AD-A222 608

COMPRESSIONAL WAVE/SHEAR WAVE SEISMO-ACOUSTIC PROBE

FINAL TECHNICAL REPORT

Line Item No. 0001AD
Contract No. N00014-89-C-0098
SwRI Project No. 15-2861

Submitted to:

Office of Naval Research
800 Quincy Street
Arlington, VA 22217-5000

April 30, 1990

SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO HOUSTON DETROIT
WASHINGTON, DC DALLAS/FT. WORTH

SOUTHWEST RESEARCH INSTITUTE
Post Office Drawer 28510; 6220 Culebra Road
San Ant io, TX 78228-0510

COMPRESSIONAL WAVE/SHEAR WAVE SEISMO-ACOUSTIC PROBE

FINAL TECHNICAL REPORT

Line Item No. 0001AD
Contract No. N00014-89-C-0098
SwRI Project No. 15-2861

Prepared by

Thomas E. Owen, Ph.D.

Submitted to:

Office of Naval Research
800 Quincy Street
Arlington, VA 22217-5000

April 30, 1990

Approved:

for James L. Burch, Vice President
Instrumentation and Space Research Division

FOREWORD

The experimental seismo-acoustic probe system reported herein and delivered under Contract No. N00014-89-C-0098 is the first device of its kind designed to measure the geo-acoustic parameters of seabed sediments at substantial penetration depths into ocean bottom sediments [i.e., 27 meters (88.6 ft.)] and in water depths at which diver support of the seabed measurements is impractical [i.e., to 88.5 m (290 ft.)]. This new probe was developed as a prototype instrument for use in the shallow water ocean acoustics research program at the NATO SACLANT Undersea Research Centre at La Spezia, Italy.

The probe was designed and fabricated by Southwest Research Institute and delivered to the NATO SACLANT Undersea Research Centre where it underwent initial sea trials in March 1990. The assistance of Wentworth V. Harned, Scientific Officer, Code 125P, U.S. Navy Office of Naval Research is acknowledged in establishing and scheduling the development contract. Technical services and support efforts provided by the SACLANT Undersea Research Centre, La Spezia, Italy are acknowledged in connection with the initial specification of the probe measurement parameters and in organizing and conducting the seabed testing activities aboard *R/V Alliance*. Special recognition and appreciation is given to SACLANT Center staff members T.G. Muir, T.M. Akal, A. Kristensen, E. Michelozzi, A. Caiti, and their supporting staff and to Capt. L. Schmidt and the officers and crew of *R/V Alliance*.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

I. INTRODUCTION

The Compressional Wave/Shear Wave Seismo-Acoustic Probe is designed to measure the propagation velocity and attenuation of compressional (P) waves and horizontally polarized shear (SH) waves in seafloor sediments. The submerged section of this system employs an electrically-driven vibrator to cause the acoustical measurement probe and its riser pipe to penetrate into the seabed sediment without the need for drilling and probe reentry into boreholes. Surface components of the system provide operating power to the probe, audio frequency excitation power to the acoustic source transducer, post-amplifier gain adjustments for the two detector output signals, power and control of the vibrator module, hydraulic pressure and control of the riser pipe clamping mechanism, and water supply to the penetration assist water jets on the probe. Separate equipment not included as part of this system is required to furnish the audio-frequency excitation signal for driving the power amplifier and for recording the detector output signals.

The Seismo-Acoustic Probe incorporates several new design and operating capabilities for the measurement of P waves and SH waves in unconsolidated seafloor sediments. These capabilities include:

(1) Novel acoustic transducers which provide selectable generation and detection of compressional waves and shear waves in the frequency range of 150 Hz to 1,500 Hz.

(2) Acoustic source transducer and power amplifier ratings are adequate for measurements in high attenuation sediments.

(3) A high-power electrically driven vibrator is clamped to the riser pipe extending above the top of the probe for use in driving the probe downward into the sediment.

(4) Four joints of riser pipe provide a potential probe penetration depth of up to 28 m (92 ft) into penetrable sediments.

(5) Penetration and retrieval of the probe is aided by the use of a stiff riser pipe which is smaller in diameter than the probe housing and by an upward-directed water jet located at the top of the probe to reduce sediment friction on the riser pipe.

This probe system is the first version of equipment designed and constructed to provide the seabed seismo-acoustic measurements and operating features described above. The system is, therefore, a prototype model by which the various design characteristics and operating capabilities are to be experimentally tested and evaluated in practice. Modifications of the equipment components, changes in design, and changes in the operating procedures as presented in this Operation and Maintenance Manual may be necessary as a result of such experimental tests in order to achieve successful measurements and practical shipboard operation of the system.

II. DESCRIPTION OF THE PROBE SYSTEM

A. System Application Concept

Figure 1 illustrates the application concept of the Seismo-Acoustic Probe system. The probe is suspended vertically in contact with the sediment bottom at the position where measurements are to be made. The probe is allowed to sink into the bottom under its own weight until it penetrates to a depth of about 2.5 meters, the shallowest depth station at which measurements can be made. The vibration driver attached to the riser pipe may be operated as needed to achieve this initial penetration. Seismo-acoustic measurements are made at this depth by exciting the source transducer from the power amplifier at the surface, first in the compressional wave mode and next in the shear wave mode. Digital recordings of the detected signals are recorded at the surface. Several measurements may be performed at this initial depth station and at deeper depths to obtain information on the frequency-dependent propagation effects for both compressional and shear waves. Upon completing the acoustical measurements, the probe system is de-energized and the vibrator is activated to cause the probe to penetrate downward to the next depth station for measurements. Typical depth penetration and measurement intervals might be in the range of about one meter (40 in.) in order to obtain a continuous measurement profile.

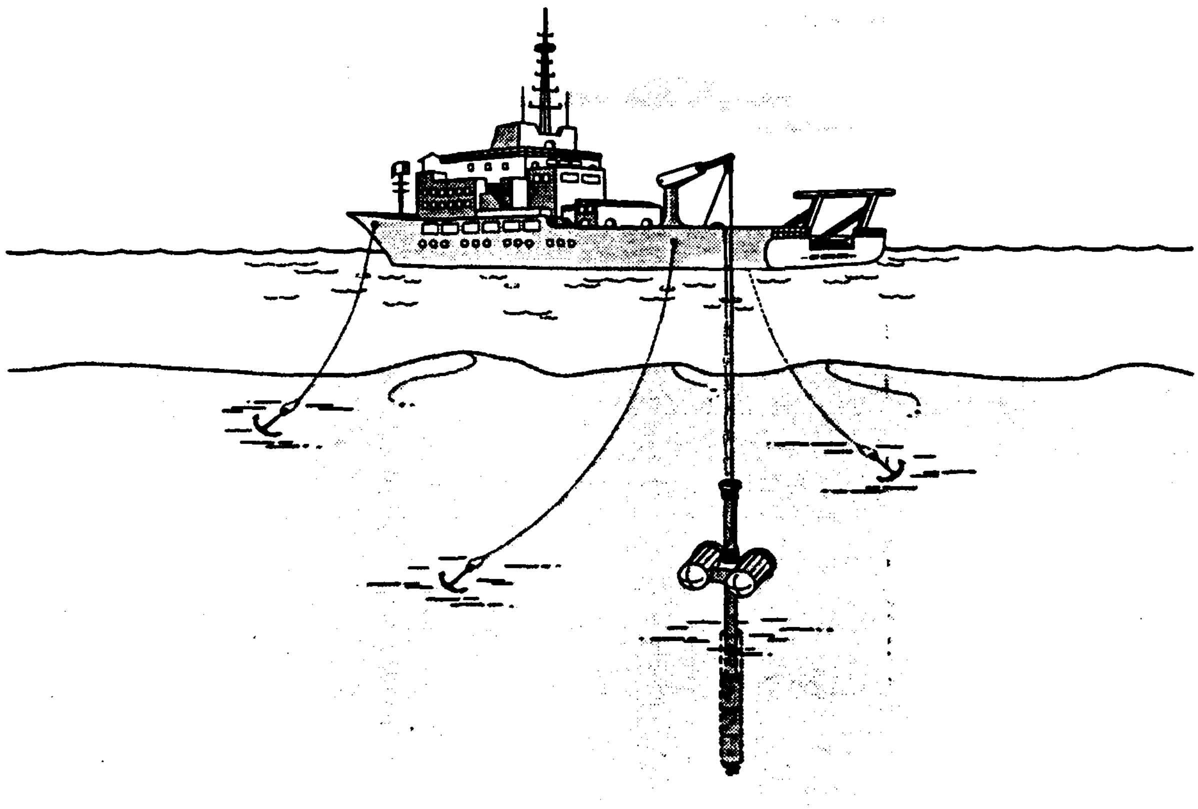


FIGURE 1. SHIPBOARD APPLICATION CONCEPT
FOR THE SEISMO-ACOUSTIC PROBE

B. System Configuration

Figure 2 shows a diagrammatic illustration of the submerged section of the probe and its principal components. The measurement probe consists of a source transducer module located near the upper end of the probe housing and two detector modules located at distances of one meter and two meters, respectively, below the source in the lower part of the probe housing. Acoustic pulse signals radiated from the source travel downward through the sediment to be detected by the two sensors spaced one meter apart. The detected acoustic pulses may be digitally recorded as full waveform signals at the surface for subsequent analysis to yield the propagation velocity and the amplitude attenuation as measured over the one-meter path length difference between the two detectors and at various depths of penetration into the seabed. The measurement probe is 101.6 mm (4.0 in.) in diameter and 4.5 m (14.5 ft) long without riser pipe attached. The riser pipe consists of four joints of thick-wall aluminum pipe 89 mm (3.5 in.) in diameter and 24 m (79 ft) in total length.

