Presented at Oceanology International 1992
Brighton, UK

A SIMPLE LOW COST ACOUSTIC CURRENT METER

Neil L. Brown
Woods Hole Oceanographic Institution
USA

INTRODUCTION

This paper describes an experimental acoustic current meter presently under development. The objective of the program is to develop a current meter that is inherently low cost, low power consumption, small and yet is capable of excellent performance, both static and dynamic. The rationale for this development is as follows.

If the science of climatology and oceanography is to advance significantly it is essential that observations at sea be obtained more frequently and at shorter geographic intervals. The high cost of existing current meters, mooring systems and the ships to deploy them is limiting our understanding of oceanography and climatology. Satellite telemetry has facilitated obtaining data from remote sensors. Hence the oceanographic community is considering expendable moorings, air dropped moorings and possibly moorings deployed from "ships of opportunity". Regardless of which method is used, current meters must be much less expensive, consume much less battery power, be much smaller, lighter and reliable than existing instruments. It should be noted that the size and weight of current meters adversely effects the size and cost of the moorings and the cost of deploying the resulting system.

Current meters in routine use today have relatively large, expensive electronics and battery packages and have limited operational life. Current meters using mechanical sensors (rotors or impellers) are vulnerable to damage and are easily stalled by marine fouling or flotsam of various kinds. Existing acoustic current meters using two orthogonal pairs of transducers and an acoustic mirror have poor vertical and horizontal cosine response due to flow interaction with the mirror and the struts used to carry the mooring tension around the pressure housing. These instruments also consume excessive power and hence have limited operational life. All of the above instruments use gimballed compasses (magnetometer or mechanical with optical readout) which tend to be fragile, expensive and of limited accuracy.

Existing acoustic instruments transmit pulses [l],[2),[31 or continuous wave bursts [41,[53 simultaneously in opposite directions and then compare the difference in arrival time or phase difference of the received signals to determine the current velocity. They require two receivers, and tend to have errors due to changes in phase shift or time delay differences of the two receivers. Consequently these receivers must be very carefully designed and adjusted to avoid these errors. Typical acoustic path lengths are 10 cm, where an uncertainty of 1 nanosecond in the measurement of time results in an uncertainty of approximately 1.1 cm/sec in velocity. Hence the pulse type sensor requires two wideband receivers and very fast circuitry to measure extremely small time differences. Williams [3] in his BASS design eliminated this particular problem by reversing the receivers and transducers to determine any differences in time delays.

The continuous wave type sensor described by the author [43 eliminated the need for very high speed circuits by heterodyning the two received 1.6 mhz carrier frequency signals to obtain a beat frequency of 34 hz and by measuring the phase difference at 34 hz with low power CMOS logic circuits. However this required a second oscillator phase locked to the first at a frequency difference of 34 hz. The requirement of two receivers, the 2nd oscillator and the phase locked loop required a substantial amount of circuits, with a corresponding contribution to overall size, cost and power consumption.

The direction sensors in previous designs used either gimballed compass cards with optical readout or gimballed 2 axis fluxgate magnetometers. The compass card design was fragile, expensive and did not have good dynamic response due to inertia of the card and the low magnetic torque inherent in compass cards. Similarly, the gimballed fluxgate designs required jewel bearings to minimize errors due imperfect levelling caused by bearing stickiness, and this in turn required enclosure in an oil filled chamber to provide damping.

THE NEW DESIGN

Figure 1 illustrates external appearance of the proposed final design. At the time of this writing the system was in essentially breadboard form. The existing prototype has a total of 4 axes (see fig. 1). Each axis is 15 cm in length and has a vertical separation of 10.5 cm. It can be shown that only one of the four paths will be significantly contaminated by the wake from the center support strut. The microprocessor is used to determine which axis is contaminated by wake from the center support strut, and to reject the data from this axis. This is done by simply determining from which quadrant, in the XY plane, the current is flowing. Only three axes are required for a complete solution of the X, Y and Z components of velocity, thus permitting the accurate determination of current flow essentially uncontaminated by flow interaction with the center strut.

The photographs shown in figures 2 and 3 show the details of the breadboard electronics. These electronics use conventional components on a "through hole" printed circuit board. The small circuit board in figure 2 has the same circuits as the experimental assembly except that it uses surface mount components and packaging with a substantial reduction in size for the same function and will be used in the final design.

The design includes a "no moving parts" direction sensor described below. It avoids the need for expensive and fragile gimbals and oil filled damping chambers used in the earlier instruments. It uses a combination of a very low power 3 axis magnetometer and 2 axis accelerometer. The data from these sensors are processed in the microprocessor to determine tilt and magnetic direction, and are combined with velocity sensor outputs to determine the N/S and E/W components for vector averaging.

Figure 3 shows the experimental version of the 3 axis magnetometer, which is described in detail below.

VELOCITY MEASUREMENT

The new design transmits a 1 mhz continuous wave signal for a period of 1 ms, first in one direction where the total phase shift including the receiver phase shift is measured, and then in the opposite direction where the total phase shift is measured again, using the same receiver. The current velocity is proportional to the difference in phase for the two directions. A simple but accurate very low power circuit for measuring phase shift at the carrier frequency has been developed. Since the same receiver is used for both directions the errors due to the different phase shift of two receivers or offset errors in the phase sensitive detector are eliminated when the difference is taken.

