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A SUSPENDED-DROP CURRENT METER

by

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Technical Report No. 4
CU-4-62 Nonr. 266(48) Geology

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INTRODUCTION

Very little is known about the currents near the floor of the oceans. However, it seems probable that they will usually be very small, but perhaps will occasionally be moderately large. The present investigation was aimed at providing a current meter capable of measuring these currents.

EXISTING CURRENT METERS

A comprehensive study of existing current meters has been made by Johnson and Wiegel (1958). This report includes an extensive bibliography and considerable information about some current meters. It classifies current measuring procedures into "flow methods" and "path methods". In the former: "The velocity at a given point is measured by instruments which operate on various principles as follows: (a) A rotating element such as a propeller or series of cups or vanes whose speed of rotation is a function of the stream velocity; (b) by the pressure exerted by the flowing water on a pendulum, plate or pitot tube; (c) the electromotive force which is produced when an electrically conducting water-body moves in a magnetic field; and (d) an ultra-sonic device in which the phase difference of sound traveling in still water and flowing water is a function of the stream velocity. Considerable work has been devoted to the development of a hot-wire anemometer, but such a device is limited to laboratory work." In the latter: "The three most common general methods of tracing paths are (a) the aerial, (b) the end point, and (c) the path.

"The 'aerial' method consists of introducing a dye or a large number of floats and recording the nature of the water movement by periodic vertical aerial photographs. This procedure is common practice in hydraulic model studies where overhead photographs of confetti floating on the water surface are obtained.

"The 'end point' procedure involves the use of either drift bottles or drift cards being released in a certain area and then recovered at a later date when they are stranded on shore. Instructions in each serially numbered container provide a reporting procedure by which the final destination can be determined and plotted. No information is obtained by this procedure on the path between the point of release and the point of recovery.

"The 'path' procedure overcomes the disadvantages of the drift bottle and drift card technique in that the paths of travel of floating objects are observed at intervals from the time of release to the time of recovery. Such float tracking can be done either visually or by radar." Underwater sound is used for submerged floats such as the Swallow float (1955).

There are many instruments of the "flow" type suitable for measuring velocities in the range from approximately 0.1 knot to a few knots, a few capable of measurements below 0.1 knot, but essentially none capable of measurements below 0.01 knot. Existing instruments of the "path" type such as

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the Swallow float can be used to measure currents over a wide range of values. They can be used to measure very slow currents if the floats are observed for long enough periods of time. However, they are not suitable for giving detailed information about slow currents.

It is clear that there is need for a current meter capable of measuring very small currents. It is also clear that a meter having a long range, from very slow currents to large currents, will be particularly useful. There are indications that a simple current meter which can measure from 0.1 knot up may well find use even in this region where meters are now available.

GENERAL CONSIDERATIONS

A very simple and direct method for measuring ocean currents is to provide an identifiable point in the water and to determine its displacement in a known time interval. Then, the speed is obtained by dividing the displacement by the time, and the direction of the velocity is the direction of the displacement. A speed of 5×10^{-4} knot corresponds to a displacement of 1 mm in 4 seconds, while a speed of 5 knots corresponds to a displacement of 10 cm in 0.04 seconds. Either of these sets of measurements can be made without great difficulty. Clearly, the method is capable of measuring very small velocities and also rather large ones. The range can be extended to even smaller velocities but greater care will be needed.

An identifiable point can be provided by a small drop of colored liquid having approximately the same density as sea water

but being immiscible with it. Positions can be obtained from photographs of the drop. Knowledge of the time intervals between photographs can be provided by a motor-driven timer or by a watch. A magnetic compass in the field of view of the camera that photographs the drop can provide the direction.

If the drop has exactly the same density as the water around it, it will neither rise nor fall and its motion will be identical with that of the water. If its density is not exactly the same as the surrounding water, it will have a vertical velocity through the water given by the equation:

$$v = \frac{2}{9} \frac{ga^2}{\eta} (\rho_d - \rho_w)$$

where v is the velocity in cm/sec

g is the acceleration of gravity, 980
cm/sec²

a is the radius of the drop in cm

η is the coefficient of viscosity of the
sea water, 1.2×10^{-2} dyne-sec/cm²

ρ_d and ρ_w are the density of the drops and
of sea water in gm/cm³

If, for example $\rho_d - \rho_w = 0.001$ gm/cm³ and $a = 0.05$ cm, v becomes approximately 0.05 cm/sec. A drop will rise or fall only 2 mm during the 4 seconds needed to measure a horizontal current of 5×10^{-4} knot. It may be difficult keep $\rho_d - \rho_w \leq 0.001$ gm/cm³ but the radius of a drop can easily be made smaller than 0.05 cm so that a vertical velocity of 0.05 cm/sec or less can be attained.

