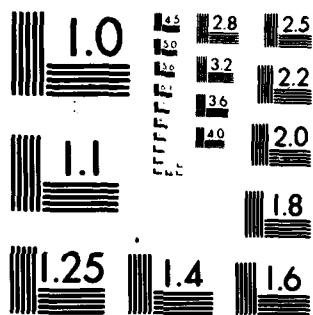END
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A THREE-AXIS ACOUSTIC CURRENT METER FOR SMALL SCALE TURBULENCE

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INTRODUCTION

Design on the current meter described in this paper began early in 1975 at Neil Brown Instrument Systems, Inc. (NBIS) and the Applied Physics Laboratory of Johns Hopkins University (APL/JHU) in an attempt to develop an instrument having characteristics suitable for horizontal profiling of small scale turbulence in the ocean. The result of this program was a three-axis instrument suitable for mounting on the bow of a submersible and capable of resolving turbulence phenomena as small as 10cm with frequency components up to 50Hz. Included in the overall instrument package was a conductivity - temperature - depth (CTD) system and three-axis accelerometer. The CTD sensor and electronics are described elsewhere[1]. During a single scan interval of .01s all three axes of the acoustic current meter, the three axes of the accelerometer and the conductivity, temperature, and pressure sensors are digitized, resulting in 900 measurements every second. The accelerometer and velocimeter outputs are digitized to 14 bit and the CTD to 16 bit resolution. Figure 1 shows a block diagram of the overall system. This paper will be limited to a discussion of the three-axis acoustic current meter.

CURRENT METER CHARACTERISTICS

An examination of the characteristics of current meters in general leads to the conclusion that the mechanical types are generally quite unsuitable for this application. The Savonious[2] rotor's unequal acceleration and deceleration rates and non cosine response make it particularly unsuitable. The electromagnetic current meters have the disadvantage that their electrical output is proportional to magnetic field. This field decreases rapidly with distance from the coil. Consequently, they are sensitive only to fluid flow in the immediate vicinity of the coil which, due to its bulk, severely affects the flow being measured. The open Helmholtz coil E.M. current meter described by Olsen[3] could possibly be adapted to meet the stated requirements. The acoustic backscatter type[4] while appearing to have theoretically ideal characteristics has not been generally successful due to the poor distribution of suitable scatterers in clear ocean water.

Thus it was felt that current meters in which current is sensed by measuring the differential travel time of acoustic signals travelling with and against the fluid flow offered better possibilities. The reasons are (1) response is inherently linear and extremely fast (2) sensitivity is uniform over the acoustic path (3) the transducers are small (4) signal to noise ratio is usually excellent (5) it can be made to have close to ideal cosine response (6) calibration can be inferred from frequency, sound velocity and transducer spacing.

Numerous acoustic current meters using this basic concept have been described in the literature. The concept has been implemented in a number of different ways some of which are (1) short pulse using 2 transmitters and 2 receivers for each axis[5] (2) short pulse using 2 transducers each acting as both a transmitter and receiver[6] (3) dual "sing-around" sound velocimeters with straight line sound paths in opposite directions (the difference in the "sing-around" frequency being a linear function of current.) (4) continuous wave using two widely different high frequency carriers (e.g. 1.1 and 1.6mHz, but modulated with an identical signal of lower frequency (e.g. 20kHz) where the phase difference of the modulating signal on the received carriers is a linear function of current velocity.[8] (5) continuous wave bursts using a single frequency (e.g. 2mHz) on a single pair of transducers, the burst interval being approximately equal the acoustic travel time between the two transducers.[8] The received bursts resynchronise "slave" oscillators which maintain phase information between bursts. The continuous output of the "slave" oscillators is heterodyned with a local oscillator resulting in outputs of 8kHz. Phase difference between the 8kHz signals is a linear function of current.

