boxes were filled with paraffin wax. Though the flexible leads passing into the sea from the junction box were sealed by rubber rings, yet the continual movement of the leads led to a slight ingress of sea water which crept along the metal surfaces and also along the surfaces of the ebonite. The use of wax has been discontinued and a soft compound called " Seelax ", made specially for sealing the junction boxes of electric cables, has been used with great satisfaction. Further, it does not corrode the terminals whereas wax softened by vaseline has a corrosive action. The flat ebonite plates for the connectors have also been dispensed with, and now the connections are made by soldering, after which a close-fitting rubber tube is slipped over the joint and further protection is ensured by wrapping the ends of the tubes with strong thread. There are now no plane surfaces along which water can possibly creep. The passage between the junction box and the main compartment of the meter is effectively blocked by tightly fitting rubber. The oil does not come into contact with the " Seelax ", which is disintegrated by oil, for between the rubber and the oil is a tight-fitting cork.

All the wires are insulated by one or more coverings of " sleeving " which consists of highly glazed cotton tubing which is not affected by oil and which has high insulation properties.

The junction box on the swivel, for the connections to the cable, is insulated in the same manner.

It will be realised that water must inevitably creep along the axle of the meter at the nose, and provision for this has been made. Just inside the meter is a baffle plate which prevents all water creeping further along the axle, and deflects it to the bottom of the first compartment, where it collects. When the meter is lowered into the water the oil begins to be compressed slightly and water enters the meter at the nose. When the meter is raised again the oil expands in the absence of a special provision for this contingency and it is oil and not water which is forced out again at the axle. Continual raising and lowering the meter will ultimately cause the water level to rise to the axle in the first compartment and thereafter it will be water which is forced out on raising the meter. There is thus a limit to the amount of water which may enter. Since the connecting link between the two shafts passes through a slot high up in the plate between the first and second compartments, water cannot normally pass into the second, or middle, compartment except by careless handling of the meter on deck, by tilting it. Even so, a great quantity would have to pass through before the level in the second compartment would rise to the level of the axle, after which there would be a danger of water creeping into the main compartments, but this danger is very remote.

Experience has shown that very little water enters even the first compartment, probably never so high as half way to the axle, but provision has been made for automatically dealing with such water, by carrying a brass tube (Fig. 5) from the "sump" to an orifice at the side on a level with the axle, and it may be easier for the water to enter this orifice as the sectional area is greater than is available at the axle. Thus, when the meter is raised, the pressure of the expanding oil will tend to force water from the sump. A drain tap is provided for emptying this compartment of water when the meter is hauled on deck after the day's work.

The whole of the water sealing is tested before filling with oil, by screwing a special plug into the oil filler socket, through which air is pumped to a high pressure. The body of the meter is placed in water for the detection of air bubbles; the axle orifice, of course, is sealed for the test.

9. *METER SUPPORTS AND SWIVEL.*

The meter body is supported in a framework (Plate 1) attached to a stout plate which acts as a tail piece to the meter in order to keep it in the plane of movement of the current. One end of the plate is cut away to take the meter body and its pressure wheel, and to this end is attached a guard ring for the protection of the pressure wheel. Further protection to the wheel is afforded by a strut across the front of the wheel, the plane of the strut being in the same plane as the main plate of the meter frame-work. Two other struts, made in L-section, pass backwards from the guard ring to the main plate. The meter body is screwed to the main plate and to the struts, so that the whole forms a very rigid and very strong framework.

Attached to the top of the plate is a swivel (Fig. 6), which has received a great deal of care in design. It has to grip the cable and also to allow free movement of the meter. The latter duty is accomplished by means of the free use of phosphor-bronze ball races. The cable itself, while it is armoured in phosphor-bronze, has a flexible rubber core so that there is a measure of yieldingness to the clutches of the swivel for which allowance has to be made. There are three independent clutches in the body of the swivel. The centre clutch consists simply of a split cylinder with side flanges, and the two halves are screwed tightly together under great pressure. At each end of this central clutch are two split-cone clutches whose solid ends engage freely in grooves in the central clutch. The central clutch slides on grooves in the body of the swivel so as to prevent rotation relatively to the swivel body, and similarly projections in the cone clutches prevent rotation relatively to the central clutch. These three clutches are placed on the cable and the whole inserted into the body of the swivel. Then two large nuts compress the core clutches and lock the whole assembly.

