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AN ULTRASONIC CURRENT METER FOR ESTUARINE RESEARCH

BY

FOSTER H. MIDDLETON

The Johns Hopkins University

ABSTRACT

An instrument that measures the velocity and direction of water flow in estuaries is described. The magnitude is obtained by measuring the phase lag or advance, caused by motion of the water, in an ultrasonic wave. The instrument can be towed or suspended from a vessel or operated unattended at a remote station for a week.

This ultrasonic instrument was designed to measure water velocity and direction of flow in estuaries. Preliminary design specified that the instrument gather current magnitude and direction data intermittently for a period of one week at an unattended station in an estuary; the magnitude was desired over a range of 0.08 to 5.1 feet/sec, with a maximum error throughout the range of 1% of full scale velocity; the direction had to be read simultaneously with the magnitude and had to be within 10 degrees around the compass. The instrument had to be sufficiently light so that it could be carried on board a research vessel; furthermore, the construction had to be such that it could be launched and recovered with relative ease.

The velocity of acoustic propagation in sea water is the order of 5,000 fps, hence it would seem futile to transmit an ultrasonic signal in the direction of water flow with the objective of measuring the change in transmission time caused by a water velocity of only 5 fps. From the standpoint of instrumentation and accuracy requirements, it would be necessary to measure the propagation velocity with a maximum error of 0.001%. This approach looks even less promising when the relationship of propagation velocity to temperature and salinity of the water is considered (Beranek, 1949: 52). A water temperature change of only 0.5°C or a salinity change of 1‰ would

1 This work was supported by the Office of Naval Research, Department of the Navy.
2 Instructor, Department of Electrical Engineering, The Johns Hopkins University.
be sufficient to change the propagation velocity by an amount equivalent to the full range of water velocity to be measured.

The measurement scheme employed in this ultrasonic current meter avoids the above problems and is quite simple. Basically, a continuous-wave acoustic signal is generated at one point (the transmitter) and is detected at another (the receiver). The phase relationship between transmitted and received ultrasonic signals is easily measured and the process can be repeated with the transducers electrically interchanged. If the two phase measurements are made close enough together in time, there will be no detrimental effects from temperature or water velocity changes (see Fig. 1).

![ULTRASONIC SCHEMATIC](image)

The two transducers are attached to the instrument body, which is aligned with the direction of water flow. A phase measurement is made first with the acoustic transmission direction in line with the water flow and then with the acoustic transmission direction reversed. It is apparent then that the difference in the two phase measurements is caused primarily by water velocity, since water temperature, salinity, and pressure are assumed to be constant during the short reading period.
The acoustic frequency employed here is $10^6$ cycles/sec (1Mcps). With a propagation velocity of 5,000 fps ($1.5 \times 10^6$ cm/sec), the wavelength is then 0.15 cm. The spacing of the transducers is 60 cm, or 400 wave-lengths. In Fig. 1, then, the separation of the curved lines between the two transducers is 0.15 cm and the speed of advance of these wave-fronts from transmitter to receiver is 150,000 cm/sec. Under some assumed operating condition (with water velocity, temperature, and salinity constant), the received signal will be exactly in phase with the transmitted signal. That is, a pressure front will arrive at the surface of the receiving transducer at the same instant as another will be leaving the surface of the transmitter. This condition will prevail, of course, so long as none of the assumed "constants" changes and so long as the phase meter will be sensitive to changes from this condition. This is the principal advantage of the phase measurement scheme.

A change of as little as 0.1% in the propagation velocity will result in an effective change in the transducer spacing from 400 to 400.4 wavelengths. Thus it is quite simple to measure accurately a phase change of 0.4 times 360 degrees, or 144 degrees. The amount of phase shift available for a given change in propagation velocity is directly proportional to ultrasonic frequency and to transducer spacing. The transducer spacing of approximately two feet and the operating frequency of 1 Mcps were selected to obtain the necessary phase resolution while keeping the size of the instrument down to requirements.

A water velocity of 5 fps will have the same effect on phase relationship as the above 0.1% change in propagation velocity. And, since one measurement is made with the acoustic path in the direction of the water velocity and the other with the acoustic path in the opposite direction after commutation, the total phase difference to be measured is 288 degrees. Of course these two phase measurements could be made simultaneously with two identical electronic and acoustic circuits, but, since this would involve duplication of instruments, it was decided to use only one system and to make the two measurements in rapid succession. Naturally this presents some limitation to the ultimate accuracy of the instrument.

Fig. 2 shows the arrangement of the components of the instrument on station in an estuary. The anchor unit, resting on bottom, serves to restrain the "fish," the lift buoy, and the surface buoy; furthermore, it has enough negative buoyancy to resist the upward force of the lift buoy so that the fish can be positioned at any desired distance from the bottom. The components are connected by means of a mooring cable of steel hydrographic wire, along which an eight-
conductor electrical cable runs between anchor unit and fish. A box-like bridle not only supports the fish but permits the fish to rotate and align itself with the direction of the current; furthermore, it provides the fish with necessary pitch-axis freedom.