The first three methods require the measurement of arrival time differences of pulses with sufficient speed to resolve currents less than 1cm/sec. It can be shown that

$$\Delta T = \frac{2vd}{c^2}$$

where ΔT = arrival time difference
v = current velocity
d = transducer spacing
c = velocity of sound

For d = 4cm, c = 1500m/s, the time difference is
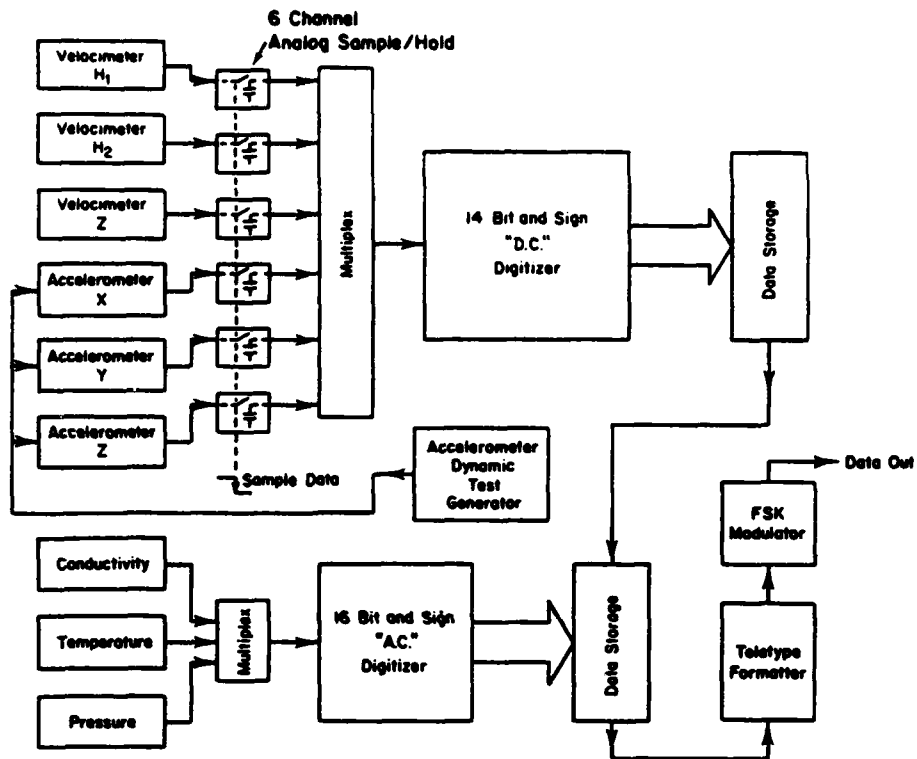
Fig.1 System Block Diagram

Fig.2 Continuous Wave Concept

3.6×10^{-10}s. Time resolution as short as this requires extremely high speed circuitry and auto calibration features such as those described by Cytre[6]. The first method using separate transducers for receiving and transmitting suffers from the additional disadvantage of requiring extremely stable relative position between the receiver and transmitter of each pair. For example, a change in relative position of 10^{-6}m for an acoustic path length of 4cm causes a change in arrival time equivalent to a current change of 2cm/s. The fourth method while free of the problems associated with threshold detection of pulses, etc. does require the measurement of phase difference to the same time resolution as types 1, 2 and 3 above. The fifth method has the advantage that the phase angle measured at the relatively low beat frequency is the same phase angle difference that occurs at the carrier frequency. This permits a time measurement that can be slower by the ratio of the carrier to the beat frequency for a given current speed.

CONTINUOUS WAVE CONCEPT

The continuous wave concept described in this paper is shown schematically in Figure 2. Each axis utilizes a single pair of transducers 4cm apart. Each transducer simultaneously transmits one frequency (approx. 2.7mHz) and receives another frequency (differing by 500Hz) acoustically from the other transducer. Since the signal sources driving the transducers are high impedance (essentially constant current) both frequencies exist simultaneously at each transducer. The composite signals at each transducer E_1 and E_2 (see Figure 2) are each square law detected and band pass filtered resulting in 500Hz beat frequency signals E_5 and E_6. These signals are in turn multiplied in M_3 resulting in a 1kHz signal E_7 which forms one input to the phase meter. A 1kHz reference is the other input E_{11} to the phasemeter and is derived from a reference generator E_{10}. An examination of the theoretical discussion below shows that resulting output E_{12} from the phasemeter is a linear function of current, and that the required time resolution for an acoustic path length of 4cm and a current of 1cm is 10^{-6}s. Thus, the required time resolution for this continuous wave concept is approximately 2750 times longer than that required for the pulse technique. This drastically simplifies the circuitry and results in an instrument that does not require the use of ultra high speed circuitry or the need to correct for changes in internal circuit delays due to temperature, etc. to achieve sensitivities and stabilities better than 1cm/s.