The armour on the free end of the cable is turned back and compressed into a ring by the junction box which screws into the lower part of the swivel. This is an additional safeguard against the cable slipping through the clutches.

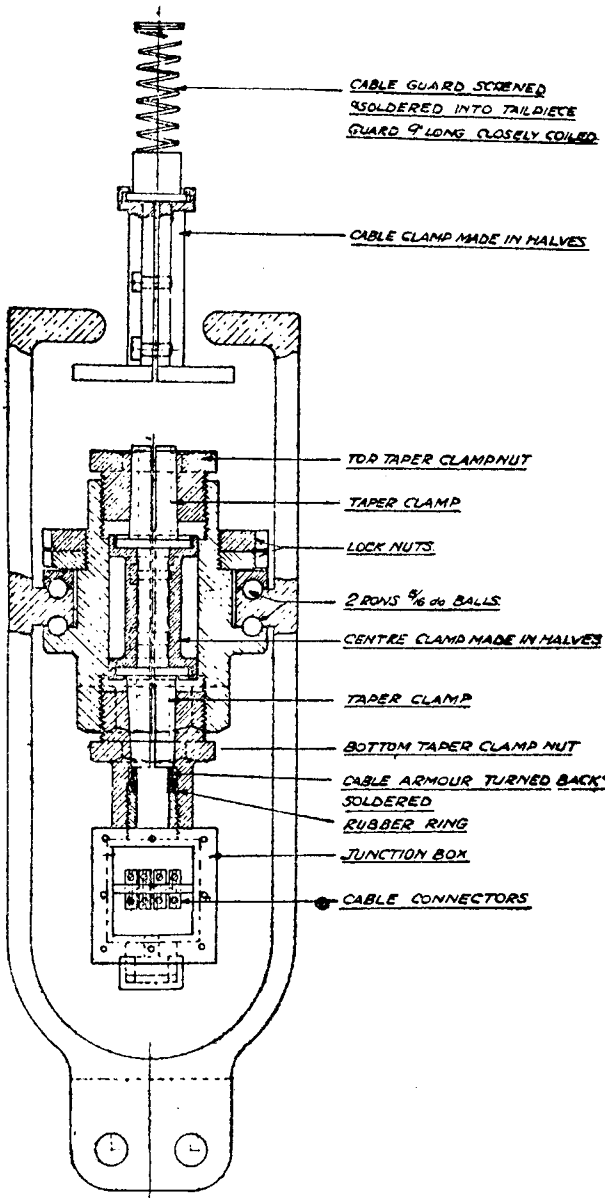

FIG. 6. — The swivel.

The body of the swivel is extended downwards by a U-shaped stirrup which is bolted to the main plate of the meter framework. The stop of the plate is strengthened by two other small plates so as to give triple thickness for the junction with the swivel. This stirrup also serves to protect the junction box, from which flexible leads, of course, are essential to the free angular movement of the meter relatively to the swivel.

The stirrup is extended upwards beyond the body of the swivel so as to carry a circular ring above the swivel (Plate 3). Inside this ring, but not touching it, is a split cylindrical clutch on the cable, similar to the central clutch of the swivel but with a semi-circular plate attached to each half. The upper ends of the clutch contain bosses and holes for the use of a safety-wire independent of the cable. If for any reason the cable slips through the clutches or if the armour breaks at the junction with the swivel (the most likely place for such breakage) then the meter will drop through a distance of about half an inch until the upper ring falls onto the semi-circular plates of the safety clutch. The cable should be held by this safety clutch even without the aid of the safety-wire, but by one means or another the meter is thus saved from loss.

10. *NOTES ON PROTECTIVE PLATING.*

Many enquiries were made as to the best types protective plating to be used for the meter and swivel, without any great satisfaction being obtained, so that specimens of brass were plated by different processes and submitted to tests in sea water, care being taken to test the effects of wetting and drying and also the effects at the junction of sea and air.

