An Electromagnetic Current Meter*

Yutaka NAGATA**

Abstract: We have developed two types of electromagnetic current meters, one employing permanent magnet (P-type) and the other, using electromagnet (E-type). The P-type current meter is easy to operate. It is suitable for the measurements of rapidly varying flows such as orbital wave velocities. However, as the signals are contaminated with polarization potentials of the electrodes, the accuracy of the measurement is limited especially for steady flows. On the other hand, stable and accurate recording of flows is possible with the E-type current meter. Here we get the output of the alternating electromotive force which is amplitude-modulated in proportion to the flow speed. Since the polarization potentials vary slowly with time, only the A.C. components of the current meter output is amplified by the A.C. amplifier. This signal is demodulated and we obtain the final output signal.

The directional response characteristics of the current meter depend on the shape of the meter. We examined several shapes in order to make the directional characteristic curve be of cosine shape.

1. Introduction

The waves are one of the most dominating agents that transport water mass and sediments in the beach. The waves yield nearshore current system through their breakings and their mass transports. Also the waves move directly the bottom sediments and lift them into suspension by their orbital currents and by the turbulence due to their breaking. We often experience after a large storm that the bottom topography is considerably changed and a vast volume of the sand is relocated. But in the present state of our knowledge, we cannot forecast the direction and amount of the sediment transport quantitatively from the data of the wave properties alone. Therefore, the investigations of intermediate processes, such as the deformation and breaking mechanism of the waves, and those of the properties of various wave currents and other nearshore currents are most essential in the present stage. For such investigations, it is required that we develop current meter that can measure currents varying with periods of several seconds and that can be used in breaker zone or on foreshore where the destructive force by breaker and the strong turbulence are existing and where the immense quantity of sediments

are suspended and floating.

Moreover, such current meter will enable the recording of two horizontal components of the orbital velocity, from which the directional wave spectrum could be derived. In this case, we require that the response of the current meter decreases by the factor $\cos \theta$, where θ is the angle between the current direction and the current meter direction.

To measure the velocity of steady flow, the current meters of the propeller type are used widely. But they are unsuitable for the measurement of the rapidly varying current, both in magnitude and in direction. Moreover, they cannot be used in presence of strong turbulence and floating sand as in the breaker zone. So, we developed an electromagnetic current meter as the suitable one which can measure rapid variation of the current velocities and which is not influenced by floating sand.

2. Principle of electromagnetic current meter

When the conductive fluid flows in the insulation pipe which is mounted between the magnetic poles, an electro-motive force is induced in the direction perpendicular to the direction of the magnetic field and to the direction of the pipe in accordance with the law of the electromagnetic induction. If we set

* Received Jan. 24, 1964

** Geophysical Institute, University of Tokyo

the electrodes in the pipe, we can pick up the voltage V as

$$V = B \cdot d \cdot v \times 10^{-8} \quad (\text{volts}),$$

where B is the density of the magnetic flux in gauss, d is the distance between the electrodes in cm and v is the mean flow speed in the pipe in cm/sec. The electromagnetic current meter follows this principle and measures the flow speed in the pipe. A similar principle is followed in the Geomagnetic Electrokinetograph in which the geomagnetic field takes part instead of an artificial magnetic field.

In the electromagnetic method of measuring current velocity, the induced electromotive force is proportional to the mean speed of the fluid and is not influenced by the profile of the flow in the pipe. Also it does not depend on the conductivity of the fluid and so it is not influenced by the existence of the floating sand. Moreover, the response is rapid enough and the telemetering is easy.