The theory of operation is as follows. If we consider an acoustic path with two transducers at points A and B where each transducer is alternately transmitting and receiving, we can say that total phase shift between the received and transmitted signals is as follows.

$$\Theta_{ab} = \Theta_{ta} + \Theta_{rb} + \Theta_{ttab} + \Theta_{rec}$$
$$\Theta_{ba} = \Theta_{tb} + \Theta_{ra} + \Theta_{ttba} + \Theta_{rec}$$

Where Θ_{ta} and Θ_{tb} are the phase angles between the applied voltage and the resulting acoustic pressure wave for transducers A and B acting as transmitters. Similarly Θ_{ra} and Θ_{rb} are the phase angles between the output voltage and the arriving acoustic pressure wave for transducers A and B acting as receivers. Θ_{ttba} and Θ_{ttab} are the phase shifts due to the acoustic travel times from A→B and from B→A respectively. Θ_{rec} is the phase shift through the receiver. It can be shown that for any piezo-electric transducer driven by an essentially zero impedance generator or loaded by an essentially zero impedance receiver, the transmitting and receiving phase angles between the electrical current and the acoustic pressure wave are identical.

$$\therefore \quad \Theta_{ta} = \Theta_{ra}$$
$$\Theta_{tb} = \Theta_{rb}$$
$$\therefore \quad \Theta_{ab} - \Theta_{ba} = \Theta_{ttab} - \Theta_{ttba} \qquad (1)$$
$$= \frac{\omega d}{c-v} - \frac{\omega d}{c+v}$$

WHERE ω = *Angular frequency (rads per Sec)*

d = *Distance between transducers A and B (cm)*

c = *Velocity of sound (cm per sec)*

v = *Component of velocity along path A→B*

$$\therefore \quad \Theta_{ab} - \Theta_{ba} = \frac{-2\omega v d}{c^2+v^2}$$
$$\therefore \quad v = c2\left[\frac{\Theta_{ab} - \Theta_{ba}}{2\omega d}\right] \qquad (c>>>v)$$

CURRENT METER CIRCUIT OPERATION

Figure 4 shows a block diagram of the current meter circuit showing just one of the four pairs of transducers and the one set of the switches. The phase shifting circuit output is either 0, 90, 180 or 270 degrees, depending on the command from the microprocessor. The circuit operation is as follows. First the switches Swi and 5w2 are set by the processor to connect transducer A to the transmit circuit and transducer B to the receiver thus transmitting from A to B. Initially the phase shifting network is set to 0 degrees and the output of the phase sensitive detector is digitized by the AID converter and the result is stored. This is repeated for settings of 90, 180 and 270 degrees. The 0 and 180 degree readings are used to determine the "in-phase component" which is directly proportional to the difference between the 0 and 180 degree readings regardless of any DC offset in the phase detector. Similarly the 90 and 270 degree readings are used to obtain the "quadrature" component of the received signal. These two signal components are then used to calculate the phase angle between the received signal and the transmitted signal. The T/R switches Swi and 5w2 are then reversed and the above process repeated to calculate the phase shift for a signal going from B to A. As shown above difference in phase shift for signals going from B to A compared to A to B is then directly proportional to the component of current velocity parallel to the acoustic path between A and B. The above process is then repeated for the remaining 3 acoustic paths and the results are temporarily stored in the micro-processor memory.

For this scheme to work accurately it is necessary that the impedance of both the transmit and the receive circuit be very small compared with impedance of the transducer. When these conditions are met, the phase angle between the acoustic and electrical signals are the same for each transducer whether it is transmitting or receiving thus ensuring the integrity of the phase shift information. As mentioned earlier, this scheme has been breadboarded and tested in the lab at zero velocity, and in the small tow tank at WHOI at speeds to 52 cm/sec. Figures 6a through 6d show that the zero error is less than 0.3 cm/sec and that the phase measuring circuit works well and gives stable and predictable results. It is suspected that the residual errors are due to the "lumpiness" of the soldered connection at the front of the piezo-electric transducers. Lack of a planar surface would result in a distortion of the wave front radiated from the transducer which in turn would result in a different mechanical impedance in the transmission mode compared with the receiving mode where the received wave front is essentially planar. This in turn would tend to disturb the exact reciprocity of the two modes and could result in a non-zero value for O~ - Oba when the velocity (V) was zero. The "noise" of the data when the carriage was at speed was due to the speed fluctuation of the output shaft of the ball and disc variable speed drive of the tow carriage.