Cadmium plated brass, unprotected, soon discoloured more or less uniformly, but did not scale. Specimens plated with cadmium and sprayed with aluminium were very resistant to the effects of sea water. Nickel plating proved to be much the most satisfactory of all, as its resistive properties are about equal to those of aluminium, but it has the advantage of a more pleasing and durable finish.

Tests at sea have shown that the nickel plating is quite satisfactory under working conditions and all machined surfaces have been plated, while the rougher castings have been nickel plated and also sprayed with aluminium.

11. *THE CABLE, CABLE DRUM AND WINCH.*

One of the earliest items of interest in the design of the meter arose in connection with the cable which had to support the meter and convey the electrical currents. Much help was rendered by the British Insulated Cables, Ltd., Helsby, who suggested and supplied the cable consisting of 4 insulated cores, each conductor being made of 16 strands of tinned copper wire of diameter 0.012 inch, the rubber insulation for each conductor being of 600 megohm grade, the whole sheathed with resilient tough rubber and braided with tinned phosphor-bronze wires. The overall diameter of the cable is 0.50 inch.

The breaking strain of the complete braid is 520 lbs., and tests of the cable at the University of Liverpool showed that the cable was even stronger than the estimate. The weight of the flexible cable per 100 yards is about

45 lbs. and it can be wound round a drum, or can pass through a block of 9 inches diameter.

The cable was marked out in yellow paint at every 5 metres, using a simple colour code to specify the markings.

The drum was made in teak with a metal band round one flange and a special winch was made to take the drum. This allowed a friction band to control the drum and stops were also supplied to fix the drum in any required position. At a later stage the drum was fitted with a spring-controlled friction band so that it would slip at any pre-determined strain on the cable. The whole weight of the meter is not much more than 100 lbs,. but it was believed that the rolling of the ship imposed considerable strain on the cable owing to the jerking of the meter up and down. At first, therefore, the spring was loaded so that the drum would slip at a tension in the cable of 100 lbs. in excess of that due to water and cable, so yielding at least 100% margin of safety before breaking the cable, but it was found that even with severe rolling of the ship the drum never moved under this control and that a control tension equivalent to any extra 50lbs. strain on the cable was ample. Under severe rolling the drum would slip an inch or more and after a time the operator would restore it to its original position.

The value of this safety device cannot be over-estimated.

The electrical connections to the cable were made by the use of plugs and sockets, the sockets being on the end of the drum. The plugs were removed prior to working the winch.

12. *ELECTRICAL DETAILS FOR THE VISUAL INDICATOR.*

The electrical circuit for the visual indicator is much simpler than that for the photographic recorder, so that we shall describe this first.

The electromagnets are in parallel with a joint resistance of 20 ohms, and the resistance of two cores of the cable is about 3 ohms. The electromagnets can be operated by an applied EMF of 3 volts, but allowing for cable losses and an ample margin for certainty of operation the circuits are operated by a 6 volt accumulator.

The potentiometers have resistances of about 50 ohms, and as the galvanometers only require one milliampere for full scale deflection, resistances of about 200 ohms are placed in series with the potentiometers. While the consumption of current by the potentiometers is thus made negligibly small, the voltages across them are sufficiently high to require resistances of more than 3000 ohms in the galvanometer circuits. These high resistances make the contact resistances of the velocity arm and magnet frame negligible.

The electrical supply for the visual indicator is a 6 volt accumulator of capacity 15 ampere hours and this is amply sufficient to operate the indicator even at very frequent intervals for more than a week.

Two cores of the cable are required for the feeding and returning circuits to the electromagnets and two more for the galvanometer circuits. A fifth core would be desirable for the common return of the galvanometer circuits, but the cable armour has proved to be quite satisfactory. It is necessary to provide a return circuit for the galvanometers separately from