THEORY OF OPERATION

The following is a discussion of the theory of operation of one of the axes of the 3 axis current meter. For the Z axis E_1 and E_2 have frequencies of 2.7505 and 2.7500mHz respectively. The frequencies for the other two axes are 2.7700 and 2.7705mHz for H_1 axis and 2.7300 and 2.7305mHz for the H_2 axis. Different frequencies were used for each of the 3 axes to avoid possible interference between the different axes.

Referring to Figure 2, E_1 is derived from a fixed crystal controlled oscillator having a frequency

of 2.7505mHz. E_2 is derived from a voltage controlled crystal oscillator whose frequency is maintained by a phase locked loop at a frequency exactly 500Hz lower than E_1 (i.e. 2.7500mHz). The phase-locked loop maintains the phase of the beat frequency E_8 at exactly $90°$ difference from the 500Hz reference frequency E_9 which is derived via a binary divider from the 1kHz reference signal E_{10}. E_8 and E_9 are the inputs to a multiplier M_2 whose output is low pass filtered resulting in a d.c. signal used to correct the phase error of E_2 (crystal VCO) and, consequently, the phase error between E_8 and E_9. Except for the additional mixer M_1 and low pass filter LP_1, this circuit is a conventional phase-locked loop. The circuit parameters are such that the maximum phase error is less than .003 rad. The theory of operation is as follows.

$$E_1 = \cos \omega_1 t \ldots\ldots\ldots (2.7505\text{mHz from crystal oscillator})$$

$$E_2 = \cos \omega_2 t \ldots\ldots\ldots (2.7500\text{mHz from crystal VCO})$$

$$E_3 = \cos \omega_1 t + k_1 \cos (\omega_2 t + \omega_2 T_2)$$

$$E_4 = \cos \omega_2 t + k_2 \cos (\omega_1 t + \omega_1 T_1)$$

$$k_1 \ \& \ k_2 = .002 \text{ (typical)}$$

T_1 and T_2 are travel times from A to B and B to A. After mixing and removing zero and high frequency terms

we get $E_5 = \frac{1}{2}k \cos ((\omega_1 - \omega_2)t - \omega_2 T_2)$

and $E_6 = \frac{1}{2}k \cos ((\omega_1 - \omega_2)t + \omega_1 T_1)$

After mixing E_5 and E_6 in M_3 and high pass filtering

we get $E_7 = \cos(2(\omega_1 - \omega_2)t + \omega_1 T_1 - \omega_2 T_2)$

$$E_8 = \cos(\omega_1 - \omega_2)t \quad \text{(500Hz output)}$$

$$E_9 = \sin(\omega_1 - \omega_2)t \quad \text{(500Hz reference)}$$

$$E_{10} = \sin 2(\omega_1 - \omega_2)t \quad \text{(1kHz reference)}$$

$$E_{11} = \cos 2(\omega_1 - \omega_2)t$$

Therefore phase angle between E_7 and E_{11} is

$$\theta = \omega_2 T_2 - \omega_1 T_1$$

Now $T_1 = \dfrac{d}{c + v}$ and $T_2 = \dfrac{d}{c - v}$

where d = acoustic path length
c = velocity of sound
v = component of current velocity parallel to acoustic path

Therefore

$$\theta = \frac{d}{c^2 + v^2} (c(\omega_1 - \omega_2) - v(\omega_1 + \omega_2))$$

$$\theta = \frac{d}{c}(\omega_1 - \omega_2) + \frac{vd}{c^2}(\omega_1 + \omega_2) \text{ since } c >> v$$