PHASE MEASURING CIRCUIT

The phase sensitive detector shown in figures 4 and 7 ideally can be treated as an analog multiplier whose instantaneous output is the instantaneous product of the two inputs.

$$E_s = K_s SIN(\omega t + \Theta_s)$$

$$E_r = K_r SIN(\omega t + \Theta_r)$$

WHERE K_5 , K_r are constants

$$\therefore\ E_{out} = E_s \text{ x } E_r$$

$$= \frac{K_s K_r}{2}[\cos(\Theta_s - \Theta_r) - \cos(2\omega t + \Theta_r)]$$

Low pass filtering E_{out} gives E_{dc}

$$\therefore\ E_{dc} = K\cos(\Theta_s - \Theta_r) + E_{os}$$

Where $K = \frac{K_s K_r}{2}$

and E_{os} = *zero offset of the detector*

If $\Theta r = 0$, *then* $E_0 = E_{dc} = K \cos(\Theta_s) + E_{os}$

If $\Theta r = 90$, *then* $E_{90} = E_{dc} = -K \sin(\Theta_s) + E_{os}$

If $\Theta r = 180$, *then* $180 = E_{dc} = -K \cos(\Theta_s) + E_{os}$

If $\Theta r = 270$, *then* $E_{270} = E_{dc} = K \sin(\Theta_s) + E_{os}$

$$E_0 - E_{180} = 2K \cos(\Theta_s$$

$$E_{270} - E_{90} = 2K \sin(\Theta_s)$$

$$\Theta_s = \arctan \left[\frac{(E_{270} - E_{90})}{E_0 - E_{180}} \right]$$

Hence Θ_s is independent of the gain or any d.c. offsets in the phase sensitive detector. The only requirement is that there be a linear relationship between the detector output and the cosine of the phase angle between the signal and reference input.

DIRECTION SENSOR OPERATION

The direction sensor consists of a 3 axis fluxgate magnetometer designed for very low power consumption and two commercially available accelerometers used as a 2 axis tilt sensor. The accelerometers are solid state accelerometers made by IC Sensors of Milpitas, California, USA. The data from these sensors is used to compute magnetic direction and tilt of the instrument. The flux gate magnetometer achieves very low power consumption by using a magnetic core of very small cross section thus reducing the energy required to magnetically saturate the core. The X and Y axes of the magnetometer are parallel to the X and Y axes of the tilt sensor. Small errors in alignment of any of the axes of the sensors will be determined at the time of calibration and numerically corrected by the processor. Initial results indicate that the combined power consumption for the 3 magnetometers and 2 acceleroometers will be less than 2.4 mw.

Figure 5 is a simplified schematic of the magnetometer. It is an adaptation of the “ring-core” design described by Geyer [6]. Each axis consists a Supermalloy tape wound bobbin core with a 100 turn drive winding on the core and a “sense coil” surrounding the outside of the toroid with its axis parallel to the plane of the core. The drive winding of the 3 cores are connected in series and excited with a 1 khz square wave of d.c. magnetic field, the signal in each sense coil contains only odd harmonics of the drive signal, because all parts of the core go into saturation at the same instant. However the presence of a d.c. field will cause one side of the core to go into saturation slightly before the other (d.c. and a.c. components add on one side and subtract on the other). This results in an unbalance signal in the sense coil. This unbalance signal results in a 2khz component in the output of each sense coil. The 3 sense coils are sequentially connected to the input of an amplifier tuned to 2khz. The unbalance signal is amplified in the tuned amplifier (see fig 5) and detected by the phase sensitive detector. Since the detector reference is a 2 khz square wave the output will contain a d.c. term which is integrated in the integrator. The d.c. output from the integrator is fed back to the sense coil. The complete circuit is a negative feedback system which balances the earth's field with an equal and opposite field in the sense coil. The field generated by the sense coil is proportional to the product of the number of turns and the feedback current Ifb. To minimize power consumption the maximum value of required feedback current was minimized by winding the sense coil with a large number of turns (5000 turns). The output voltage E_{out} is given by

$$E_{out} = I_{fb}.R_1$$

Hence E_{out} is directly proportional to the component of magnetic field (H) parallel to the axis of the sense coil. The advantage of this negative feedback scheme is that the calibration of the magnetometer is essentially insensitive to changes in the magnetic properties of the core.

PACKAGING

The experimental velocity sensor and direction sensor electronics were fabricated using conventional components on standard printed circuit boards. Work is in progress to re-package the electronics using surface mount technology. Electronics packaged in this way are dramatically smaller and rugged and most important, can be fabricated on automatic assembly lines with significant cost savings. Work is in progress to re-design the 3 axis magnetometer using 1.2 cm diameter cores to reduce the overall size of the magnetometer to approximately 3 cm x 3 cm x 4.5 cm. Present indications are that the overall size of the pressure housing to include the 4 axis velocimeter, direction sensor, micro-processor, solid state memory, and batteries for 2 years operation will be approximately 5 cm OD x 30 cm long. The center strut is intended to carry the mooring load.

Since the overall size is expected to be so small the intention is to fabricate the housing from titanium, thus avoiding the magnetic problems of stainless steel and the corrosion problems of high strength aluminum with essentially no significant increase in cost.

MICROPROCESSOR

Figure 7 is a schematic of the intended final design. The experimental prototype is interfaced to a PC via one of the COM ports connected to a simple micro-controller in the prototype. This was done to permit direct keyboard control of the various functions of the prototype for laboratory testing and evaluation as well as testing the various algorithms running in the PC.