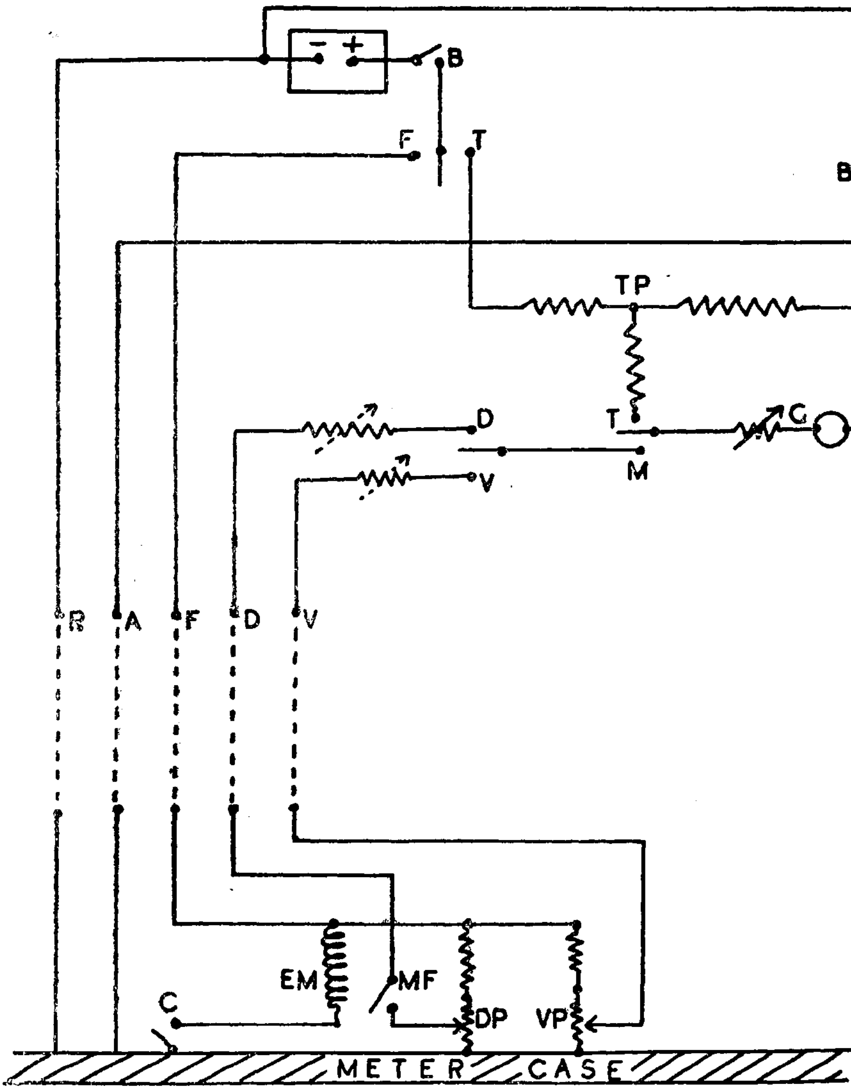

FIG. 7. — Electrical circuit for visual indicator.

that of the electromagnets owing to the large current required by the latter, yielding an appreciable drop in voltage along the conductor. The complete circuit is shown in Fig. 7. The broken lines indicate the four cores and the armour of the cable. DP and VP are the potentiometers and associated resistances, and EM represents the coils for the electromagnets. It will be noticed that these three parts of the circuit are in parallel; that is, the two potentiometers are energised together. The switch MF represents the effect of the depression of the magnet frame by the electromagnets. Switch C represents a provision made outside the junction box on the meter body whereby the wire connecting the electromagnet coils to the case of the meter may be disconnected, when velocity readings only are required.

The meter is operated by switching on the battery through B. There are two independent circuits, one for testing the voltages and adjusting the galvanometer, and one for operating the meter. The switches for the test circuit are indicated by T. If we follow these through, we see that from B the voltage is applied through a switch (FT) to a test potentiometer (TP) and the return circuit of the negative pole of the battery is effected through a second switch (BT). The two switches (FT) and (BT) are operated together, using a double-pole double-throw switch. It will be noted that this test potentiometer can be conveniently operated if the cable is disconnected from the indicator.

From the test potentiometer (TP), a tapping transmits voltage to the galvanometer through the switch (TM). The galvanometer resistance (G) is then adjusted to compensate for the variation in voltage of the accumulator. This test needs to be made daily, or as required.