The accuracy of the method can be illustrated by measurements at 5×10^{-3} knot. With a time interval of 4 seconds, the horizontal displacement will be one cm. Liberal estimates of the uncertainties in time interval and displacement are $2\frac{1}{2}\%$ for each giving an overall accuracy of approximately 5%.

SUSPENDED-DROP CURRENT METER

The complete current meter designed to operate in the manner outlined in the last section consists of an ejector to provide small drops of suitable liquid, a magnetic compass, and a stereo camera with a light and control circuits and timers to photograph the drop and compass. The individual units of the meter are described below.

Ejector

The ejector for providing small drops of liquid is shown in Figures 1, 2 and 3. It consists of a tuberculin syringe with a #27 x 1/2" needle (1) which is operated by an electromagnet (2) by means of a pawl (3) and ratchet (4) and a threaded rod (5). When the magnet is energized, the armature is attracted and the pawl moves the ratchet one tooth. The rod which is threaded through the ratchet is prevented from rotating by the screw (6). It, therefore, advances pushing the plunger of the syringe and forcing approximately 0.001 cm^3 of liquid out through the needle. The pin (7) engages a second ratchet fastened to the first but with its teeth facing in the opposite direction in order to prevent the ratchet from advancing more than one tooth. When the

magnet is de-energized, the armature is pulled away by the spring (8) and the ratchet is prevented from turning by the pawl (9). The unit is now ready for another ejection. If a single drop is ejected, the radius will be approximately 0.05 cm. However, usually a spray of several smaller drops is formed. The mechanism of the ejector is located inside a neoprene cap (10) which is kept full of oil. Thus, the mechanism is protected from sea water and there is no pressure difference between the inside and outside of the syringe.

An ideal liquid would have the same density as "sea water" at all pressures, temperatures, and salinities, would be immiscible with water, and would be opaque. Clearly, such a liquid does not exist, but reasonable approximations can be obtained. In preliminary work, mixtures of aniline and benzene darkened with the dye, Sudan 3, were used. At present, ethyl benzoate and n-heptyl alcohol dyed with Sudan 3 are being tried*. Some properties of these liquids follow:

Ethyl benzoate (Benzoic acid, ethyl ester; Ethyl benzene-carboxylate) E. K. #112

Density (International Critical Tables, Vol. III)

$$d_t = 1.0651 - 0.9046 \times 10^{-3}t - 0.2423 \times 10^{-6}t^2$$

Melting point - 34.6°C (Handbook of Chemistry and

Physics, 34th Edition, Page 752, #1454)

Boiling point - 212.6°C

Solubility in water 0.08 gm per 100 ml at 20°C

* We are indebted to Dr. A. P. Marion for suggesting these liquids.

n-heptyl alcohol (1 Heptanol) E. K. #381)

Density (Heilbron: Dictionary of Organic Compounds)

t d (compared with water at 4°C)

0 0.83622

15 0.82601

$$\alpha = 0.68 \times 10^{-3}/^{\circ}\text{C}$$

Melting point - 34.6°C (Handbook of Chemistry and
Physics, 34th Edition, page 932, #4478)

Boiling point 176°C

Solubility in water 0.09 gms per 100 ml at 18°C

Calculated densities of mixtures of ethyl benzoate
and n-heptyl alcohol follow:

<u>Fraction of</u> <u>ethyl benzoate</u>	<u>Fraction of</u> <u>n-heptyl alcohol</u>	<u>Density</u> <u>at 20°C</u>	<u>Density</u> <u>at 0°C</u>
1.0	0.0	1.047	1.065
.9	.1	1.024	1.042
.8	.2	1.002	1.019
.7	.3	.979	.996
.6	.4	.957	.973
.5	.5	.934	.951

Clearly the density of either fresh water or sea water can be matched. A check on the equality of the densities of a sample of sea water and a mixture of the liquids is easily made by putting them in two arms of a long U-tube. If the densities are equal, the upper surfaces will be at the same level regardless of where the interface between the liquids is located. If this test can be made at the same temperature

at which the liquids are to be used, the only uncertainty will be the effect of pressure. Of course, actual experience in which drops of a given composition are observed to rise or fall provides the best guide for the preparation of ejector liquids.