The first term is in effect a "zero offset" term and the second term is the current velocity term. For $d = 4$cm, $c = 1.5 \times 10^5$cm/s, the relationship between θ and v is given by

$$\theta = .0838 + .00614v \text{ rad/cm/s}$$

Thus, the zero offset term is equivalent to a velocity of 13.63cm/s. The d.c. output of the
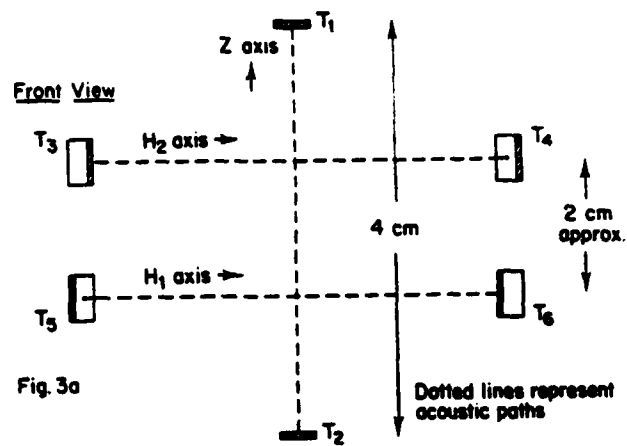
Front View

Fig. 3a

Z axis

T_1

H_2 axis →

T_3

T_4

H_1 axis →

T_5

T_6

4 cm

2 cm approx.