If all the switches (except B) referred to are now thrown over to their alternative positions, the voltage through B and FT feeds the meter through the core F. The readings from the potentiometers DP and VP are then read on the galvanometer through the alternative positions of the switch DV. The leads from these potentiometers include adjustable resistances which are set to give correct maximum readings from the meter potentiometers when the voltage correction has been made with the galvanometer resistance. These are to be regarded thereafter as fixed resistances, but their operation can always be tested as required.

13. *THE VISUAL INDICATOR.*

In its present form the indicator and the accumulators are self-contained in a cubical box seven inches in dimensions. The lower half contains the accumulators and access to them is simply obtained since the two halves of the box are hinged together. The upper half contains a single galvanometer and resistances for calibrating and testing. A top lid contains corrections to the galvanometer readings to give the direction and speed of the current.

The procedure is very simple. After adjusting the galvanometer resistance against the artificial test circuit so as to correct for the changes in voltage of the accumulator (say, once a day), the observations are taken as required, say at hourly intervals. The accumulator is switched into the circuit. Immediately the galvanometer (absolutely dead-beat) indicates the reading for the direction potentiometer; this is noted; then a switch is thrown over for the reading from the velocity potentiometer, and this reading is noted. At leisure, the corrections can be made.

When the velocity indications are being examined, the fluctuations due to turbulence will be evident. For the measurement of turbulence it is sufficient to read the maximum and minimum readings of the needle and the period, but for the estimation of current velocity it is only necessary to estimate the average reading.

(It will be seen, therefore, that the indicator can be used for direct readings of high scientific value, but for purposes of hydrographic surveys the high sensitivity to turbulent motion is not required. It has been suggested that for such purposes the indications of velocity would be made easier if the more rapid oscillations of the galvanometer needle could be damped. While no attempt has been made to do this, it is obviously possible to damp the oscillations, without affecting the accuracy of the reading of mean velocity, by filling the nose of the meter with thicker oil and fastening a set of vanes on the axle).

14. *ELECTRICAL DETAILS FOR THE PHOTOGRAPHIC RECORDER.*

The modifications to the circuits for the visual indicator are rather extensive, so that the complete circuit is shown in Fig. 8. For convenience two separate accumulators A and B are shown, the latter being used to operate relays and lamps, while the former operates only the meter circuits, but in practice only one accumulator is used. It is necessary however, to provide separate leads from the accumulator to the two circuits associated with A and B, as otherwise the switching in of the lamps disturbs slightly the positions of the galvanometer needles which are at rest and a blurred image results, due to the small resistances in any leads made common to the two circuits.

The broken lines indicate the four cores and the armour of the cable. DP and VP are the potentiometers and associated resistances, and EM represents the coils for the electromagnets. It will be noticed that these three parts of the circuit are in parallel; that is, the two potentiometers are placed across the coils of the electromagnets so that all three are energised together. The switch (20) represents the effect of the depression of the magnet frame by the electromagnets. Switch (21) represents a provision made outside the junction box on the meter body whereby the wire connecting the electromagnet coils to the case of the meter may be disconnected, when velocity readings only are required.

The switches indicated in the circuit diagram are of four types :—

(a) switches (19), (17), (15), (13), (11) and (12) which are used in connection with the testing of the voltage of the batteries;

(b) switches (1), (2), (9), (18), (14), (5) and (6) which control the batteries, and determine whether the readings are continuous or at intervals of 15 seconds or 30 seconds, and also the time of operation (10 minutes or 15 seconds or 30 seconds) for the "time flag" (TF) which gives the time on the record;