An electrically-driven vibrator unit is used to mechanically excite the probe and riser pipe string so as to break any contact friction between the sediment and the probe and, thereby, allow the combined weight of the vibrator unit, probe, and riser pipe to sink into the unconsolidated sediment. The total weight of the submerged system is 440 kg (970 lbs) including the four joints of riser pipe at 31 kg (69 lbs) each. The vibrator unit is part of a standard offshore bottom coring probe modified to provide the capability of being located at any position along the riser pipe and rigidly clamped to the pipe by means of a hydraulically operated chuck controlled from the surface. Two 2-hp electric motors in this unit are used to rotate eccentric flywheel masses at 3,600 rpm to produce a total centrifugal force of 31 kN (7,000 lbs) which is transferred to the riser pipe through the clamping chuck to cause the probe to vibrate with a displacement of approximately ±2 mm (±0.08 inch) at 60 Hz.

The submerged probe system is suspended by a mechanical cable attached to the vibrator unit for purposes of handling the system over the side of the survey vessel, measuring and controlling the depth of probe penetration, and for retrieving the system after penetration. Electrical power and hydraulic clamp control pressure are connected to the vibrator unit by separate power and hydraulic lines bundled onto the mechanical suspension cable. Two electrical cables for operating the source and detector sections of the probe are coupled to the submerged system via a cable junction module at the top end of the riser pipe. A water supply hose is also attached to the top of the riser pipe for operating the upward-directed water jets located at the upper end of the measurement probe. These water jets provide water flow and possible enlargement of the penetration hole at depths above the measurement probe section, thereby reducing the resistance to seabed penetration to only that of the 4.5-m long (14.5-ft) measurement probe housing. The probe system is designed to penetrate into unconsolidated sediments to a maximum depth of about 28 m (92 ft) as limited by the length of the riser pipe. Depths less than this maximum may occur when the probe encounters a sediment layer or obstruction which is rigid enough to prevent deeper penetration. The total riser pipe length may be assembled in single-joint increments of 6 m (20 ft) each.

Figure 3 shows a block diagram of the complete Seismo-Acoustic Probe system including the surface components and the various cables and hoses. This diagram indicates

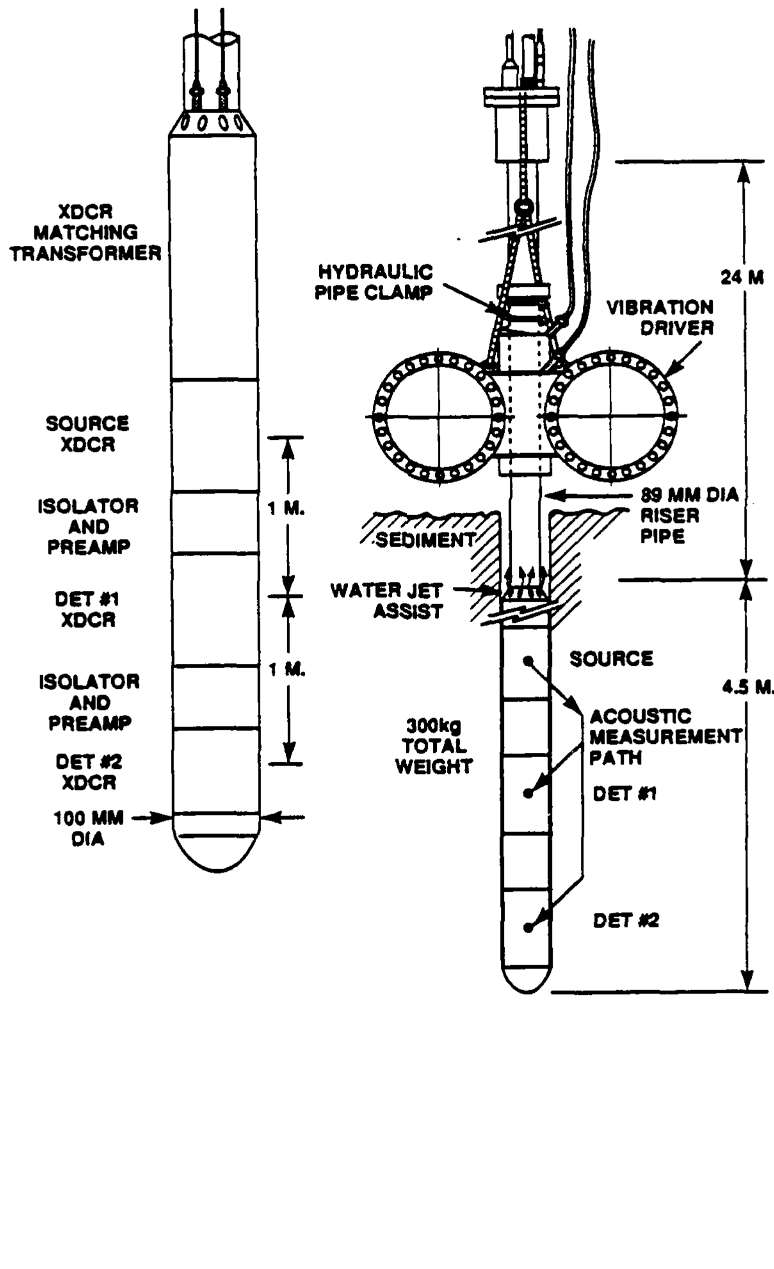


FIGURE 2. DESIGN FEATURES OF THE SEABED PROBE AND UNDERWATER VIBRATION DRIVER

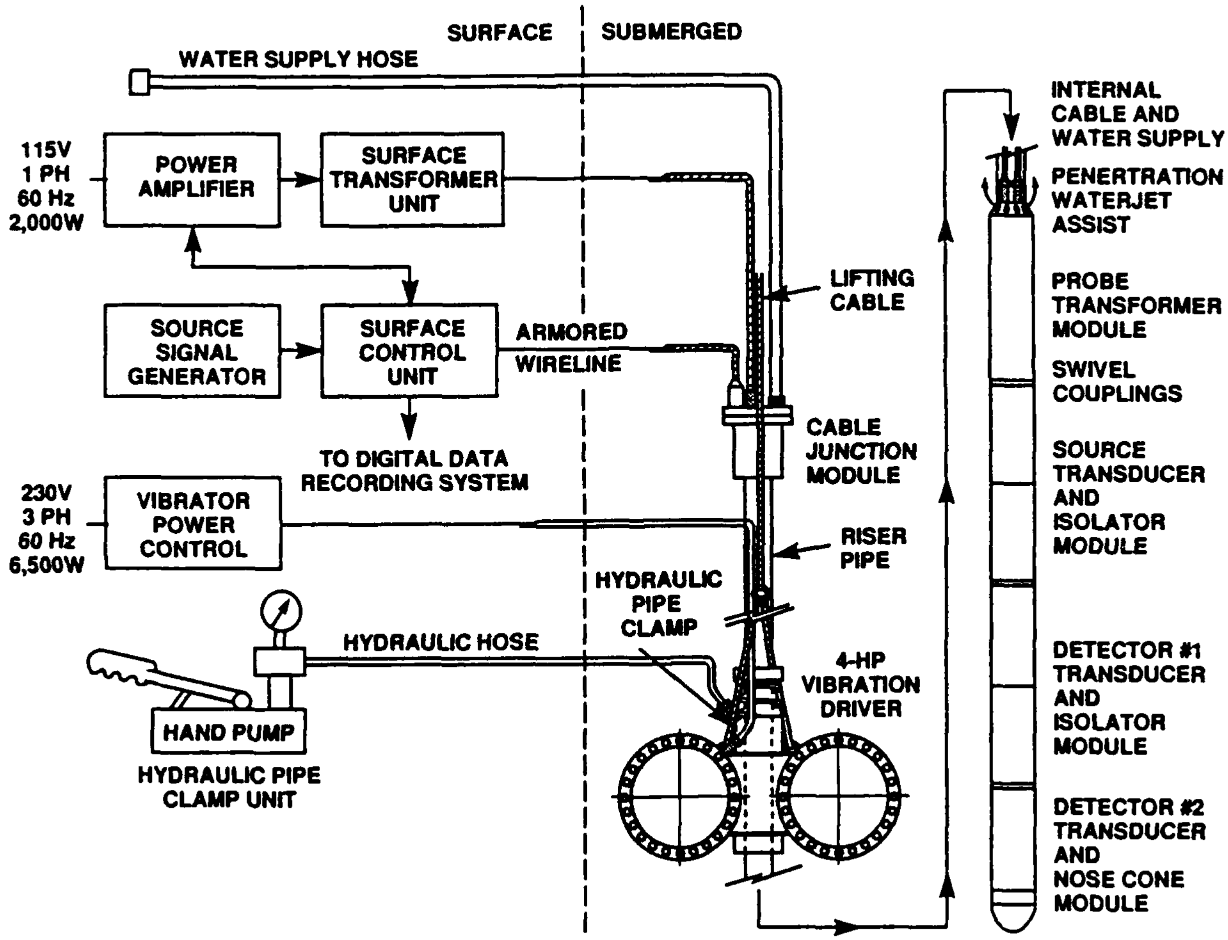


FIGURE 3. BLOCK DIAGRAM OF THE SEISMO-ACOUSTIC PROBE SYSTEM

the distribution of the source and detector electrical and electronics modules within the measurement probe and schematically illustrates the electrical cable jumpers and water flow path through the riser pipe. All cables leading from the surface to the submerged probe are 100 m (328 ft) or longer in length, making bottom sediment measurements possible to a depth of 28 m (92 ft) in water depths to about 80 m (262 ft). Electrical power and pressurized water for the water jets are supplied by the survey vessel whereas hydraulic pressure for the vibrator clamping mechanism is provided by a manually operated pump with a lock/unlock control valve and a pressure gauge. The acoustic source transducer is driven by a 1,200-VA audio power amplifier via a wireline matching transformer in the Surface Transformer Unit and a transducer matching transformer in the upper end of the measurement probe. This arrangement permits the maximum excitation energy to be delivered to the transducer at frequencies in the range of 150-1,500 Hz. These matching transformers are provided with winding taps and have sufficient magnetic core volume to handle excitation levels up to about 25 kVA at a ten percent operating duly cycle in future measurement applications.