T_2

Dotted lines represent acoustic paths

Fig. 3b

Plan View

T_5

T_4

120°

T_1

H_2

H_1 →

T_3

T_6
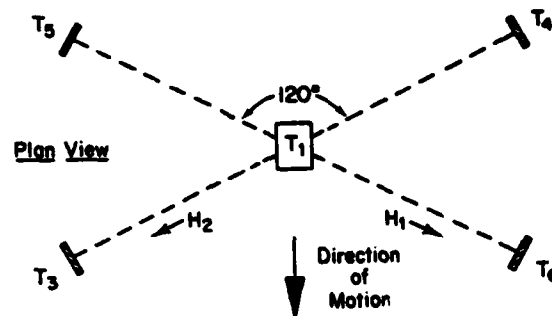
Direction of Motion

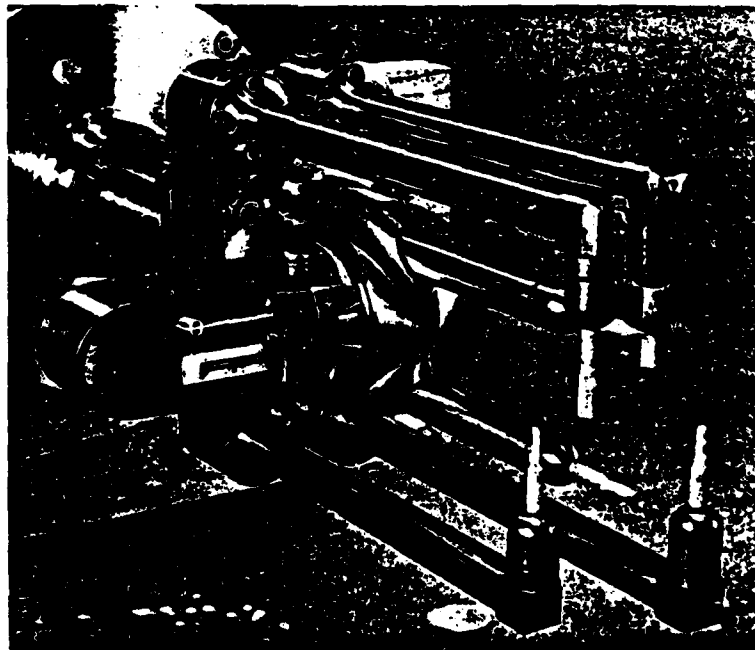Fig 3 Transducer Array Schematic

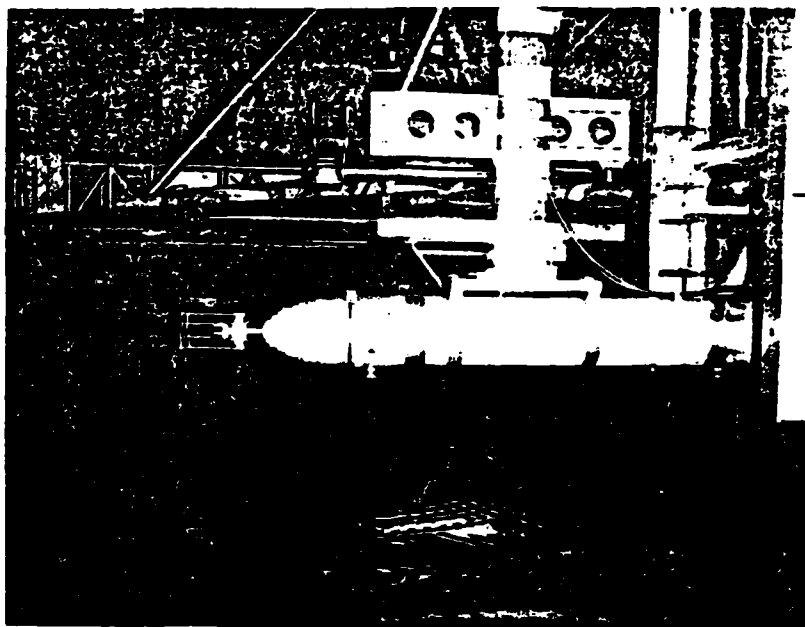Fig.4 Velocimeter and CTD Transducers

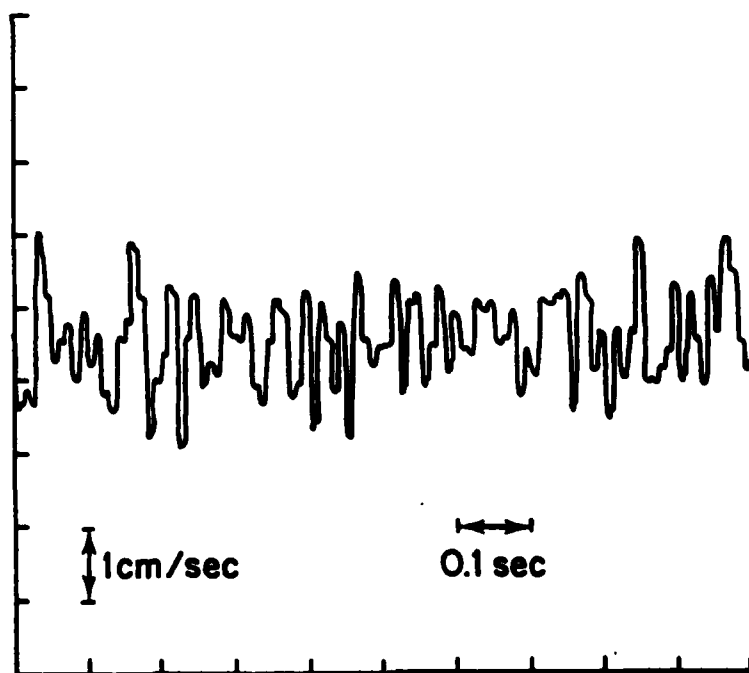Fig.5 Tow Tank Test Rig

1cm/sec   0.1 sec

Fig.6 Wideband Noise

phasemeter is thus a linear function of current velocity. The "zero offset" and the dependence on sound velocity are corrected numerically during data processing.

Since the zero offset term is proportional to the difference frequency $(\omega_1 - \omega_2)$ it could be reduced to an insignificant value by decreasing $(\omega_1 - \omega_2)$. However, this would also reduce the upper frequency response of the velocimeter.

TRANSDUCER ARRAY

Figure 3a and 3b show the spatial arrangement of the three axes of the current meter. The two horizontal axes H_1 and H_2 are at an angle of 120° and the plane of the H_2 axis is displaced vertically from the H_1 axis by about 2cm.

Since the forward motion of the submersible results in an incident current vector that is within 30° of the reference axis, this particular spatial arrangement ensures that no wake of any transducer crosses any of the acoustic paths thus resulting in minimal contamination of the measurements by the instrument itself.

Figure 4 shows a photograph of the three pairs of acoustic transducers and also the conductivity and temperature sensors of the conductivity - temperature - depth CTD) system.