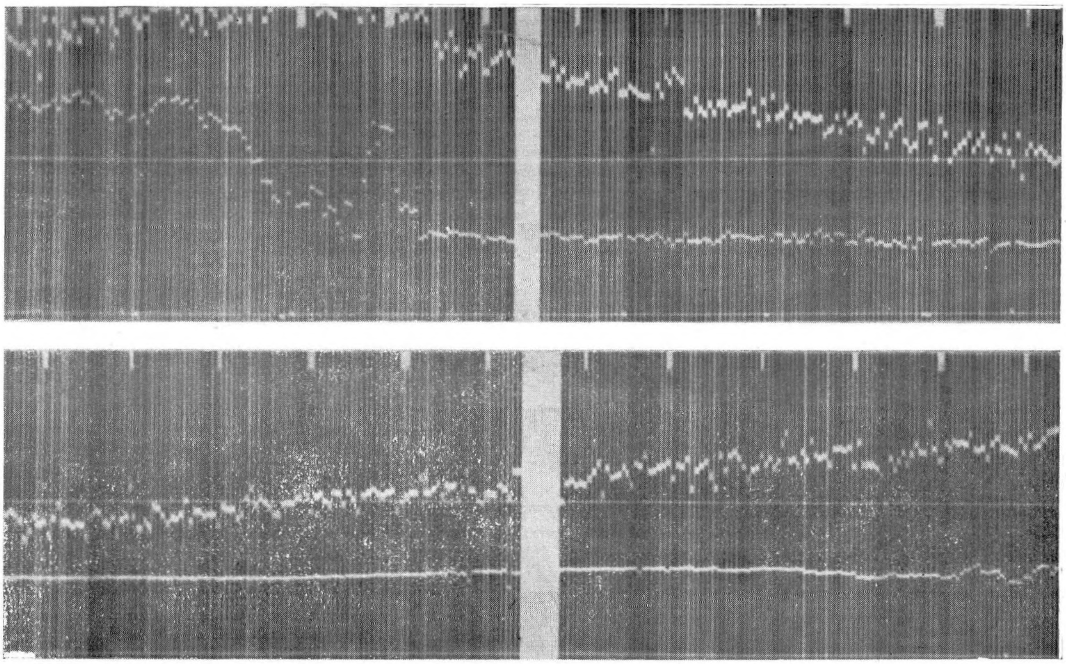

Plate 5. — Planche 5.

Illustrations of type of records-intermittent.
Exemple d'enregistrements intermittents.

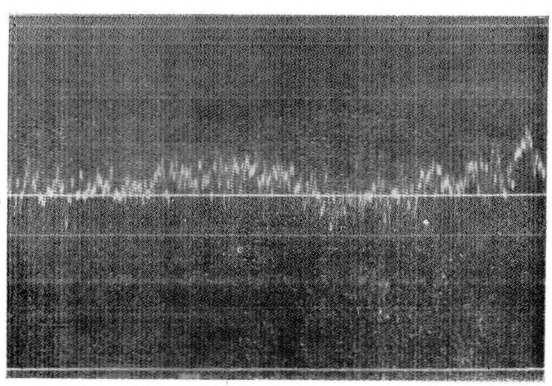

Plate 6. — Planche 6.

Type of continuous record.
Exemple d'enregistreur continu.

(c) switches (3), (4) and (16) which are operated by the clock, so that through switch (3) the meter circuits are all energised, and the photographic record made through (4), while (16) normally operates the time shutter at intervals of 10 minutes;

(d) switches (7) and (8) which are operated by relays.