The Surface Control Unit contains the power and control circuits for operating the two-channel measurement probe detector preamplifiers and selecting the source transducer mode of operation for either compressional or shear wave measurements. Two low-noise bandpass JFET preamplifiers are used in each detector module to accommodate the selectable modes of operation. Each preamplifier is followed by a balanced line driver which sends the detected analog signals to the surface via a four-conductor armored wireline. Selection of either the compressional or shear wave operating modes is accomplished by change-over relays in each detector preamplifier and in the primary winding of the source transducer matching transformer. Commands for controlling these relays are in the form of momentary step changes in the negative line of the ±18 VDC power supply to the probe and are generated by the Surface Control Unit. Status of the selected mode is recognized by the fact that the change-over relays are off in the compressional wave mode and on in the shear wave mode whereby the current delivered by the power supply is sensed and displayed to indicate the selected mode. The surface control unit is designed to interrupt the excitation signal to the power amplifier prior to changing the transducer operating modes.

Not shown in Figure 3 is the necessary equipment required to digitize and record the seismo-acoustic measurements. Appropriate field data to be collected at each depth station consists of three full waveform digital recordings: the source excitation signal and the two detector output signals. A desktop microcomputer equipped with three channels of analog-to-digital converter electronic circuits is recommended for this purpose. The analog-to-digital conversion system should operate at a sampling time interval in the range of 50 microseconds/sample to provide accurate time resolution and high frequency response in the recorded signals. Header information should be entered on each three-channel data file to document information on the various test conditions, including the probe test site location and date, the measurement depth, the selected mode of operation, the type of source excitation signal, the surface unit post amplifier gain settings, and the digital sampling rate and amplitude sensitivity used to record the data. The data recording system should be capable of storing the data on 5-1/4-inch flexible disks or other form of permanent data storage.

C. Probe Transducers

The transducers used to generate and detect the acoustic measurement signals are piezoelectric cylindrical bender devices[(1-3)*] modified to operate either in an axisymmetrical mode for compressional waves or an asymmetrical mode for shear waves. The cylindrical bender device consists of a hollow piezoceramic cylinder rigidly bonded to the inside surface of a close-fitting metallic cylinder to form a bilaminar tubular transducer useable either as a generator or detector of acoustic waves in a medium external to the metal tube. The inside surface of the piezoceramic cylinder has two silver coatings separated by longitudinal gaps to form semicircular half cylinder electrodes. When these electrodes are connected in parallel, the transducer operates in an axisymmetrical mode which can be described as a cylinder whose ends remain stationary while the center of the cylinder increases or decreases in diameter depending upon the polarity of the applied voltage. The radial volumetric changes of this composite cylinder are much greater than the normal radial motions of the piezoelectric cylinder alone, and are a result of the flexural behavior of the bender design.

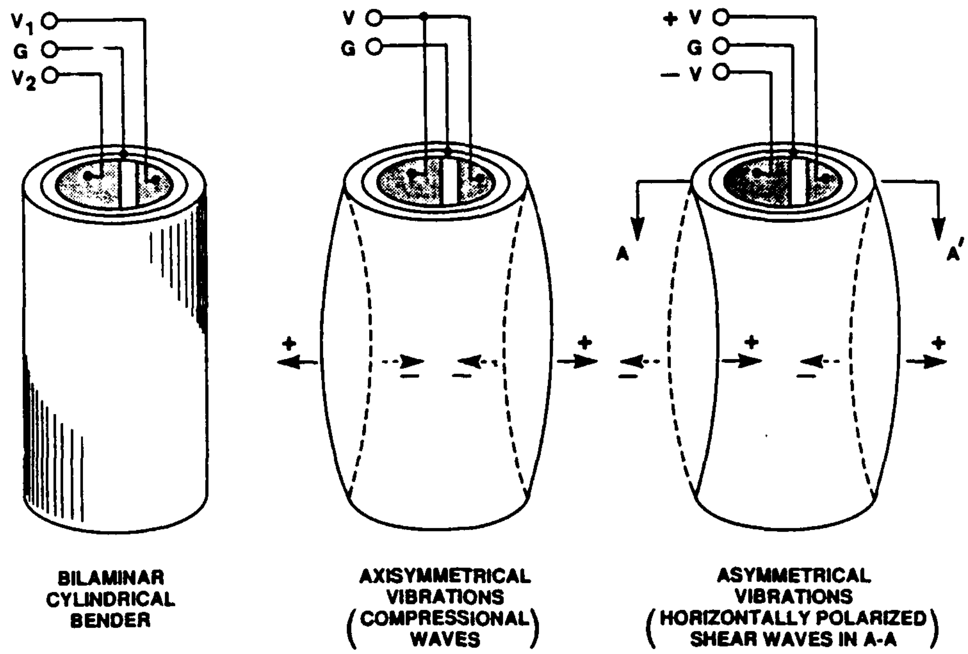
Figure 4(a) illustrates the axisymmetrical and asymmetrical vibration modes of the piezoelectric cylindrical bender source transducer. By connecting the two internal electrodes in parallel, the volumetric changes produced by the axisymmetrical vibrations generate compressional waves in the surrounding medium. When the internal electrodes are driven out of phase, the asymmetrical flexure vibrations generate shear stresses in the transverse plane A-A' depicted in the figure. This mode of vibration does not involve a volumetric change in the transducer cylinder but, instead, introduces alternating lateral forces in the sediment medium in intimate contact with the outer metallic cylinder. These forces and the associated particle displacements in the sediments correspond directly with those of horizontally polarized shear waves whose transverse displacements are oriented in the plane of flexural motion. Figure 4(b) shows an interior view of the piezoelectric cylindrical bender transducer illustrating the piezoceramic cylinder bonded to the 10.2 cm (4-in.) diameter stainless steel cylinder, one of the two gaps in the ceramic electrodes, and the internal electrical wiring.

When operated as a detector, compressional waves incident on the cylinder induce axisymmetric flexure stresses in the bilaminar bender element which, in turn, generate corresponding in-phase voltages on each semicircular electrode with respect to the grounded metallic tube. These voltages are combined in parallel to yield the detected compressional wave signal. Conversely, shear waves incident on the cylinder induce asymmetric flexure stresses in the bender element which result in out-of-phase voltages on each of the electrodes. These voltages, when combined differentially, yield the detected shear wave signal. If the two halves of the bender element are balanced to have equal sensitivities, then the detection responses to compressional and shear waves are mutually exclusive.

Figure 5 shows the components of the piezoelectric cylindrical bender transducer prior to final assembly. Figure 5(a) shows the components of the cylindrical bender source module ready for final assembly. The 5-cm (2-in.) diameter steel axial mandrel covered with PVC insulating material provides rigid stiffness in the probe housing, whereas the transducer

---

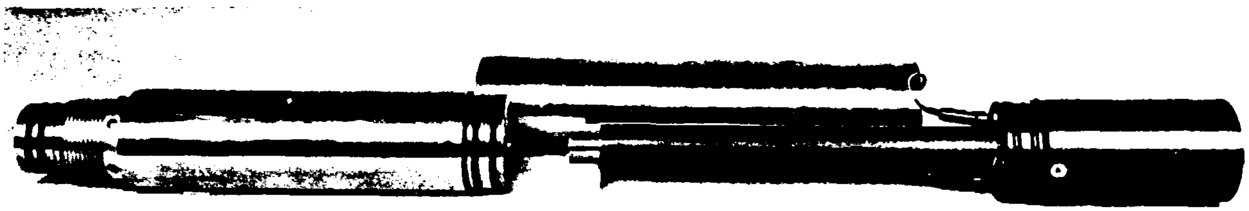
*Superscripts refer to references cited in References.



(a) Compression (P) and shear (SH) modes of vibration

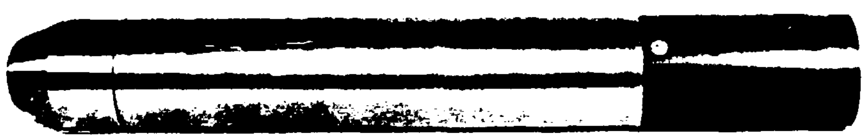
(b) Internal construction showing piezoceramic cylinder element and One of two electrode gaps

FIGURE 4. PIEZOELECTRIC CYLINDRICAL BENDER TRANSDUCER OPERATING MODES AND INTERNAL CONSTRUCTION



(a) Source Transducer Module Prior to Final Assembly

(b) Probe Detector #1 Module



(c) Probe Detector #2 Module

FIGURE 5. PIEZOELECTRIC CYLINDRICAL BENDER PROBE TRANSDUCER MODULES

cylinder is supported entirely on elastomer 'O'-ring seals. After assembly, the annular volume between the mandrel and the transducer cylinder is filled approximately 90 percent with silicone oil for electrical insulation. Figures 5(b) and 5(c) show the two probe detector modules after final assembly.

Relay switching is used to change the phase polarity of the excitation signals applied to the source transducer so as to preferentially excite either compressional waves or horizontally polarized shear waves. Relays are also used in the detector preamplifier circuits to achieve similar preferential responses in the detection of these waves. The transducer modules are marked by blue color index lines on their stainless steel cylinders at the position of one of their internal electrode gaps. These index marks must be aligned along the assembled length of the probe in order that the source and detector transducers are properly oriented to generate and detect the horizontally polarized shear waves.

D. *Seabed Probe Assembly*

The seabed probe assembly consists of three separate modules joined together using conventional well logging tool swivel couplings. Ascending from the lower end of the probe, these modules are: (1) cylindrical bender (Detector #2) with bottom-penetrating nose cone and self-contained preamplifier; (2) cylindrical bender (Detector #1) with self-contained preamplifier; and (3) cylindrical bender (Source) and source transducer matching transformer with riser pipe coupling head. The Source and Detector #1 modules incorporate permanently attached stainless-steel cylindrical mass sections which serve as spacers between the transducers and as acoustic isolators to reduce the acoustic signals transmitted through the probe housing. The swivel couplings used to join these modules together provide the ability to physically align the modules according to the blue index marks as well as seal the connecting interfaces against water leakage. All components contained within the probe modules are shock mounted using cork-neoprene composition materials to prevent damage whenever the vibrator module is operated.