The processor will be required to perform the following functions.

1. Control the switching of the acoustic transducers sequentially to the receive and transmit circuits.
2. Control the phase shifting circuit.
3. Control the switching of the magnetometers and tilt sensors.
4. Control the A/D converter and temporarily store the data from the A/D conversions.

5. Perform the calculations on the stored A/D data to derive the N/S and E/W components of current.
6. Perform the vector average at the required averaging interval and store or transmit the data as required.

The micro-processor to be used in the final version is still under consideration. Initial indications are that at 5 scans per second there are several possible candidates that will perform the above functions at an average power consumption of less than 5 mw.

CONCLUSION

The results to date show that the velocimeter design is simple and small with a power consumption of 2.1 milli-watts. It performs is essentially as predicted and with ongoing refinement of the design it is expected that a high level of performance will be achieved. Similarly the complete direction sensor (magnetometer and accelerometers) consumes 2.5 mw and will be quite small and extremely rugged and clearly meets the accuracy requirements for a good current meter. So far the only testing has been on the system components (velocimeter and direction sensor). Extensive testing remains to be done on the complete system to determine the static and dynamic performance of the final design.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the valuable contribution of Stephen Smith of the Woods Hole Oceanographic Institution to this work and to the Office of Naval Research who funded this work under ONR contract no. N00014-86-K-0751.

This is WHOI contribution number 7962.

BIBLIOGRAPHY

Gytre, Trygve "Ultrasonic Measurements of Ocean Currents Down to 1 mm/sec", IERE Conf Proc #32 Instrumentation in Oceanography, 23-25 Sept., Univ. College N. Wales, Bangor, U.K., pp 69-80.

Williams, A.J. 3rd "An Acoustic Sensor of Velocitv for Benthic Boundarv Laver Studies", Bottom Turbulence, Proc. 8th Intern. Liege Colloquium on Ocean Hydrodynamics. Elsevier Oceanogr. Ser 19, Jacques C.J. Nihoul, Ed. Elsevier Sci. Pub. Co., Amsterdam-Oxford-N.Y. 1977

Williams A.J., 3rd et al,"Measurement of Turbulence in the Oceanic Bottom Boundarv Layer with an Acoustic Current Meter ", Amer. Meteor. Soc., Jour. of Atmos. and Oceanic Tech., Vol. 4, No. 2, June 1987,

Brown, N.L., and K.D. Lawson, Jr., "A high precision acoustic current sensor," Near Surface Ocean ExDerimental Technology WorkshoD Proceedings, Naval Ocean Research and Development Activity, pp. 57-74, February 1980.

Lawson, K.D., Jr., N.L. Brown, D.H. Johnson, and R.A. Mattey, "A three-axis acoustic current meter for small scale turbulence, Instrument Society of America, ASI 76269, pp. 501-508, 1976.

Geyger, W.A.,"The Ring-Core Magnetometer--a New TVDGof Second Harmonic Fluxgate Magnetometer", Trans. AIEE (Commun. Electron.), vol. 81, pp. 65-73, Mar. 1962.