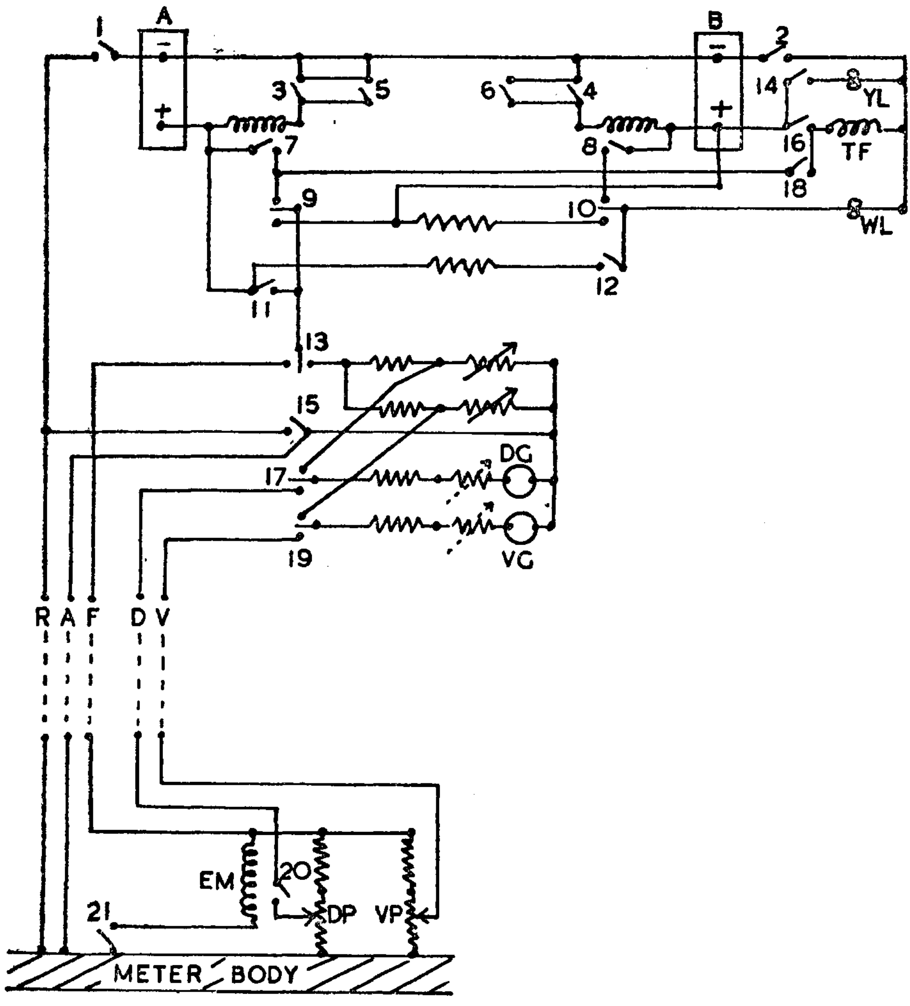

FIG. 8. — Electrical circuit for Photographic Recorder.

YL :	Yellow Light.	VG :	Velocity Galvanometer.
TF :	Time Flag.	EM :	Electromagnet.
WL :	White Light.	DP :	Direction Potentiometer.
DG :	Direction Galvanometer.	VP :	Velocity Potentiometer.

Switches in Group (a) are necessitated by the changing voltage of the accumulators. Tests are required each day in order to alter the resistances in the galvanometer circuits so as to give correct full scale deflections on the test resistances (or artificial circuits comparable with the meter circuits). These are made to correspond to the meter readings (once for all or whenever it is thought necessary to do so) by altering the pre-set variable resistances in the test circuits. These switches are on the panel of the recorder box.

Group (b) are placed on the relay box which is near the clock. The relays are necessary because the resistances of the rubbing contacts made in the clock are rather variable and flicker of the galvanometer needles is caused if the clock actually switches on the currents. The resistances between (9) and (10), and between (11) and (12) cut down the illumination over the galvanometer needles when continuous readings of velocity are required.

The normal operation of the circuit is designed to take place when the clock contacts at every 30 seconds are operated, and the convention is made that all switch knobs are then pointing downwards. The first contact made by the clock (3) operates the relay (7) which " feeds " the meter circuits through switches (9), (11) (13) and the core F. The return current flows through core R to the negative pole of the accumulator. The galvanometer circuits are completed through cores D and V and the armour A. The galvanometers therefore measure the voltages from the potentiometers to the case of the meter, and the resistance of the common part A is so small as to be negligible; it would not be possible to use R because of the voltage drop in it.

After the galvanometer needles are steady (in 5 seconds), the white light (WL) is switched on by the clock through (4) and the relay (8). This contact is very short, of the order of 0.1 second. The circuits are all broken again at the end of 7.5 seconds.

The galvanometers come to rest in about 2 or 3 seconds, and the clock which operates the switching of the circuits was designed to allow 5 seconds before operating the switch for the lamp which is used in the photographic recording. The voltage is thus applied to the currents for 7.5 seconds (with the clock in question) and if the readings are taken every 15 seconds the accumulator is used for 50% of the time. The total current is about 0.3 ampere so that a 20 A.H. accumulator will be usable for 40 hours on the above basis, and 80 hours of the readings are taken at intervals of 30 seconds instead of 15 seconds. If the meter is operated at intervals of 30 minutes or one hour the accumulator will last a week or fortnight without recharging. Also, if the meter is used to record continuously the variations of velocity, the electromagnets can be disconnected externally to the meter, and the main part of the consumption is then due to the lamp required in continuous glow for the photographic recording. As the lamp under these circumstances is run at a reduced voltage the current consumption is about 0.1 ampere and the accumulators will give 60 hours' continuous service.