The anchor unit is a cylindrical tank having two compartments, one for the batteries, the other for the recorder unit.

Fig. 3 shows the ultrasonic head and an exploded view of the transducers. The coaxial cables are brought through a hole in the fish body when the ultrasonic head is originally attached to the fish body. Of course electrical shielding is important throughout to prevent the relatively strong transmitter signal from getting into the receiver channel by means other than the acoustic path through the water to the receiving crystal. The center conductor of the shielded leads is soldered to the back of the quartz crystal while the front (exposed to the water) surface of the crystal is grounded to the head body, as is the shield of the coaxial cable. Each crystal,
then, is connected alternately to the driving oscillator on the phase meter chassis and to the receiving channel amplifier. The transducers clear the body of the fish by approximately six inches, which is an adequate distance to prevent detrimental effects of acoustic reflection from the fish body.

The fish body, which contains phase meter, compass transmitter, ultrasonic head and commutator (coaxial switch) consists of a cylindrical brass sleeve (about two feet long and six inches in diameter) with a one-quarter inch wall thickness. Turned wooden fairings for both nose and tail provide streamlining, and the brass fins provide the necessary means for alignment of fish body with water flow. On the top side of the fish body is an eight-pin watertight Cannon cable connector, on the underside an ultrasonic head (see Fig. 4a). Fig. 4b shows the arrangement of the internal components of the fish, which are, from left to right, compass transmitter, phase meter, and commutator.

The compass transmitter, an aircraft-type magnetic compass with a built-in 400 cps synchro unit, is connected by cable to the excitation generator and synchro repeater in the anchor unit.
Figure 4a (upper). Assembled underwater section of ultrasonic current meter (note the tail fin assembly finally employed is approximately three times the area of that shown).

Figure 4b (lower). Interior of the underwater unit showing coaxial switch, the phasemeter chassis, and the magnetic compass transmitter in their inverted positions.
Figure 5. The anchor unit with one end opened showing recorder unit in the recorder end of the anchor unit shell.
As mentioned earlier, the commutator serves to interchange the transducers between the functions of transmitter and receiver. This is a DC motor-driven coaxial transfer switch which was selected for its low cross-talk characteristic. That is, essentially none of the transmitter signal is allowed to be coupled into the receiver channel, since any such leakage would result in a phase error in the phase meter.

The transfer switch connects the ultrasonic transducers to the phase meter chassis. Since the phase meter is an involved electronic circuit that requires special design, it will not be described in detail except for its general function in the instrument. It receives both filament and plate power through the cable from the anchor unit, and its output is in the form of a DC current that varies linearly with phase difference from 0 to 1.0 milliampere (0 to 360° phase difference). It also has simple controls so that routine maintenance procedures can take account of tube aging or other effects that would tend to disturb the output current vs. phase difference correspondence.

The anchor unit body, a cylindrical shell of one-quarter inch steel, is about 4 feet long by 15 inches inside diameter. A one-quarter inch steel plate, which divides the body approximately in half, was welded to the inside in order to prevent possible battery damage from harming the remainder of the components in the recorder unit.

The battery unit is made of 12 lead-acid cells connected in series for a nominal terminal voltage of 24 volts. The batteries, with plastic cases and visual indication of state of charge, are rated at 24 ampere-hours. To permit rapid servicing, they are held in a steel frame that slides readily into the battery compartment. A watertight connector on the partition bulkhead delivers the energy of the batteries to the control panel of the recorder unit.

Fig. 5 shows the anchor unit with the end plate removed and with the recorder unit extending from its compartment. Components of the recorder unit can best be described in three groups; the camera display, the recorder (camera), and the control unit.

The camera display includes the compass repeater, the indicating milliammeter, an eight-day clock, and a light to indicate the direction of ultrasonic transmission. These units, closely grouped on the aluminum plate in the background of Fig. 5, are in the field of view of the camera which appears in the foreground of this photograph.

Because of the difficulty of converting the 400 cps synchro output from the compass transmitter into some electrical quantity that would be easy to record, a camera was employed for the recording job.

On the control panel with the camera are located the necessary
motor driven timers and relays to initiate and complete a recording cycle once each half hour. The recording cycle, of one minute duration, includes a 28 second period for filament warm up. The two short recording periods within the recording cycle, one for acoustic transmission in the direction of water flow and the other for acoustic transmission against the direction of water flow, are separated by six seconds in the present control circuit arrangement. A commutator indicator light appears in the recording frame to indicate when the acoustic transmission direction is in the direction of flow.