We usually use the alternative magnetic field and get the output of alternating electromotive force which is amplitude-modulated in proportion to flow speed. As the polarization potentials vary slowly with time and as the only A.C.-component of the output is amplified by the A.C.-amplifier, the influence of the polarization potential of the electrodes can be eliminated from the signal. Besides, the amplification of the signal can be easily made by A.C.-amplifier without being disturbed by the noise such as drift in the D.C.-amplifier. We may call this the electromagnetic current meter of electromagnet type or E-type electromagnetic current meter. On the other hand, the electromagnetic current meter, in which the magnetic field is provided with permanent magnet, may be called the electromagnetic current meter of permanent magnet type or P-type electromagnetic current meter. Measurement by P-type current meter is not so accurate as that by E-type current meter. It is difficult to make the stable recording for long time by P-type current meter because the zero line of the records would drift owing to the change in polarization potential with time. But P-type current meter has no trouble of

supplying electric power for the excitation of magnetic field. Thus the merit of P-type current meter is in its handiness and in its low cost. Especially it is useful where it is difficult to provide enough electric power.

The insulation pipe is not always necessary in the current meter. But we use the insulation pipe for the protector and for the mounting of electrodes. The use of insulation pipe makes the directional characteristics of the current meter better as we shall discuss later.

It is too difficult to make the direction of the current meter follow after the rapidly varying current direction. So, we intended to measure the current speed at a fixed point and in fixed direction. Actually the current meters are mounted on a iron pedestal which is installed on sea bottom. In order to measure the directional variation of the current, we may use two current meters as a pair and set the direction of one of the current meters perpendicular to that of the other on a pedestal. Then we can measure two horizontal components of the current velocity if the directional response characteristics of the current meter are cosine characteristics.

3. P-type electromagnetic current meter

As a handy and low-priced electromagnetic current meter, we developed the P-type electromagnetic current meter. The magnetron magnet manufactured by Tokyo Precision Instrument Co., Ltd. is used to provide the magnetic field in the pipe. Uniform magnetic flux density of about 5,000 gauss is provided in the space between the pole pieces, 16mm apart, of the magnet. We used a vinyl pipe of about 16mm in inside diameter as the insulation pipe and so the distance between the electrodes is about 16mm. Then the induced electromotive force for the current speed of 1cm/sec is expected to be about 0.08mV. So, it is necessary that the polarization potential difference between the electrodes is less than the order of 0.1mV. We adopt the Ag-AgCl electrodes, considering that we use the current meter in sea water.

If a suitable potential difference is established between the two silver electrodes in KCl solution of 0.1N, electrolysis will result in the

occurrence of Ag-AgCl at the anode. The Ag-AgCl electrodes so made are used in our current meters. The polarization potential difference between the two electrodes is within $0.1\mu\text{V}$ when they are made. But these electrodes are not so stable and degenerate in several days or sometimes even in a period of a series of measurement. Fortunately, the change of the polarization potential difference due to the degeneration of electrodes is steady and sufficiently slow within usual observation time (for example, we take 20 min. records in the observations of orbital wave velocities). So we can expect the accuracy of about 2cm/sec if we concern only with the measurement of rapidly varying current such as the orbital wave current and other related wave currents. But in the measurement of steady flow, the accuracy falls to about 10cm/sec even excluding the other observational errors because of the difficulty in eliminating the polarization potential difference.

In each electrode, the Ag-AgCl pole is kept in the small glass tube which is filled with saturated KCl solution and is avoided from direct contact with sea water in order to minimize the degeneration. One end of the glass tube is plugged with agar saturated with KCl and is lead to the inside of the insulation pipe of the current meter. The leading wire is lead out from another end of the glass tube. A pair of glass tubes is fastened by binding neoprene tape to the insulation pipe which is fixed between pole pieces of the magnet. The potential difference which is picked up by the electrodes is amplified by a D.C.-amplifier and is fed into a recording voltmeter. In Fig. 1, the P-type electromagnetic current meters are shown.

The P-type electromagnetic current meters are calibrated in the water tank at the Geophysical Institute, University of Tokyo. The current meter is suspended from the moving frame and is reciprocated in the water tank. The period and the amplitude of the reciprocation can be changed in 6, 8, 12 and 16 seconds and in 55, 70 and 85cm respectively.