Figure 1

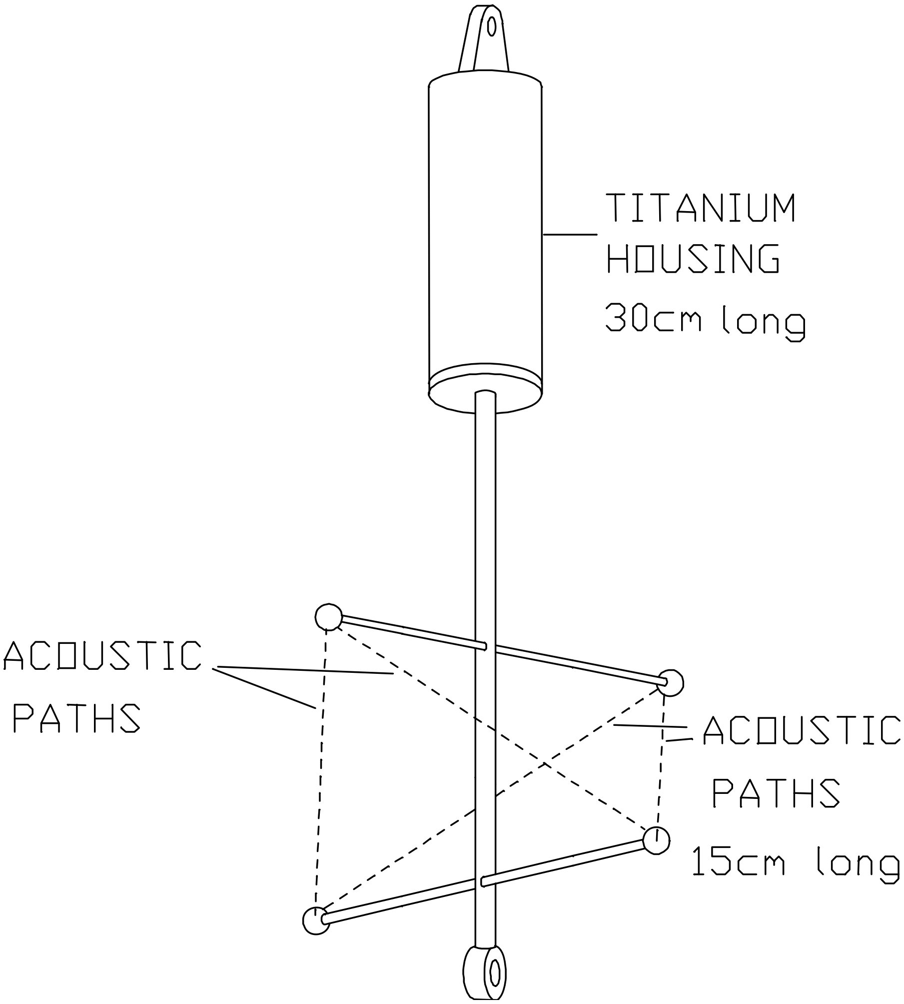


Figure 2
(not available)

Figure 3
(not available)