The camera, an 8-mm Bell and Howell, Model No. 172, has provisions for stepping the film one frame at a time by means of the film advance solenoid, which simply pushes the button provided on the camera for this frame stepping. The film is stepped by a manually-wound spring built into the camera; one winding of this spring will provide somewhat more than 800 exposures, which corresponds roughly to eight days of current data at half-hour intervals (two exposures per reading cycle). Originally it was felt that four exposures per reading cycle, alternating upstream and downstream, would provide a useful check on the reliability of each piece of data, but this plan was not possible because of the limitation imposed by the spring. Except for this limitation, the remainder of the control circuitry will readily permit four-exposure reading cycles with only slight modifications.

The time between readings in one reading cycle can be either three or six seconds, depending on the control circuit arrangement; the lower limit to this time is determined only by the response time of the indicating milliammeter. Most any type of recorder could be used if one wished to speed up the reading process to eliminate fluctuations that might be caused by either water-flow eddys or thermal layers in the water. One-half second for the completion of the commutator operation and short switching transients would probably be sufficient to avoid any eddy current problems, since, at the high end of the water velocity scale (5fps), the time between readings would permit water motion of the same order of magnitude as the transducer spacing (approximately two feet).

Since the ultrasonic current meter reads the water velocity along the line between the two transducers, it is necessary to keep the fish body aligned with the current. Even at the low end of the scale no trouble has been encountered on this point with the present tail fins.

The presence of the transducers in the water that is being measured will certainly have some effect on the flow itself; this will be called the stagnation effect. Ignoring stagnation, calculation of the cor-
respondence between the water velocity and the current as indicated by the milliammeter yields the relationship of 4.12 knots per milliampere difference between two successive meter readings. Since an accurate consideration of the stagnation effect would be extremely complicated geometrically, several simplifying assumptions about the flow pattern were employed and a different calibration constant was obtained by drawing an electrical analogue field plot. The result was 4.9 knots per milliampere, a figure which has been fairly well verified by towing runs made by the Chesapeake Bay Institute personnel; timed runs between channel buoys in the Bay gave results within the range of 4.8 to 5.0 knots per milliampere.

Finally, a particular field experience during which the ultrasonic current meter was being checked against other instruments bears mention. Erratic results were being obtained by a drag-line meter and by a VonArx propeller-type meter at a depth of 20 to 24 feet in waters where a tide was running. With the vessel riding fairly steady from a single anchor, the ultrasonic meter was lowered slowly from 18 to 24 feet and readings of water velocity and direction were taken at one-foot intervals. At 21 feet, readings were small and decreasing to zero, and at 22 feet the instrument read negative 0.02 knots with the same heading as that at 21 feet. But at 23 feet the instrument read a positive 0.05 knots and the heading had reversed 180 degrees, indicating that the instrument had swung around to align itself with a reverse current direction. Since the instrument was being lowered slowly and since the water velocity was small, the negative reading at 22 feet indicated that there was insufficient righting moment to swing the fish around as it crossed over the barrier between flow in opposite directions. With these data, then, there was no difficulty in ascertaining the reason for the erratic results from the other current meters.

Conclusions

The ultrasonic current meter has been used in the field without serious trouble, and it is reasonable to conclude that the ultrasonic method of measuring water velocity is a sound one. When compared with other meters, it is quite expensive to build, at least in its present form, and the method is somewhat involved. But, as in the case of all experimental models, the present model does not represent the ultimate, for there is undoubtedly much room for improvement. However, this instrument seems to be advantageous in that there is no inherent limitation to its accuracy near the low end of its velocity range, as in so many other measurement approaches. In other words, there is no static friction effect as found in propeller-type instruments.
The ultrasonic instrument hangs with its support wire nearly vertical at towing velocities up to 5 knots because of the low ratio of drag force to weight.

If the current velocity being investigated is a slow function of time (as, for example, tide cycles), there is no upper limit to the velocity that may be measured with the ultrasonic meter. This might be an advantage in some applications.

Furthermore, this instrument, unlike others, cannot be fouled by seaweed or sea nettles. This feature has been distinctly advantageous aboard ship, and it is certainly an important factor for the operation of all unattended instruments.

The primary timer of this instrument runs for the entire time of operation, and even though it draws only 0.05 amperes, it consumes approximately half of the total battery energy delivered. Obviously a simpler device than the present primary timer would be more desirable. Recently in connection with other work for the Chesapeake Bay Institute, the author installed a sensitive microswitch in an inexpensive eight-day spring-driven clock. By replacing the hour hand with something like a pin-wheel, any reasonable number of output pulses per hour could be obtained with only one microswitch. With this suggested primary timer, and with a pen or light-beam type of recorder, the ultrasonic current meter could be modified to take readings at five or ten minute intervals for perhaps a week.

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