The speed characteristic curve of P-type current meter is shown in Fig. 2. The curve

Fig. 1. P-type electromagnetic current meters.

shows good linearity and does not depend on the reciprocating period within the range of velocity from 40cm/sec to 200cm/sec and that of period from 6 sec to 16 sec. (Deviations of the measured values in Fig. 2 and Fig. 3 are

Fig. 2. The speed characteristic curve of P-type current meter.

mainly caused by the erratic movement of the moving frame.) In this case a vinyl pipe of 13mm in inside diameter was mounted between the pole pieces. By taking the speed of outer flow as v and d equalled to 13mm in the equation in §2, the effective density of magnetic

flux is estimated at 3,000 gauss. Nominal flux density of the magnet is 5,000 gauss and so the difference between this value and the effective flux density may be explained by the velocity difference between inner and outer flow of the pipe. The flux density of per-

Fig. 3. The directional characteristic curve of P-type current meter. The experimental values are plotted for the relative angle of the current meter to the current direction in arbitrary scale and compared with cosine curve.

manent magnet decays gradually, so it is desirable to calibrate the current meters of this type before or after each observations, or preferably before and after.

The directional characteristic curve is shown in Fig. 3 where the abscissa θ is the angle

Fig. 4. P-type current meters which are swollen with iron sand after several hours observation at Niigata Beach.

between the current direction and the direction of the current meter. Near $\theta=0$, the characteristic curve departs slightly from cosine curve but it may be considered sufficiently close to cosine curve within experimental errors. Generally, the directional characteristics depend on the shape of the current meter. In the next section, various shapes of the current meter are discussed for E-type current meter. The directional characteristic curve in Fig. 3 does not depend on both the absolute value of the current velocity and on the period within the ranges covered in our experiment.

Fig. 5. E-I type electromagnetic current meter.

In conclusion, the merits of the P-type current meter are:

- (1) The construction of the current meter is very simple and therefore it can be made easily with little expense.
- (2) It does not need large electric power necessary for the excitation of magnetic field. It requires only a small electric power source for D.C.-amplified and for recording voltmeter, to which power can be easily supplied by a few batteries. So, only a few members are sufficient to make field observations.

- (3) It can be used under the existence of immense volume of floating sediments and of strong turbulence as in breaker zone provided it can be installed along the bottom.
- (4) The speed characteristic curve is linear enough and the directional characteristic curve can be approximated to cosine curve within the ranges covered in our experiment. Therefore, P-type current meter is suitable for the measurements of varying currents such as orbital wave currents.

But it has the following drawbacks:

- (1) It is troublesome that the Ag-AgCl electrodes must be newly made every time before the series of the measurements in order to minimize the polarization potential difference.
- (2) The polarization potential varied more or less in construction, in transportation and even in observation. So the zero line on the records must be examined every time before and after the measurements. As the accuracy of the zero determination on the record is limited, it is difficult to measure the absolute value of the current varying with long periods or to make a continuous measurement for long time. Namely, P-type current meter is not suitable for the observation of the steady flows.
- (3) Besides these drawbacks, another difficulty occurred in the actual observation at Niigata Beach. The permanent magnets gathered iron sand around them and pipes were clogged after several hours of observation. The P-type current meter swollen with iron sand are shown in Fig. 4. Therefore, prolonged observations are impossible at beaches where iron sands are abundant.

4. E-type electromagnetic current meter

The above-mentioned drawbacks of P-type current meter can be removed by using an alternating magnetic field of electromagnet. Fortunately, electromagnetic flow meter which is made commercially for industrial purpose to measure the flows in pipes are available. By sending A.C.-current of 50 cycles/sec to the exiting coil of the current meter, an alternating magnetic field is induced in the insulated

pipe. The resulting electromotive force also alternates with frequency of 50 cycles/sec and its amplitude is proportional to the mean flow speed in the pipe. The polarization potential difference varies slowly and it is eliminated in the stage of amplification by A.C.-amplifier. In this meter, nickel electrodes are used. The inside diameter of the insulated pipe is 50mm in our case. But it should be decided according to the scale of the current to be measured. Then the accuracy of E-type current meter can be expected to be higher than 1cm/sec.