Figure 4

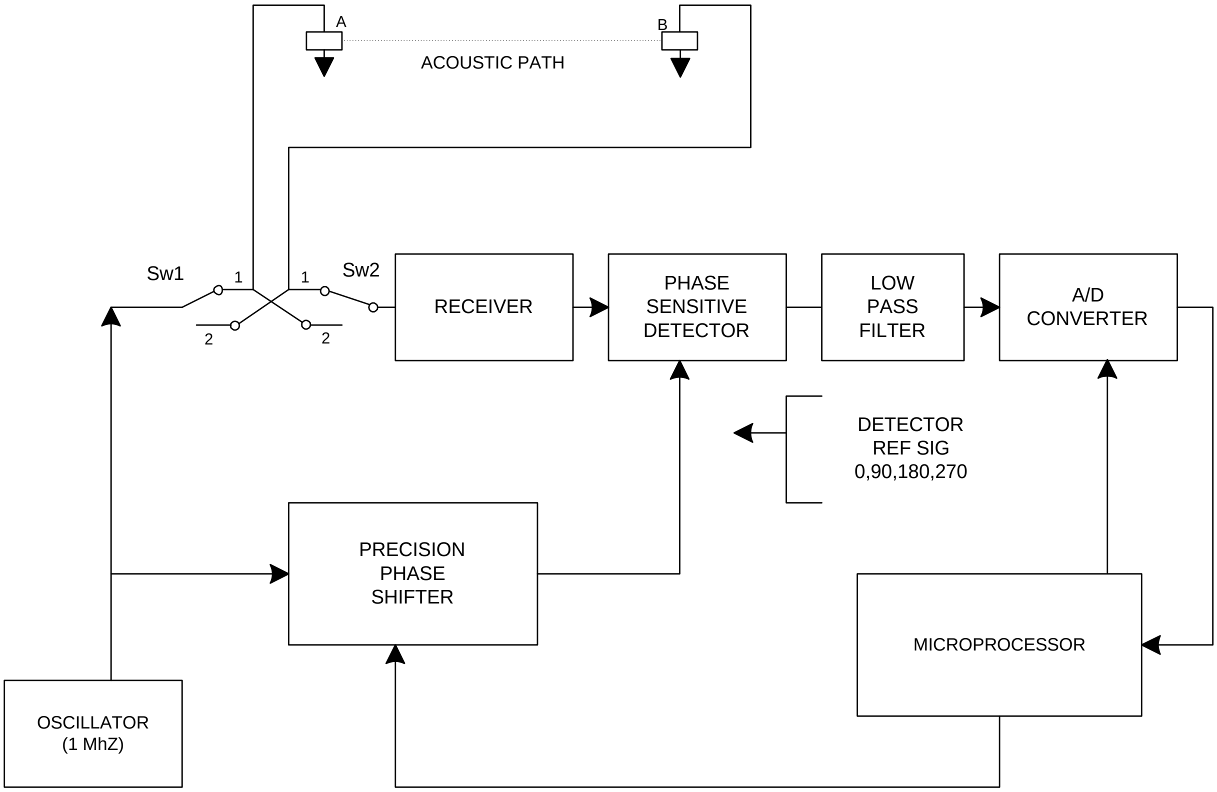


Figure 5

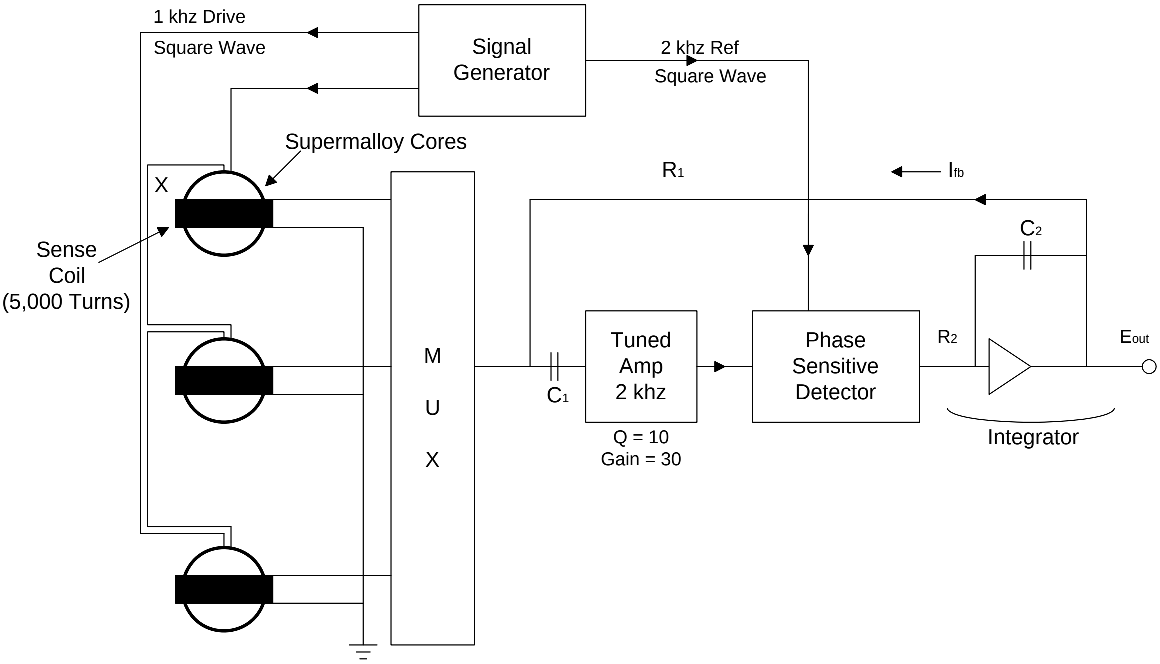


Figure 6a

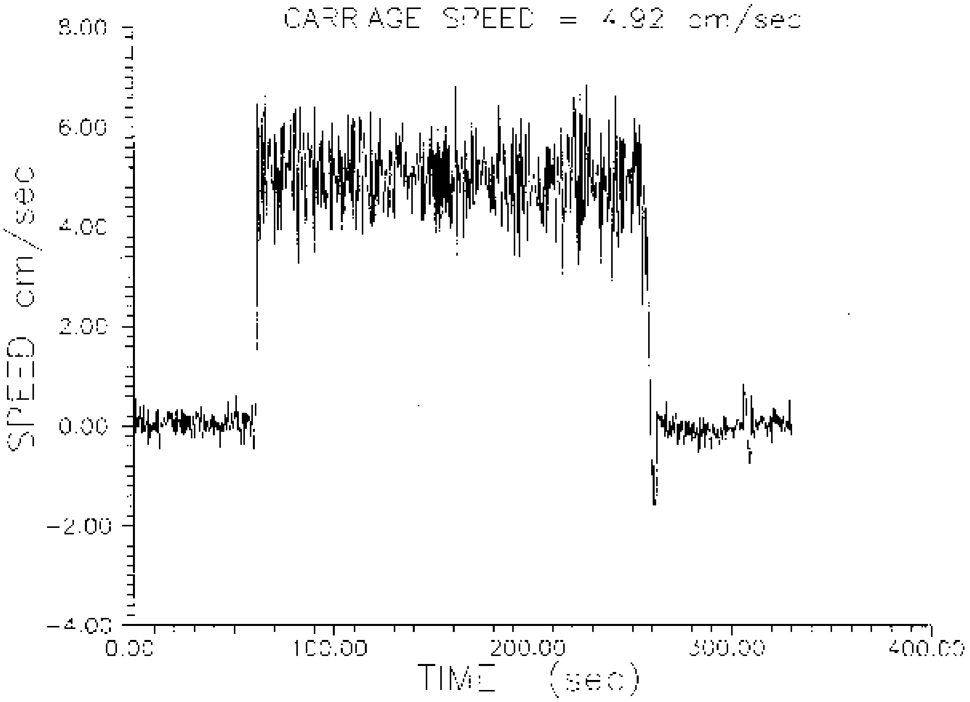


Figure 6b

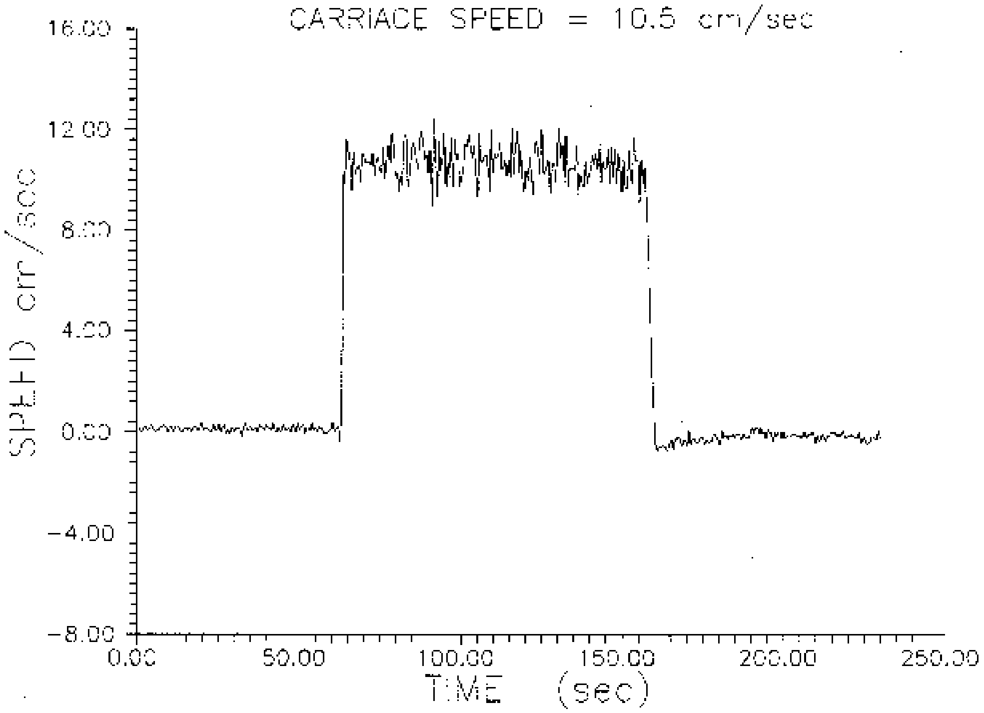


Figure 6c

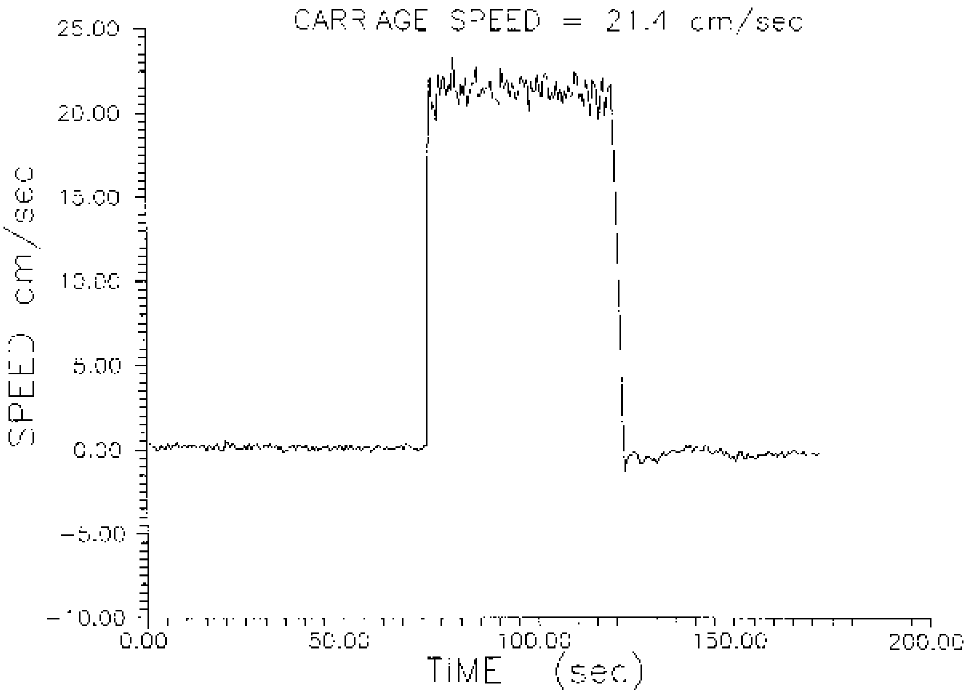


Figure 6d