The transducers are fabricated from lead metaniobate slabs 0.7mm thick, 5mm high, and 2mm wide. They were mounted in alumina assemblies which in turn were bonded using fused glass to the cylindrical stem. This ceramic and glass housing had excellent mechanical stability and inertness to seawater. The piezoelectric material, lead metaniobate, was chosen for this application because it had a low temperature coefficient of dielectric constant, low mechanical Q and essentially no acoustic radiation from the sides of the slab. At 2.75mHz this resulted in an acoustic beam width of approximately 8° on one axis and 20° on the other.

PERFORMANCE TEST

Some aspects of the steady state performance of the instrument were determined using the David Taylor Naval Ship Research and Development Center's (DTNS RDC) Deep Water Towing Basin. Flow sensitivity, angular response in both pitch and heading up to angles of 30°, and the noise characteristics of the instrument were measured.

The Deep Water Towing Basin is 15.5m wide and 6.7m deep. The tank is divided in half by a bulkhead. The west end, used for this test, is about 457m long. The velocimeter assembly was mounted on a strut of a towing carriage and inserted to a depth of 3.4m. The carriage was operated at speeds of 103, 206, 309, and 514cm/s (of 2, 4, 6, and 10 kts) for these tests. It had an electrohydraulic drive which maintains these speeds within one cm/sec. A rack and pinion device with a magnetic pickup emits a pulse every 3mm travelled by the carriage. The pulses are counted and stored in a memory which is sampled every 0.01s and recorded along with the

stream of data from the velocimeter.

Figure 5 shows the sensor package and mounting bracket. The sensor package was aligned with the Z axis vertical. The heading response of the velocity sensors was checked in this orientation at each carriage speed by rotating the assembly to 0, $\pm 30^o$ in the horizontal plane. Measuring the response at both positive and negative angles of incidence provided a check on the alignment of the transducers. The pitch response of the sensors was checked at each carriage speed by rotating the sensor package 90° about its axis to make the Y axis vertical and then rotating the assembly to 0°, $\pm 15^o$, and $\pm 30^o$ in the horizontal plane. The possibility of asymmetries in the flow about the sensor assembly was checked by repeating each measurement discussed above, but with the sensor package rotated 180° about its longitudinal axis.

Table I shows the linear response of the horizontal transducers. Each has a zero offset with a magnitude larger than the theoretical. This discrepancy from offset errors in the electronics was not corrected for lack of time but is easily remedied. The response is linear to within $\pm 1.1\%$ over the test range of 0 to 514cm/s (10 knots), but the sensitivity is lower than theoretically predicted by about 15%, probably due to a stagnation flow effect. A potential flow calculation, summing the effects of the elliptical fairing and flat base plate behind the array, predicts about a 10% flow reduction, independent of the carriage speed. Stagnation flow around the transducers themselves may contribute to the reduction.

TABLE I - VELOCIMETER RESPONSE

Carriage Speed (cm/s)	Velocimeter Reading* (cm/s)		Deviation** (%)	
	H_1 Axis	H_2 Axis	H_1 Axis	H_2 Axis
0	0.0	0.0	0.0	0.0
103	90.1	91.8	+0.2	+1.1
206	174.5	172.8	-0.9	-0.2
309	264.7	263.6	-0.6	+0.7
515	445.8	434.2	0.0	0.0

*Velocimeter Reading corrected for zero offset
**Deviation from best fit straight line thru end points

Figure 6 shows the wide-band (0-50Hz) noise of the vertical channel. The r.m.s. amplitude is about 0.3cm/s. Thus the noise is less than 0.1% of full scale over a 50Hz band-width. This is a very acceptable figure, but can be improved upon by better crystal design and mounting.

CONCLUSION

Preliminary test results show that the continuous wave acoustic current meter is very promising. The technique of heterodyning two very close frequencies

(at the transducers) allows excellent current resolution using conventional low power electronics since all the critical signal processing is done at the beat frequency. The use of a single pair of transducers avoids errors due to small mechanical instabilities and differential phase responses that occur when separate transmitting and receiving transducers are used. Development of the concept is being continued at NBIS, Inc. and data analysis and evaluation at APL/JHU. Unfortunately, the publication deadline did not allow time for analysis and presentation of more complete test results in this paper.

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