E. *Vibrator, Pipe Clamp, and Riser Pipe*

The vibrator unit used to drive the probe into the seabed is a modified version of a Geomarex Model P-4 Vibrocorer adapted to be remotely clamped at any position on the riser pipe. Two 2-hp electric motors within the vibrator head turn eccentric flywheels in synchronism to impart longitudinal vibrations to the riser pipe at a frequency of 60 Hz. Forces on the order of 31 kN (7,000 lbs) are generated under normal operation to produce vibratory displacements of about ±2 mm (±0.08 in.) at the nose cone of the probe. This vibratory motion is sufficient to break any contact friction between the probe housing and the sediment being penetrated so that the probe will sink into the sediment under its own weight. When the vibrator operation is stopped, friction on the probe will prevent it from penetrating farther into the sediment.

The riser pipe clamping mechanism consists of a hydraulically operated four-jaw chuck designed to conform to the 89-mm (3-1/2-in.) diameter of the pipe. A spring release on the jaws causes the clamp to open whenever hydraulic pressure is removed, thereby allowing the vibrator to be raised or lowered to a new position along the pipe. A hand-operated hydraulic pump is used to actuate the clamp at a typical hydraulic pressure of 8.9 MPa (1,300 psi).

The riser pipe is composed of four 6-m (19.7-ft) joints of 89-mm (3-1/2-in.) diameter Schedule 80 aluminum pipe. Integral male and female stubbed Acme threads are machined on each end of the joints to provide smooth joint connection interfaces which will pass through the pipe clamp mechanism. These joints may be assembled to form a riser pipe length up to 24-m (79-ft) in length which is topped with the Cable Junction Module and water supply hose connection. Two rubber-jacketed electrical cables pass through the riser pipe to connect the probe circuits to the junction module. One of these cables carries the source transducer excitation signal and the other carries the DC power, the mode control commands, and the two detector output signals from the probe.

Figure 6 shows the assembled seabed probe system set up temporarily for testing the vibration driver and riser pipe clamp mechanism. Full functional testing of the system requires suspension of the probe and riser pipe in a water column, either at a pier or aboard ship, in an area where the probe can penetrate into the bottom sediment.

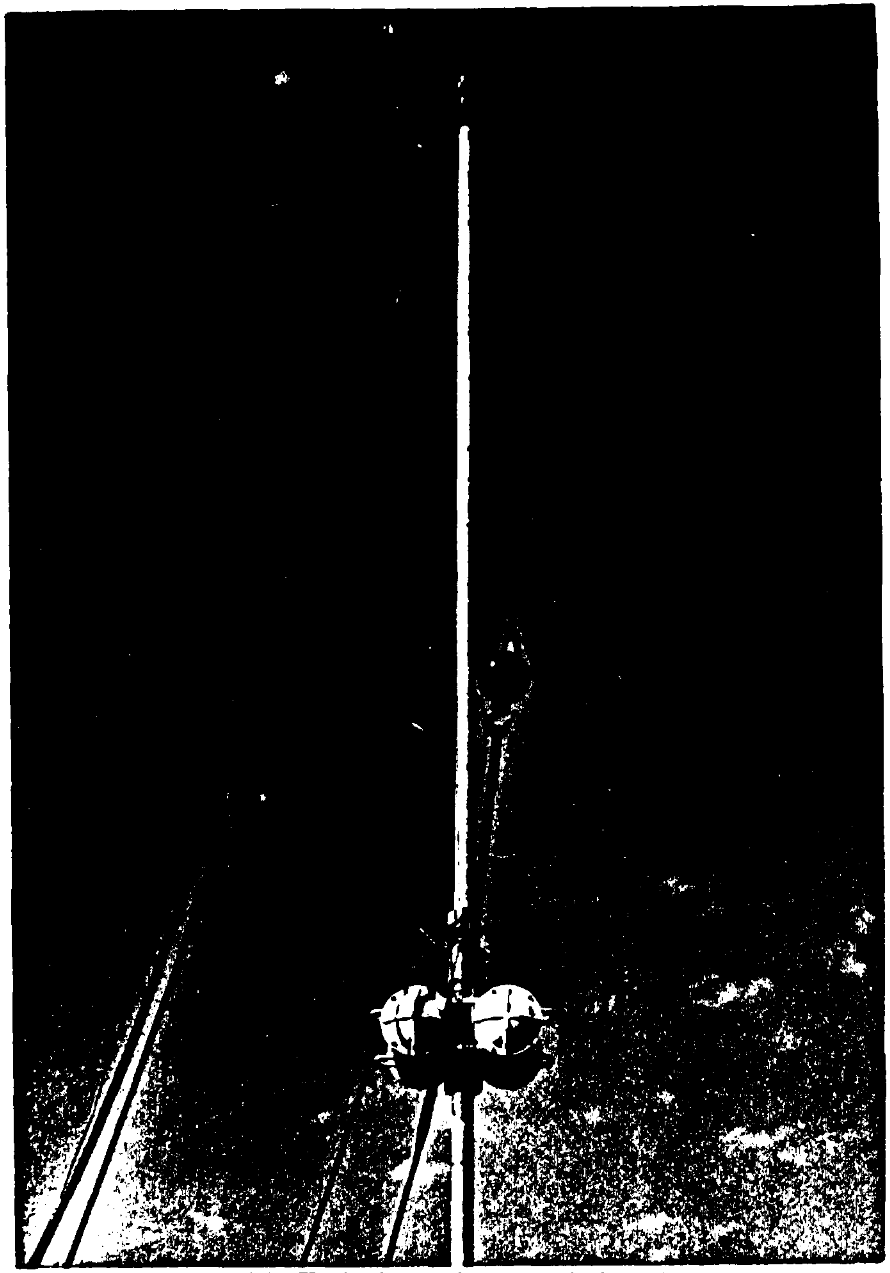
Water may be introduced into the riser pipe to supply the upward-directed jet outlets located at the top end of the probe housing. The water flow is designed to be approximately 10^{-3} m^3/sec (15 gal/min) supplied at a pressure up to about 1.7 MPa (250 psi), depending upon the depth of the water column and the probe penetration depth into the bottom. The purpose of the water jet is to provide fluid flow up the penetration hole around the riser pipe to aid in reducing friction during penetration and retrieval. The jetting action will also serve to enlarge the penetration hole and to relieve the compaction stresses in the sediment, making the only resistance to penetration the compaction and friction of the sediment in contact with the 4.5-m (14.5-ft) long probe housing.

Cables and hoses leading from the junction module at the top of the riser pipe are bundled together with the 2-cm (3/4-in.) diameter water supply hose. The source power cable is rubber jacketed and the detector cable is an armored wireline which may be used as a probe hoisting cable if necessary.

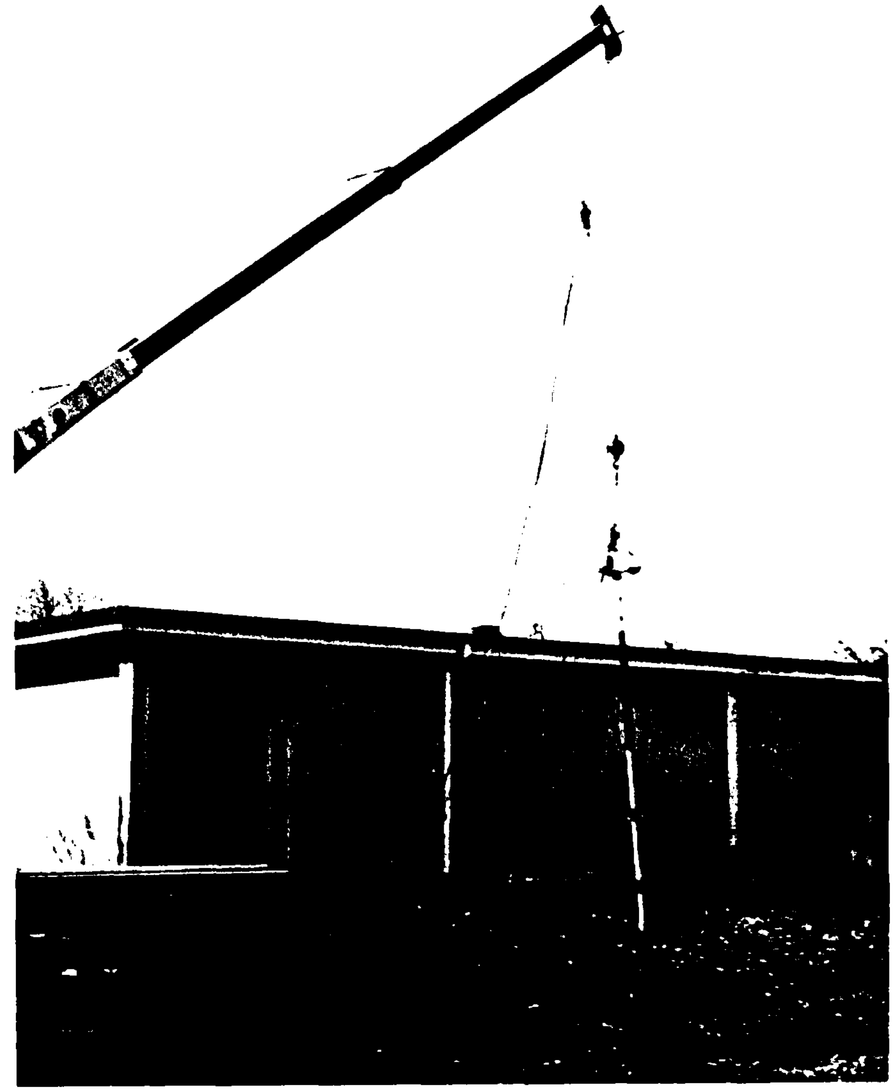
F. Surface Equipment

Surface components of the Seismo-Acoustic Probe system consist of: (1) Surface Control Unit; (2) Power Amplifier; (3) Surface Transformer Unit; (4) vibrator power control; and (5) pipe clamp pump and control. Figure 7 illustrates the principal components of the surface equipment.