There have been some indications that at low temperatures, near 0°C , the drops do not always fly clear of the needle, but tend to cling to it. More experience is needed to settle this point, but a heater has been constructed for use at low temperatures, if it is needed.

The present ejector design seems satisfactory. However, before the instrument is ready for routine use, the construction should be made more precise and substantial. Eventually, the ejector should be redesigned so that the syringe can be refilled without removing the neoprene cap which holds oil around the mechanism. At present, refilling the syringe is not difficult, but it is messy. The change in design is being delayed until more experience with the use of the equipment has been accumulated.

Magnetic Compass

The most satisfactory compass found thus far is an Airguide Fisherman's Compass, #89. This photographs well, is inexpensive, and has been undamaged by pressures up to 10,000 psi. In the present arrangement, the compass is affected slightly by the magnet of the ejector. This is not serious as the compass can be read on photographs taken just before

the ejector magnet is energized. If necessary, the effect can probably be eliminated by magnetic shielding.

Camera

The camera, Figures 4 and 5, is a modified version of the underwater camera (Thorndike, 1959) used for other purposes. Two 35 mm Leitz Summaron lenses with their axes $1\frac{1}{4}$ " apart replace the single lens normally used and provide a pair of photographs from which three coordinates can be obtained for each drop being studied. The roller and cam arrangement which controls the amount of film which is transported between exposures has been modified so that approximately $2\frac{1}{2}$ " rather than $1\frac{1}{2}$ " of film are transported. Thus the camera provides pairs of photographs, each member of a pair being approximately $1\frac{1}{4}$ " square. Various motor drives have been used. For slow transport the usual Type -AV Brailsford motor is satisfactory. Type BH Brailsford motors can be used to give somewhat higher speeds. For the fast transport needed for measuring currents of 0.1 knot or more, Hansen #7100D motors have been employed. With these motors, two pairs of photographs per second can be obtained. The film spools hold up to 25' of film giving approximately 120 pairs of photographs. If more film is needed, the camera must be redesigned to accommodate larger film spools.

Light Source

After considerable experimentation with tungsten-filament lamps, it was concluded that an electronic flash lamp was more satisfactory. At present, an FT-118 flash tube receives energy from a 30-mfd condenser charged either by two 240-volt Eveready #491 photoflash batteries or by a low-voltage battery and a transistorized push-pull DC to DC converter giving approximately 450 volts. The high-voltage battery is simpler and provides more rapid charging of the condenser but requires somewhat more space. The electronic flash lamp gives ample light and has flashes of such short duration that there is no perceptible blurring of the images even with the film in motion. The flash tube is mounted in the front of the camera housing just to one side of the two lenses.

Pendula

During preliminary tests in shallow water, currents above 0.1 knot were encountered. The water often contained considerable suspended matter. Under these conditions, it is very difficult to identify a drop or other particle and observe it on successive pairs of photographs. In order to obtain a measure of the current under these conditions, a second current-detecting device was added. It consists of three sheets of 0.020" aluminum roughly 1" x 2" hanging as pendula from horizontal axes which are 120° apart. The deflections

of the pendula give a measure of the velocity of the current in the range from approximately 0.02 to 0.5 knot. The deflections are recorded on the same photographs as the drops. It may be desirable to include these pendula as part of the suspended-drop current meter. Alternately, a very simple current meter employing pendula alone can be used for currents above 0.02 knot.

Control Circuits and Timers

A wide variety of control circuits has been used. Two typical arrangements are given below. The first, Figure 6, is intended for use when the current meter is lowered to the bottom and a single set of observations is made in a short time. This is suitable for use from an unanchored ship. The second, Figure 7, is intended for use when the current meter is buoyed and left on the bottom for several hours, or with modifications of the timer speeds, for several days.

Consider operation with the circuit shown in Figure 6. The testing Hamlin switch is used to clear the ejector syringe of air after all equipment is in the housing. The starting Hamlin switch is closed by a magnet which moves near to it when a trigger-weight strikes bottom. The camera Acro switch is closed thus firing the electronic flash tube each time that enough film for a pair of photographs has been transported. The speed of the timer motor, Brailsford Type-AG, is controlled by a governor so that it closes the timer-operated Acro switch at intervals that are equal and known. This causes the ejector to eject drops and the marking light to expose small sections

of the edge of the film. The time between one pair of exposures and the next can now be found from the known time between marking light flashes and the distance along the film between pairs of exposures, compared with the distance between flashes. In like manner, one can obtain the time interval between the ejection of a drop and the next pair of exposures. Thus the displacement of a drop in a known time can be obtained and the velocity can be calculated.