The E-type current meters were calibrated in the water channel of Department of Naval Architecture, University of Tokyo, and in the water channel of Tokai Regional Fisheries Research Laboratory. In both cases, current meters were suspended from the electric trolley which runs over the channel and were calibrated for steady flows only. The calibration for the varying flow were not done.

The current meters were made symmetrical in shape not only of the cross section perpendicular to the flow but also of that parallel to the flow, as the measurement of reciprocating flow such as orbital wave current is intended. In the first case, in order to minimize the disturbance raised on the streamlines, the current meter was designed in a shape of an ellipsoid of revolution which has the cylindrical channel along the axis. The intakes of the channel along the axis have the shape of bell mouth (E-I type). The shape and the directional characteristic curve of E-I type current meter are shown in Fig. 5 and in Fig. 6. The abscissa indicates the angle θ between the current direction and the current meter direction and the ordinate indicates the ratio of the inner flow speed to the outer flow speed of the pipe. The directional characteristic curve deviates appreciably from cosine curve. The maximum does not happen at zero degree but happens at 30 degrees. At an angle between 70 and 90 degrees, the inner flow flows against the outer flow. Therefore, E-I type current meter is not suitable for the directional measurements of the flow. But it is convenient for the measurements of the speed of the current which flows in a constant direction because the directional

characteristic curve of the meter is flat in a fairly broad range of θ near zero and we may set the current meter roughly in the direction of the current. A somewhat similar electromagnetic current meter has been reported by HERMANT and WOLF (1959) who used the more streamlined shape of the current meter.

In the case of E-II, the bell-mouth shape of intakes is removed in order to taper the directional characteristic curve near zero degree. The shape and the directional characteristic curve of E-II type current meter are shown in Fig. 7. The minimum at zero degree in the characteristic curve of E-I (Fig. 6) disap-

E - I

Fig. 6. The directional characteristic curve of E-I current meter. The ratio of the inner flow speed to the outer flow speed is taken in ordinate and the relative angle of the current meter to the current direction is taken in abscissa.

pears in this case and the maximum takes place at zero degree. But the domain of backward flow near 90 degrees is broadened and the backward flow happens even at the angle of 50 degrees. The effect of the bell-mouth

shape in intakes is recognized also in the reduction of the relative inner flow speed to outer flow speed in the curve in Fig. 7 in comparison

E II

Fig. 7. The directional characteristic curve of E-II current meter.

with the curve in Fig. 6. In Fig. 8, the directional characteristic curve of E-II' is shown, the shape of which is similar to E-II but at intakes of which threads are tapped. The threads at intakes seem to have the same effects as the bell mouth. It makes the directional characteristic curve of the current meter rather flat near zero degree and it increases the relative inner flow speed.

The mechanism of the backward flow region cannot be cleared by our limited experiments. But it is supposed that the ellipsoid of revolution placed in the flow causes the concentration of streamlines near the frontal end and the divergence near the end in the rear and that the resultant pressure difference (low in front and high in the rear) creates the flow in the channel along the axis against the outer flow. Therefore, the backward flow region would disappear if sufficiently long pipes are

attached to the intakes and so new intakes are placed out of the disturbed region of streamlines near ellipsoid or if the shape of the current meter is deformed like a single pipe.

In the case of E-III, the pipes of various length are attached to the eigher ends of E-II

Fig. 8. The directional characteristic curve of E-II' current meter.

meter. In Fig. 9 and in Fig. 10, the shapes and the directional characteristic curves of E-III'-15 and E-III-30 are shown. The numerals in the model numbers signify the length of attached pipe in cm and the primes after the Roman numerals signify the existence of threads at intakes (the above-mentioned effects of the existence of threads is recognized to some degree in all case as seen in Fig. 11). In Fig. 11 a, b, c and d, the directional characteristic curves are shown for various lengths of the attached pipes. For comparison, a cosine curve is drawn in Fig. 11 d, too. The width of the backward flow region decreases with the increase in the length of attached pipes. In our case, the directional characteristic curve is

Fig. 9. The directional characteristic curve of E-III'-15 current meter.

closest to cosine curve when the length of attached pipes are chosen to 37.5 cm long. When pipes longer than 40 cm are attached, the characteristic curve has a tendency to depart from cosine curve near zero degree and the ratio of inner flow speed to the outer flow speed decreases by the effect of the friction.