The Surface Control Unit provides all power and mode select commands to the probe and receives and amplifies the two detector signals from the probe. Power supplied to the probe system is ±18 VDC for operating the electronic preamplifier circuits, the mode control relays, and the electronic circuits in the surface control unit. The mode control switch permits the source transducer to be excited either as a compressional wave or shear wave source with the detector transducers and preamplifiers appropriately connected for



(a) Full view of assembled probe system



(b) Close-up view of vibrator module, riser pipe, and cable junction module

FIGURE 6. SEISMO-ACOUSTIC PROBE ASSEMBLED FOR PRELIMINARY TESTING

corresponding operation. The source transducer may be de-energized by switching to "standby," leaving the detectors operational in either selected mode. With this switching arrangement, changeover between the selectable modes is not possible while the source transducer is energized.

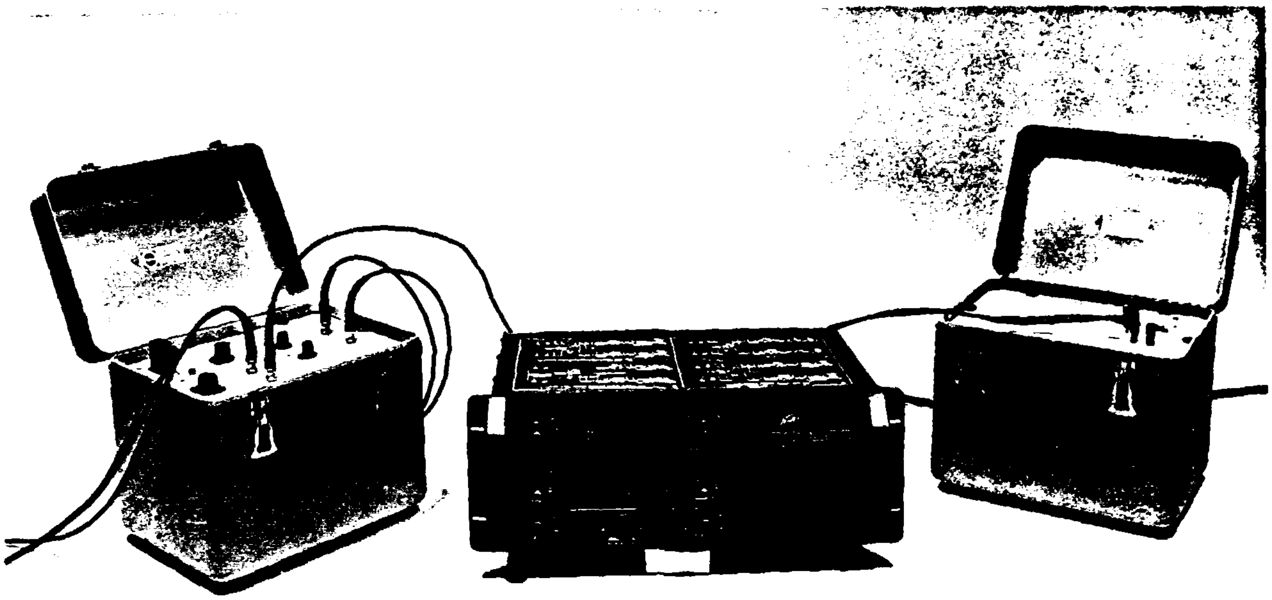


FIGURE 7. SURFACE CONTROL UNIT, POWER AMPLIFIER, AND SURFACE TRANSFORMER UNIT (Left to Right)

The power amplifier is a Peavey Model CS-1200 commercial-grade audio amplifier rated at 1200 watts continuous power into arbitrary load impedance. Maximum output voltage is 100 volts RMS. A custom-designed multi-winding surface transformer unit is used to step up this excitation voltage to as high as 700 volts RMS, depending upon the transformer winding connections. The transformer output is supplied via the submerged cables to the transducer matching transformer in the probe. The frequency response of the combined power amplifier and surface transformer unit is 20-20,000 Hz when operating into resistive loads in the range of 2-400 ohms. However, the electrical load impedance presented by the source transducer is predominantly capacitive (typical power factor at 500 Hz:0.20) and, hence, the load voltage response is not uniform versus frequency. The acoustical output of the transducer is more appropriately related to the current supplied to the device, indicative of an increase in the radiated compressional or shear wave amplitude versus frequency. The multi-winding surface transformer is supplied with its windings connected to provide a step-up turns ratio of 1:2.0 and a primary inductance of 0.750 H.

The vibrator control unit is a circuit-breaker switch box by which 230 V 60 Hz is applied to the vibrator head at a starting line current of about 14 A and a running current of 7.5 A.

The pipe clamp control unit consists of a lever-operated hydraulic pressure pump equipped with a fluid reservoir, a pressure gauge, and a pressure retaining valve. Locking forces at the pipe clamp chuck are in the range of about 45 kN (10,000 lb) in order to reliably grip the pipe during vibration. Figure 8 shows a close-up view of the Vibrator Module and the pipe clamping mechanism and hand pump.

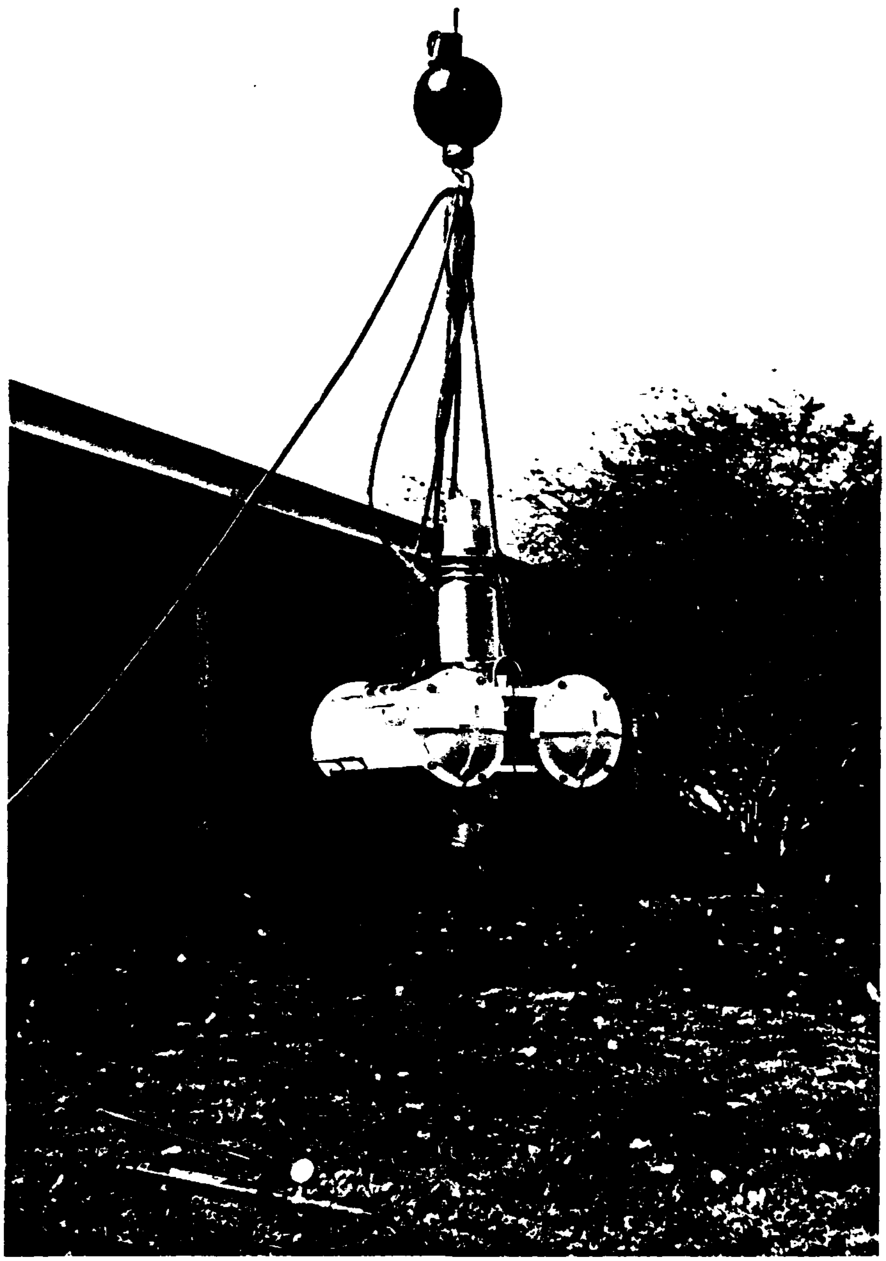


FIGURE 8. VIBRATION MODULE WITH PIPE CLAMP MECHANISM AND PIPE CLAMPING HYDRAULIC PUMP

III. PROBE TESTS AND SYSTEM CHECKOUT

The acoustic transducers employed in the seismo-acoustic probe are based upon a modification of a previous cylindrical bender transducer developed for use in fluid-filled boreholes drilled into oil reservoir rock formations. This earlier transducer was designed to generate compressional waves in the surrounding geological formations at frequencies ranging from 500 Hz to 5,000 Hz. Modifications to this transducer consisted primarily of changes in the electrodes of the piezoceramic element comprising one part of the bilaminar cylinder so as to allow the device to operate in either its original axisymmetrical vibration mode for generating compressional waves or in an asymmetrical (flexure) mode for generating shear waves. The stainless-steel cylinder comprising the outside part of the bilaminar transducer assembly was reduced in wall thickness to achieve more efficient operation and to extend the low-frequency response of the transducer.

A. *Prototype Cylindrical Bender Tests*

The previous piezoelectric cylindrical bender transducer was designed to operate as a high-power source of seismic waves in boreholes to depths of about 3,000 m (10,000 ft.) and to immersion pressures up to about 44.82 MPa (6,500 psi). To meet this requirement, the transducer was designed to have a relatively thick outside stainless steel cylinder to prevent its collapse under pressure. A transducer of this type was used as a prototype device to be modified and tested in the development of the dual-mode seismo-acoustic transducer. The materials and dimensions of this prototype bilaminar stainless steel and piezoelectric ceramic transducer element were:

Stainless-Steel Outer Cylinder

Material	316 stainless steel
Length	45.7 cm (18.0 in.)
Outside diameter	101.6 mm (4.00 in.)
Inside diameter	91.80 mm (3.614 in.)
Wall thickness	4.90 mm (0.193 in.)