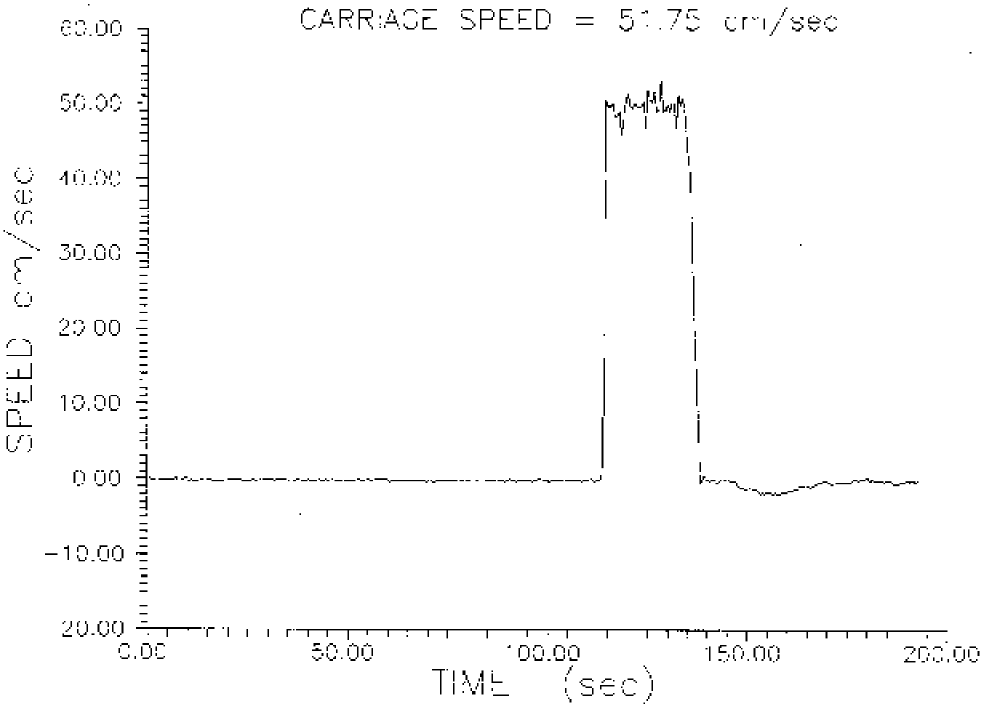
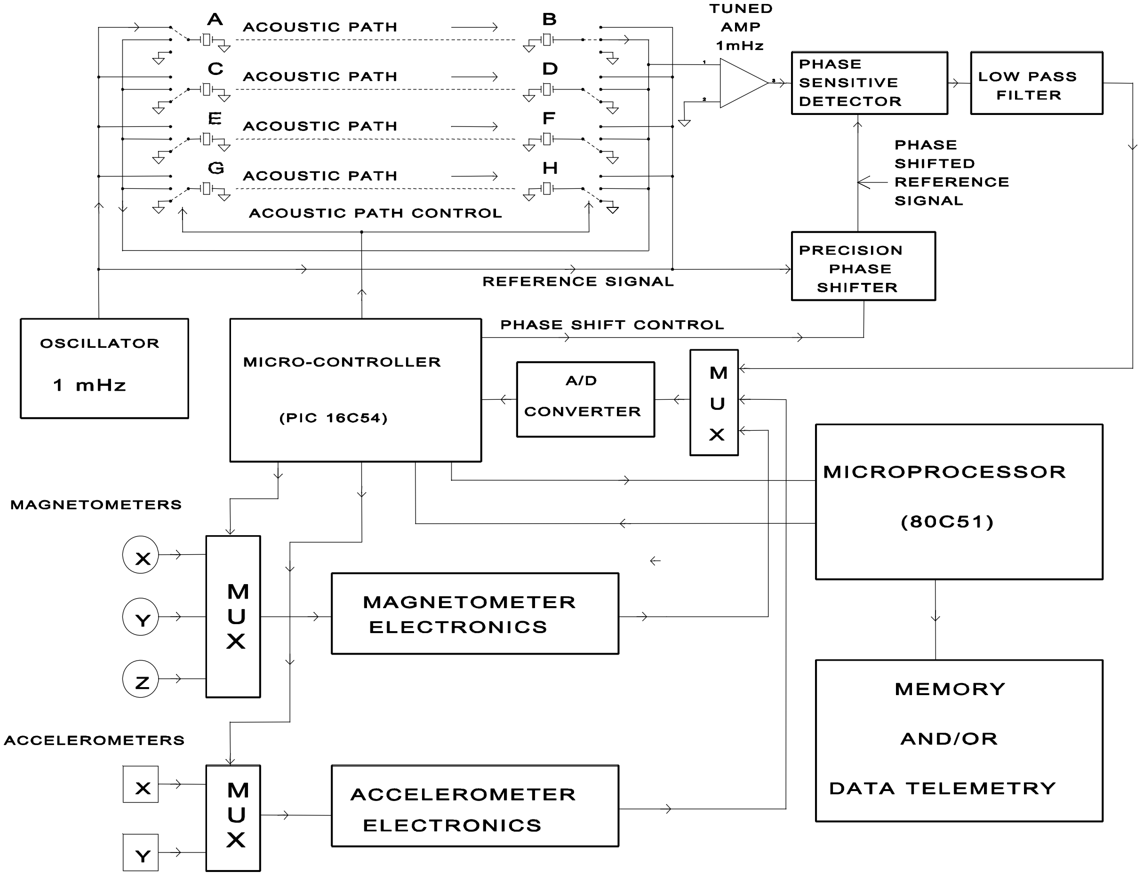


Figure 7


A
ACOUSTIC PATH
B
C
ACOUSTIC PATH
D
E
ACOUSTIC PATH
F
G
ACOUSTIC PATH
H
ACOUSTIC PATH CONTROL
TUNED AMP 1mHz
PHASE SENSITIVE DETECTOR
LOW PASS FILTER
PHASE SHIFTED REFERENCE SIGNAL
PRECISION PHASE SHIFTER
REFERENCE SIGNAL
PHASE SHIFT CONTROL
OSCILLATOR
1 mHz
MICRO-CONTROLLER
(PIC 16C54)
A/D CONVERTER
M U X
MICROPROCESSOR
(80C51)
MAGNETOMETERS
X
Y
Z
M U X
MAGNETOMETER ELECTRONICS
MEMORY AND/OR DATA TELEMETRY
ACCELEROMETERS
X
Y
M U X
ACCELEROMETER ELECTRONICS