In the case of E-IV, we designed the current meter like a beer barrel in order to investigate the effect of the abruptly cut off ends on the directional characteristic curve. The shape and the characteristic curve of E-IV are shown in Fig. 12. The characteristic curve of E-IV approaches to pedestal in its shape and even at 80 degrees the inner flow speed remains at almost 40% of the outer flow speed. The inner flow changes its direction abruptly at 90 degrees. The backward flow region does not appear in this case.

By combining the characteristics of E-II and of E-IV, the modified shape of E-V is designed in order to obtain the cosine directional characteristic curve with rather short attachments.

Fig. 10. The directional characteristic curve of E-III-30 current meter.

Fig. 12. The directional characteristic curve of E-IV current meter. The ratio of the inner flow speed to the outer flow speed is taken in ordinate.

Fig. 11. The directional characteristic curves of E-III series. The ratio of inner flow speed of each angle to that of zero angle is taken in ordinate. The numerals in model numbers signify the length of attached pipes in cm and the primes after the Roman numerals signify the existence of threads at intakes.

The shape and the characteristic curve are shown in Fig. 13. As expected, the characteristic curve has no backward region when attachments of only 15 cm length are used. Several types of the current meter similar to E-V were examined but it seems that it is not so easy to get the smooth cosine characteristic curve by this means. So, E-III-37.5 type current meter is most suitable for the directional observations.

The calibrations for the speed characteristics of the meter were also conducted in all cases. The linearity of the speed characteristic curves are very good in all cases. The shapes of the directional characteristic curves do not depend on the absolute value of the outer flow within our experimental range from 20 cm/sec to 200 cm/sec. The examples of the speed characteristic curves are shown in Fig. 14 through Fig. 16.

E - V

Fig. 13. The directional characteristic curve of E-V current meter. The ratio of the inner flow speed of each angle to that of zero angle is taken in ordinate.

Fig. 14. The speed characteristic curves of E-I current meter. Full line shows the case in which the relative angle is zero and dashed line shows the case in which the relative angle is 30 degrees.

Fig. 15. The speed characteristic curves of E-II and E-IV current meter. The cases in which the relative angle is zero are shown.

Fig. 16. The speed characteristic curves of E-III-15 current meter. Full line shows the case in which the relative angle is zero and dashed line shows the case in which the relative angle is 30 degrees.

The E-III-37.5 type current meters were tested in Shimizu Harbor, Shizuoka Prefecture. The test observation shows the superior ability of the E-type current meter. Unfortunately in the process of the remodulating of this instrument, an accident occurred, which damaged instrument. Plans are made to build another ones.

Acknowledgements

The author wishes to express his thanks to Professors Koji HIDAHA, Kozo YOSHIDA, Masashi HOMMA, Kiyoshi HORIKAWA and Takao INUI, University of Tokyo, and Professor Syo-ichiro HAYAMI, University of Kyoto, for their encouragement and advices and to Dr. Mizuki TSUCHIYA, Meteorological College, Mr. Toshihiko TERAMOTO and Mr. Susumu TABATA*, University of Tokyo, for their advices and

* On leave of absence from Pacific Oceanographic Group, Fisheries Research Board of Canada, Nanaimo, B.C., Canada.

discussions. His thanks are also due to Hokushin Electric Works Ltd. and Tsurumi Seiki Kosakusho Co., Ltd. for their supports and to Department of Naval Architecture of University of Tokyo and Tokai Regional Fisheries Research Laboratory for their kindness for permission to use their water channel.

Reference

- MM. HERMANT and WOLF (1959): Practical applications of the electromagnetic nozzle to the measurement of flow velocities. *La Houille Blanche*, No special B-1959, 883-891.