Piezoelectric Ceramic Inside Cylinder

Material	Channel Industries Type 5400
Length	30.5 cm (12.0 in.)
Outside diameter	91.64 mm (3.608 in.)
Inside diameter	78.9 mm (3.11 in.)
Wall thickness	6.35 mm (0.25 in.)

Epoxy Bonding Compound

Emerson & Cuming ECCO Bond 91 fiberglass reinforced epoxy adhesive.

Two longitudinal gaps approximately 6.35 mm (0.25 in.) wide were chemically etched diametrically opposite one another along the inside silver electrode of the piezoelectric ceramic element. These gaps form the neutral lines of the cylinder when it is excited in the asymmetrical mode (electrodes driven in series) but they have no effect on the original axisymmetrical mode (electrodes driven in parallel).

By connecting and driving the two half-cylinder electrodes in parallel with respect to the outside electrode, the composite bender transducer will vibrate with axial symmetry. When the two half-cylinder electrodes are connected and driven in series (i.e., 180 degrees out of phase with respect to one another and balanced with respect to the outside electrode), the composite cylinder will vibrate asymmetrically. The axisymmetrical vibrations result in a net change in the cylinder volume and, hence, will preferentially generate compressional waves in the surrounding medium. Asymmetrical vibrations are transverse flexure motions of the entire cylinder that produce only minimal changes in the cylinder volume and, hence, will preferentially generate shear waves in the surrounding medium. The plane of maximum transverse vibrations is oriented perpendicular to the plane containing the electrode gaps.

The ends of the modified cylindrical bender were sealed by means of rubber-cork composition stoppers and aluminum end plates so that the transducer could be immersed in water for testing under conditions similar to the mass loading effects of ocean bottom sediments. These end closures were relatively low in mass and did not impose a significant loading effect on the bender cylinder as observed during vibration measurements in air with or without the end stoppers in place. Therefore, the end conditions on the prototype cylindrical bender were approximately freely supported.

Three accelerometers were grease coupled to the cylinder surface to detect and monitor the vibrations at the center and near each end of the cylinder. Sequential acceleration measurements were made in two planes: (1) the flexural vibration plane perpendicular to the plane containing the electrode gaps; and (2) the plane of the electrode gaps. These acceleration measurements were sufficient to allow the vibration modes to be determined and to indicate the approximate mass-loaded frequency response of the cylindrical bender device when operated in its axisymmetrical and asymmetrical modes.

The grease coupling technique allowed the accelerometers to be physically scanned over the surface of the vibrating cylinder to locate the positions of maximum and minimum motion al amplitudes. Phase comparisons between the acceleration motions detected by the scanned a ccelerometer and an accelerometer placed at a reference position such as the point of maximum motion at the center of the cylinder provided information on the relative directions of motion at various points on the cylinder.

The results of these surface scans are described as follows:

Axisymmetrical Excitation

When the electrodes were driven in parallel, axisymmetrical vibrations were obser ved and identified in the accelerometer measurements. In this case, the radial acceleration motions exhibited essentially the same amplitude and phase in the two orthogonal test planes and the motions at the center of the cylinder were large compared with the motions at the circumferential nodal lines near each end. The motions at the ends of the cylinder were comparable in amplitude with that at the center of the cylinder but were 180 degrees out of phase, characteristic of axisymmetric flexural bending of a freely supported cylinder.

Asymmetrical Excitation

When the electrodes were driven in series, asymmetrical vibrations were identified by the fact that the radial motions of the cylinder were essentially confined to the flexural vibration plane and these vibrations were approximately equal in amplitude and 180 degrees out of phase on the opposite sides of the cylinder in this plane. Nodal zones were observed near the ends of the cylinder and the positions of these nodes were relatively independent of the excitation frequency. In this case, the flexural motions measured near the ends of the cylinder were 180 degrees out of phase with respect to the motion at the center of the cylinder, characteristic of asymmetric bending of a freely supported cylinder. Acceleration measurements along the lines on each side of the cylinder corresponding to the electrode gaps indicated that the radial motions along these lines were negligibly small indicative of the neutral axis of the flexural vibrations of the cylinder.

These various measurements on the prototype cylindrical bender confirmed the expected vibrational behavior of the transducer, including the independent selectability of the axisymmetrical and asymmetrical modes of vibration. The same measurements were performed on the prototype transducer for two different stainless steel cylinder wall thicknesses. In the first series of tests the cylinder wall thickness was 4.90 mm (0.193 in.). After these tests were completed, the stainless steel cylinder outside diameter was machined down to 96.7 mm (3.81 in.) corresponding to a wall thickness of 2.45 mm (0.096 in.). In both cases the vibration modes were identical although the amplitudes were different as were the fundamental resonance frequencies.

Figure 9 shows the results of calibrated acceleration measurements performed on the prototype cylindrical bender transducer when submerged in water and operated in each of its vibration modes for the two different steel cylinder wall thicknesses. These curves present the relative motional velocity of the surface of the cylindrical bender as measured at the midpoint of the flexural vibration plane. The motional velocity was derived by dividing the measured acceleration values by the measurement frequency normalized to the lowest frequency used in the measurements (100 Hz). These relative velocity curves may be returned to their absolute acceleration values by noting that the reference acceleration measured for the asymmetrical mode at the center of the cylinder having a steel cylinder wall thickness of 4.90 mm (0.193 in.) was 3.06 g(pk) for an excitation voltage of 275 VRMS applied to the series-connected bender electrodes and then adding $20 \log_{10} \left(\frac{f}{100}\right)$ dB to the other measured points on the curves.

The relative motional velocity responses of the cylindrical bender shown in Figure 9 are generally indicative of the sound pressure frequency response of the transducer when operated as an acoustic source. These curves show that the relative velocity of motion increases at about +13 dB/octave for the asymmetrical mode at about +15 dB/octave for the axisymmetrical mode. The frequency ranges of smooth response are 150-1,000 Hz for the asymmetrical mode and 200-1,500 Hz for the axisymmetrical mode. The fundamental resonance frequencies for the water-loaded cylindrical bender transducer operating with freely supported ends were found to be:

Stainless Steel Cylinder Wall Thickness	Free-Free Axisymmetrical Mode Fundamental Resonance Frequency (Hz)	Free-Free Asymmetrical Mode Fundamental Resonance Frequency (Hz)
4.90 mm (0.193 in.)	3,100	1,650
2.45 mm (0.096 in.)	2,500	1,430

Under ideal conditions, if the ends of the cylinder were rigidly clamped or heavily mass loaded, these resonance frequencies would be reduced by a factor of one half. However, such ideal end conditions are not attainable in practice and, therefore, the resonances of the final design cylinder will be greater than one half of the resonance frequencies cited above depending upon the mass-loading effects achieved by the end-mount design.

The differences in response caused by the two different wall thicknesses of the stainless steel cylinder are in the reduction of the free-free fundamental resonances by about 15-20 per cent and in improving the relative velocity excitation sensitivity of the cylindrical bender when operating in the axisymmetrical mode. These differences are depicted in Figure 9 where, in particular, the response of the symmetrical mode is 4.5 dB more sensitive for the thinner wall steel cylinder. With this increase, the ability to generate compressional waves at low frequencies is greatly improved. Reducing the steel cylinder wall thickness reduced the asymmetrical vibration mode velocity excitation sensitivity by about -1.5 dB.

Based upon the prototype tests described above, the final design of the dual-mode cylindrical bender of the seismo-acoustic probe was specified to have the same overall dimensions as the prototype and a stainless-steel cylinder wall thickness of 3.05 mm (0.128 in.). This wall thickness was selected to provide a cylindrical bender having a somewhat higher fundamental resonance frequency than that of the thinner wall prototype while still providing a useful increase in the excitation sensitivity of the axisymmetrical mode for generating compressional waves. The materials and dimensions of the final cylindrical bender transducer design are:

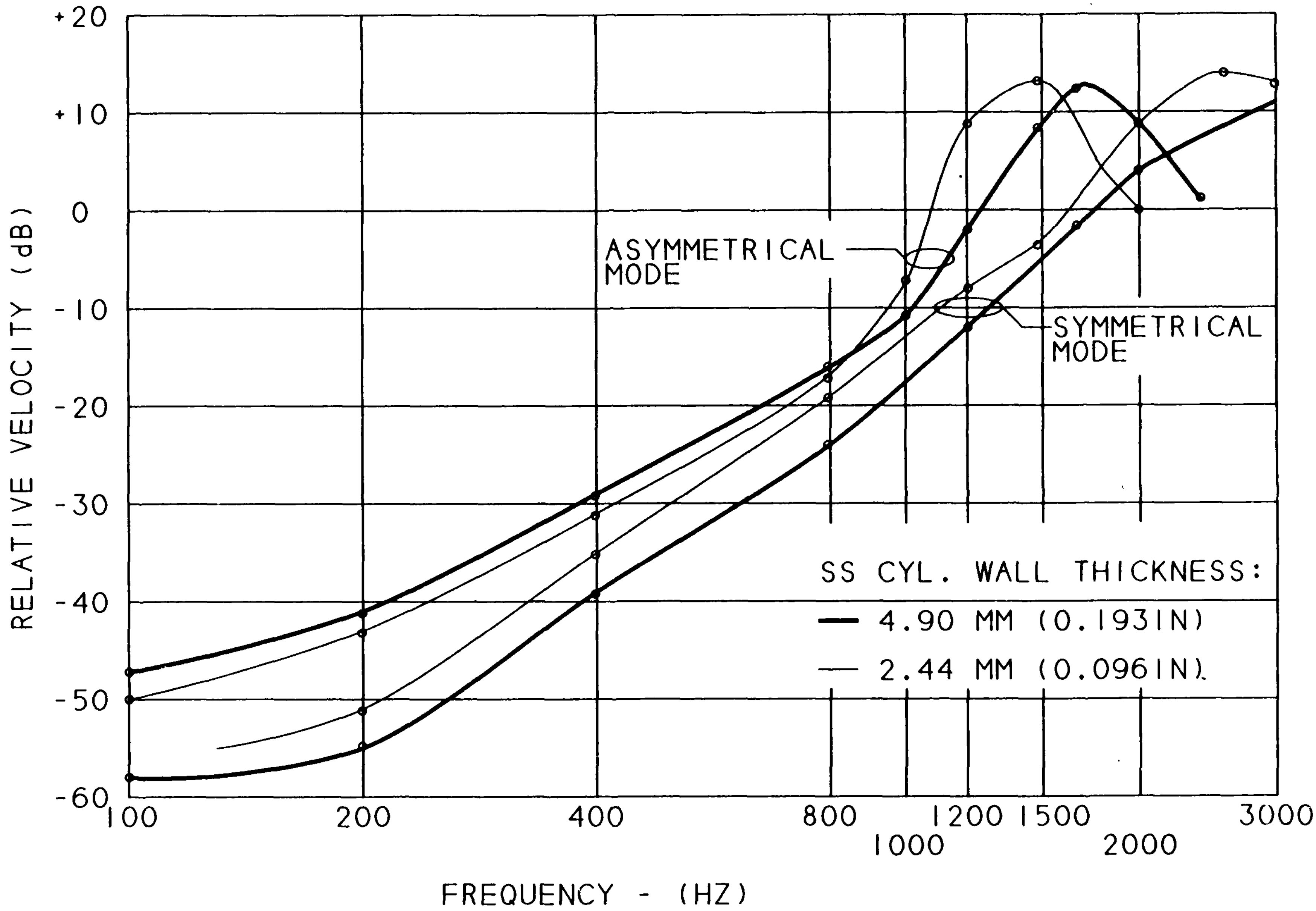


FIGURE 9. DYNAMIC RESPONSE MEASUREMENTS OF THE PROTOTYPE PIEZOELECTRIC CYLINDRICAL BENDER TRANSDUCER IMMERSED IN WATER

Stainless-Steel Outer Cylinder

Material	316 stainless steel
Length	45.7 cm (18.0 in.)
Outside diameter	101.2 mm (3.985 in.)
Inside diameter	94.70 mm (3.728 in.)
Wall thickness	3.25 mm (0.128 in.)

Piezoelectric Ceramic Inside Cylinder

Material	Channel Industries Type 5400
Length	30.5 cm (12.0 in.)
Outside diameter	94.49 mm (3.720 in.)
Inside diameter	81.79 mm (3.220 in.)
Wall thickness	6.35 mm (0.25 in.)

Epoxy Bonding Compound

Emerson & Cuming ECCO Bond 91 fiberglass reinforced epoxy adhesive.

Figure 10 illustrates, in partial detail, the method used to support the ends of the piezoelectric cylindrical bender transducer in the final probe design. As this sketch shows, the ends of the stainless steel cylinder are supported by three rubber 'O'-rings to provide the necessary pressure seal to prevent sea water leakage into the probe and to provide acoustic damping together with mass loading of the ends of the cylinder by the end adaptor. The steel mandrel extending through the center of the piezoelectric cylindrical bender element provides the necessary structural strength and rigidity of the probe housing for successful penetration into the ocean bottom. Complete mechanical design details of the cylindrical bender elements and all other parts of the probe are presented in the engineering data and mechanical drawings which accompany this report.

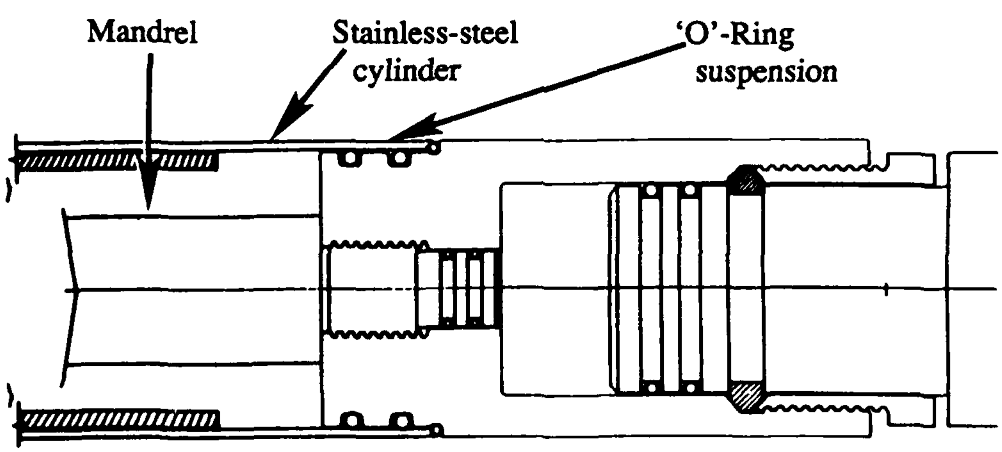


FIGURE 10. MECHANICAL ASSEMBLY SHOWING BENDER END-SUPPORT 'O'-RINGS AND CENTRAL MANDREL IN PROBE BODY

B. System Checkout Tests

The assembled seismo-acoustic probe system was tested for functional operation a nd to reveal any potential defects or failures in the design or assembly of the various system components under the expected operating vibration extremes during seabed penetration. Tests were first performed to evaluate the probe system acoustic response when buried in shallow wet soil followed by tests of the complete vibrator and probe assembly when suspended and operated in vertical contact with the ground.

1. Probe Acoustic Tests

Tests similar to those performed in the laboratory on the prototype cylindrical bender transducer were not practical on the fully assembled seismo-acoustic probe. Alternatively, the probe assembly was buried horizontally in a trench filled with wet soil at a depth of approximately 45 cm (18 in.) below surface to approximately represent the mechanical loading effects and acoustic damping of ocean sediments. The source transducer was then driven by sinewave bursts of 5-20 ms duration at different frequencies ranging from 100 Hz to 1,500 Hz and the signals received by the two detector modules were observed. The detected signals, operating in the P and SH modes, were observed before and after the probe was covered with wet soil.

The tests performed prior to covering the probe with wet soil revealed that a significant source-generated signal was detectable through the structural assembly of the probe housing. The massive isolator elements [22 kg (48.4 lbs)] between the source transducer and each of the detector transducer modules appeared to have very significant reduction effects in decoupling the source module from the detector modules, as briefly observed in laboratory bench tests using an accelerometer. Further, on the basis that any probe-borne signals would travel very much faster in the steel and aluminum probe body than those signals traveling in the ocean sediments, the signals directly coupled through the probe should be distinguishable from the sediment-borne signals by their early arrival times. However, when the probe was buried, the response observed at the detectors did not exhibit clearly recognizable late-arrival bursts as might be expected for signals transmitted through the surrounding soil. Careful tests were performed at frequencies ranging from 100 Hz to 1,500 Hz at various source excitation drive levels, for the P and SH modes, without observing soil-borne signals. Later, after recovering the probe from burial, the source and detector modules were disconnected from one another and tested so as to observe only airborne sound signals transmitted from the source to each detector. The airborne signals were clearly observed in this test and, as a result, the absence of the soil-borne signals was attributed to excessive attenuation in the freshly placed backfill soil covering the probe. Further tests aimed at demonstrating soil-borne signals were discontinued since realistic simulation of ocean sediment media was not practical. More appropriate acoustic performance tests require full-scale operation of the probe system in actual seabed sediments.

2. Vibrator and Probe Assembly Tests

The fully assembled seismo-acoustic probe system was tested for operational integrity and the basic ability to penetrate into soil when vibrating in vertical contact with the ground. For this test, the probe was assembled using one joint of riser pipe with the vibrator and pipe clamping unit clamped about one meter above the top of the probe housing. The cable junction module was attached to the top end of the riser pipe and the electrical cables and water supply hose were attached to the module. The complete assembly was hoisted by means of a crane having its lifting cable attached to the wire rope bridle on the vibrator. A photographic view of this test setup was shown earlier in Figure 6.

The first test performed using this probe arrangement was a vibration endurance test of the assembly. With the weight of the probe assembly supported on its nose cone in contact with the ground, the vibrator was activated by applying 230 V 3-phase power to its motors via the 100-meter (328-ft) electric power cable. Within a few seconds the nose cone penetrated several centimeters into the soil until the weight of the probe was supported by the crane. The 60-Hz vibrations of the probe housing were measured to be approximately ±2 mm (0.08 in.). The vibrator unit was energized for a period of about ten minutes at which time one of the electrical cables attached to the cable junctional module was observed to be loose. The vibrator was stopped and the probe assembly laid on the ground for inspection. The cable connector screw rings at the top of the cable junction module and the screw joint between the cable junction module and the rise pipe were found to be partially unscrewed. Although these screw connections were made securely tight by normal standards at the beginning of the test, they will obviously require more tightening force to withstand such sustained vibrations. Inspection of the other components of the probe assembly revealed no other loose connections or failures in the probe housing or the vibrator or pipe clamping mechanism.

With the cable junction module retightened, the probe assembly was hoisted to vertical orientation with its weight supported on the nose cone at the ground surface. The vibrator was activated and the weight of the probe was slowly lowered by the crane so that the probe penetrated into the dry and hard soil. The probe was allowed to penetrate into the ground at a rate of about one centimeter per second until it was approximately 60 cm (24 in.) deep. The vibrator action was then stopped and the hydraulic pipe clamp mechanism released to allow the vibrator to be hoisted upward on the riser pipe and re-clamped. The vibrator was activated at this new clamped position and found to operate satisfactorily. The total accumulated vibrator module operating time was approximately 15 minutes. Since the second sequence of tests involved only short intervals of vibrator operation, the screw connections on the cable junction module did not become loose. The probe system was hoisted out of the ground and the vibrator tests concluded.