15. *THE PHOTOGRAPHIC RECORDER.*

The photographic recorder hitherto used has been an experimental model using such apparatus as was to hand and which could be easily adapted. In due course a more compact recorder will probably be designed, failing the possibility of using instruments on the market. There are many visual recorders (non-photographic) which could be adapted but their great weakness is that the galvanometer takes about 15 seconds to come to rest. Assurances have been given by instrument makers that dead-beat galvanometers might be designed for use with recorders but their engagements have not permitted them to effect this. It is for this reason that we have continued to use the experimental type now to be described.

Two moving coil galvanometers are used which are not quite dead-beat because it has been necessary to fit wider pointers. These are arranged facing one another, with the needles moving in opposite directions over a slit formed by two brass plates. Underneath the slit is the system of rollers for the bromide paper, the uppermost roller being very close to the slit. Above the slit is a framework carrying a long arm which eclipses the light over a short length of the slit whenever the shutter is operated by the clock.

Across the slit near the two ends and also in the centre are very fine wires whose shadows serve to give the scale on the bromide paper.

Between the light and the slit is placed a cylindrical lens which condenses the light on the slit and advantageously concentrates it least at the centre of the slit, so counteracting the excess illumination at the centre as against the ends of the slit.

The bromide paper is 5 cms. wide and is carried over the rollers by means of a small electrical motor, suitably geared, of the type used for driving model machinery. Two speeds of drive are available, approximately 10 cms. per hour and 120 cms. per hour when the motor is driven by a 2-volt accumulator.

Originally the bromide paper was driven by means of clockwork but the electrical drive is more efficient.

The records show series of fine black lines with the shadows of the needles picked out in white. Plates 5 & 6 give illustrations of the types of records, intermittent and continuous. The velocity readings are taken from the lower edges of the records, and the full scale between the outer fine traces is 4.27 knots. The direction readings are taken from the upper fine trace downwards. The needles are of different widths so that the two records are distinguishable. Even when the exposure is made every 15 seconds the successive exposures are quite distinguishable, so that in conjunction with the time markings an exact check can be kept upon the time of the record, which is helpful in connection with the determination of periods.

During the times when the meter is being hauled up or let down for observations at other depths the exposures are stopped by a switch placed near the winch. Another switch near the winch controls the starting and stopping of the motor drive.

16. *THE CLOCK.*

Very great difficulty was experienced in obtaining a clock to give the contacts required. The power available in any clock is very small and only very light contacts can be made as otherwise the frictional forces will stop the clock. Ultimately Chadburn's adapted a clock mechanism used in some of their instruments, and this has proved to be quite satisfactory. It consists of two clock trains with separate springs, one of which acts as a slow escapement to the other. Consequently the second mechanism gives an intermittent motion every 2.5 seconds to a central spindle which completes one revolution every 30 seconds. The sudden release of the stored up energy of the second spring thus operates the contactors attached to the central spindle, rubbing over three circular tracks, one of which has a silver contact let in it for a distance equivalent to three movements of the spindle; it is this contact which energises the meter circuits. The next circular track has a short length of silver let into it at a point corresponding to the end of the second of the above three movements of the spindle. The first contact is thus on for 5 seconds before the second contact and remains on for another 2.5 seconds. The third circular track acts as a common return circuit.

Two other spindles are available, one for an ordinary small clock dial and the other for a contact every 10 minutes for operating the timing shutter. This is effected by means of 6 projecting studs in an ebonite disc which revolves over an hour.

17. *ACKNOWLEDGMENTS.*

The whole of the apparatus described in this paper has been made by Chadburn's (Ship) Telegraph Company, of Liverpool. The photographic recorder, the clock, winch, cable and the first model of the meter were constructed out of funds supplied for the purpose by the Government Grants Committee of the Royal Society. The first meter was lost at sea and a second, incorporating improvements in details, was constructed out of funds supplied by Messsrs. Alfred HOLT & C°, Shipowners, of Liverpool. The author desires to record his gratitude for the assistance he has thus received.