Now consider operation with the circuit shown in Figure 7. Before lowering, a cam extending halfway around the shaft of the $\frac{1}{4}$ rph timer is rotated to such a position that it will actuate the Acro switch #1 after any desired interval up to two hours. When the Acro switch #1 is actuated by the timer, the film transport motor, the 1 rpm timer motor, and the 20 rpm motor all start. Film is transported. If the 20 rpm timer has one cam, the Acro switch #3 is closed each 3 seconds. If it has two cams, the switch is closed each $3\frac{1}{2}$ seconds. In either case, the ejector operates and the marking light puts a mark on the film each time that the switch closes. If the 1 rpm timer has one cam extending halfway around the shaft, the Acro switch #2 will be moved to the other position in 30 seconds. If it has two equally-spaced cams, each extending one quarter of the way around the shaft, the Acro switch #2 will be moved to the other position in 15 seconds. In either case, all motors except that on the $\frac{1}{4}$ rph timer will stop. The sequence will be repeated when the $\frac{1}{4}$ rph timer turns far enough for the cam to allow the Acro switch #1 to return to

its original position, two hours if there is one cam, as stated above.

The 1 rpm timer also operates Acro switch #4 so that one can tell where one series of exposures ends and the next begins. One set will have marks and the next will not. This feature can be eliminated if a watch is imaged on the film.

Acro switch #5 opens when all film is used up thus stopping all motors.

Operation

Figure 8 shows a current meter suspended from its tripod. The ejector syringe points upward with the needle projecting through the background plate. The compass is mounted in the background plate. The camera faces down and photographs the drops, compass, and a series of lines on the background plate. From the two coordinates of a drop image relative to the images of the lines on the background plate obtained for each of the photographs of a pair and the separation of the camera lenses and the distance to the background plate, one can calculate the position of the drop in space. A second such calculation on the next pair of photographs gives the position at a known time later. (The method of obtaining the time interval has been discussed in the section on Control Circuits and Timers). The three components of the velocity can then be calculated. The vertical velocity probably is a measure of the density difference between the drop and surrounding water, and the horizontal velocities give the current.

The maximum velocity which can be measured may be taken as the radius of the field of view of the camera divided by the time between photographs, 10 cm/ $\frac{1}{2}$ sec or 20 cm/sec (0.4 knot). However, it may be possible to measure slightly higher velocities, as the time between drop ejection and the next photograph is determined by chance and may often be considerably less than the $\frac{1}{2}$ second between exposures.

The minimum measurable velocity is determined by the length of time that a drop can be followed and the minimum displacement that can be measured. With a 15-second period of observation and displacements of 1 mm being measurable, one obtains 10^{-1} cm/15 sec or 7×10^{-3} cm/sec (1.4×10^{-4} knot). However it is difficult to follow a drop for the entire period as other drops are being ejected and as the drop will tend to rise or fall because its density does not exactly match that of the water. The first difficulty can be reduced by ejecting drops less frequently and the second by careful preparation of the drop liquid.

It is estimated that the range in velocity which can be routinely measured with the present timer and film-transport speeds is from 5×10^{-4} to 4×10^{-1} knot.

Tests at Sea

During the summer and fall of 1961, the suspended-drop current meter was tested in approximately 100 feet of water off the New Jersey coast on four occasions. The design was modified as a result of the experience obtained in each

series of tests. The currents measured ranged from 0.005 to 0.2 knot.

Figure 9 is a reproduction of two successive pairs of exposures on a representative film. Figure 10 shows the positions of successive images of the largest drop in a group measured on the "right" member of each exposure pair for these two exposures and for the next four. It also shows the velocity components calculated from the data. The velocity in this case is reasonably constant, but in some instances, there was considerable turbulence. This is not surprising as the water was not deep and the surface was not calm.

The tests showed clearly that the suspended-drop current meter is capable of measuring ocean currents and of showing turbulence. They also showed that the equipment is not difficult to handle at sea.

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Acknowledgments

This work was sponsored by the United States Navy, Office of Naval Research, under Contract Nonr 266 (48) with assistance from Contract Nobsr 85077. Reproduction of this document in whole or in part is permitted for any purpose of the United States Government.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 9 (Cont'd.)

DROP POSITIONS

(Largest Drop)

Sept. 5, 1961 Film 2

Exposures 103-108

$$V_x = -0.0012 \text{ knot}$$

$$V_y = +0.0513 \text{ knot}$$

Using Exposures
103 and 108 only

Figure 10

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