The seismo-acoustic probe section of the system was energized after the vibration tests were concluded to check the acoustic operating functions of the system. All of the probe components were found to function in the same manner as that observed prior to the vibrator tests. The probe modules were disassembled to permit the internal electronics assemblies to be examined for any evidence of vibration damage. Close inspection of these assemblies and their internal cable connections revealed no detrimental effects caused by the vibrations applied to the probe.

The results of these system checkout tests led to the conclusion that the seismo-acoustic probe system was capable of operating with reliability and reasonable endurance. Precautions are necessary to ensure that the various cable connector screw rings are very securely tightened to prevent them from becoming loose. Similarly, the screw connections between the riser pipe joints and at the cable junction module and at the top of the probe housing should be very securely tightened to prevent them from becoming loose. The penetration efficiency of the vibrating probe system into firm dry soil provided excellent evidence that the probe should easily penetrate water-saturated seabed sediments. With the experience gained from these initial tests, the vibration drive should not be operated for time intervals longer than one or two minutes at a time. By following this precaution, the operating integrity of the system can be expected to be improved over that of continuous operation. In this regard, the probe system should be allowed to penetrate into the seabed at the fastest practical rate in order to minimize the vibration operating time.

IV. SHIPBOARD AND SEABED TESTS

The seismo-acoustic probe was delivered to NATO SACLANT Undersea Research Centre, La Spezia, Italy for full-scale testing and evaluation. These tests were conducted aboard the SACLANT Centre *R/V Alliance*. The objectives of these tests were: (1) to establish the necessary methods for assembling and handling the probe system aboard *R/V Alliance*, including over-the-side deployment and ship anchoring and station keeping for the seabed acoustic measurements; (2) to evaluate the probe vibration technique as a means for seabed penetration and retrieval; and (3) to evaluate the acoustical measurement functions and performance of the probe system.

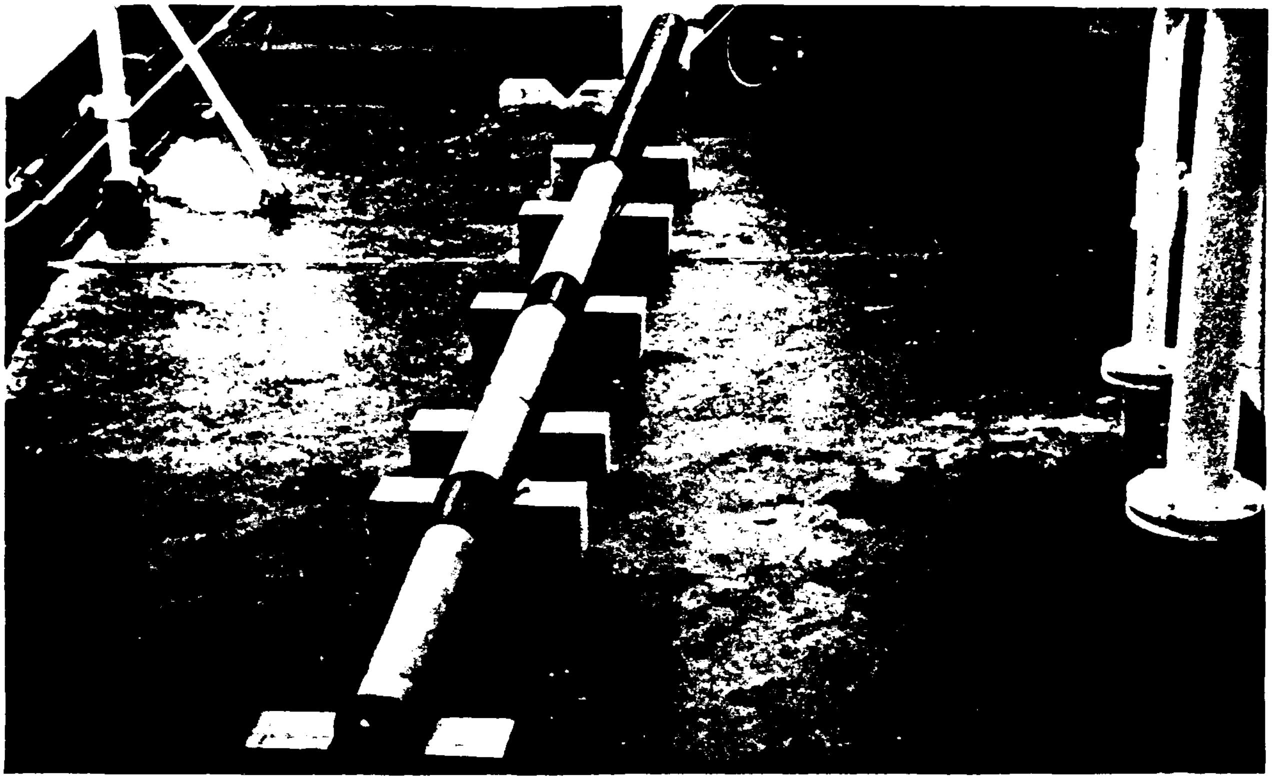
A. *Shipboard Assembly and Handling of Probe System*

R/V Alliance was fully equipped to support all aspects of assembly and handling of the seismo-acoustic probe system. Sufficient deck space was available on the forward port quarter to allow the probe to be laid out and mechanically and electrically interconnected. A nearby laboratory compartment was available in which all surface equipment could be set up for operating the system. A large hydraulic 'A'-frame and winch system located in this forward deck area provided the necessary hoisting and handling capabilities for lifting and transferring the assembled probe over the port railing and down to the seabed. The *R/V Alliance* was also capable of furnishing the 230-V 3-phase 60-Hz power required for operating the vibrator module as well as the pressurized water supply for operating the probe penetration/retrieval-assist water jets.

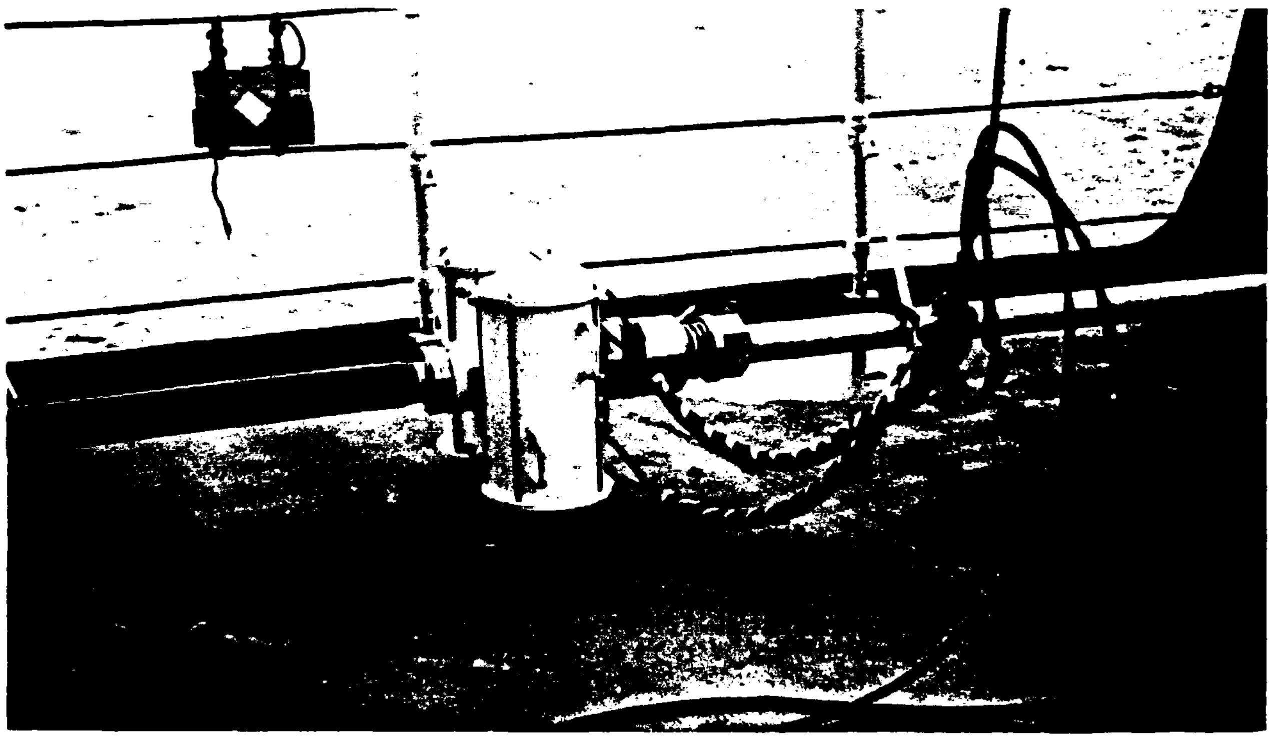
Figures 11 through 13 show the probe system during its assembly and handling aboard *R/V Alliance*. The seabed tests were conducted in the Golfo di La Spezia at a previously used sediment test site located in a water depth of 15 m (49.2 ft). The *R/V Alliance* was placed on station using a three-point anchorage consisting of its two 1.5-ton bow anchors in a 'V'-shaped spread and two aft mooring lines tied onto a large marker buoy permanently anchored at the site.

For tests in this relatively shallow water depth, the probe system was assembled with one joint of riser pipe and use of the penetration/retrieval-assist water jet was deferred unless later found to be necessary. The two jumper cables in the riser pipe were fed through a rubber packer at the top of the riser pipe and were connected to the cable junction module which remained on the deck of the ship. The source and detector cables were connected to the cable junction module and, with the exception of a brief immersion test, remained on the deck throughout the tests. The vibrator module and pipe clamp mechanism unit was tested initially while suspended off the deck on a nylon line before being attached to the riser pipe.

The assembly instructions outlined in the Operation and Maintenance Manual were followed without difficulty in assembling the probe system. The probe transducer modules were electrically and mechanically joined together and the two riser pipe jumper cables were connected to the top end of the assembled probe. Before screwing the riser pipe onto the probe, the probe system was activated and was ascertained to be electrically and acoustically functional. The jumper cables were temporarily removed and their connector screw



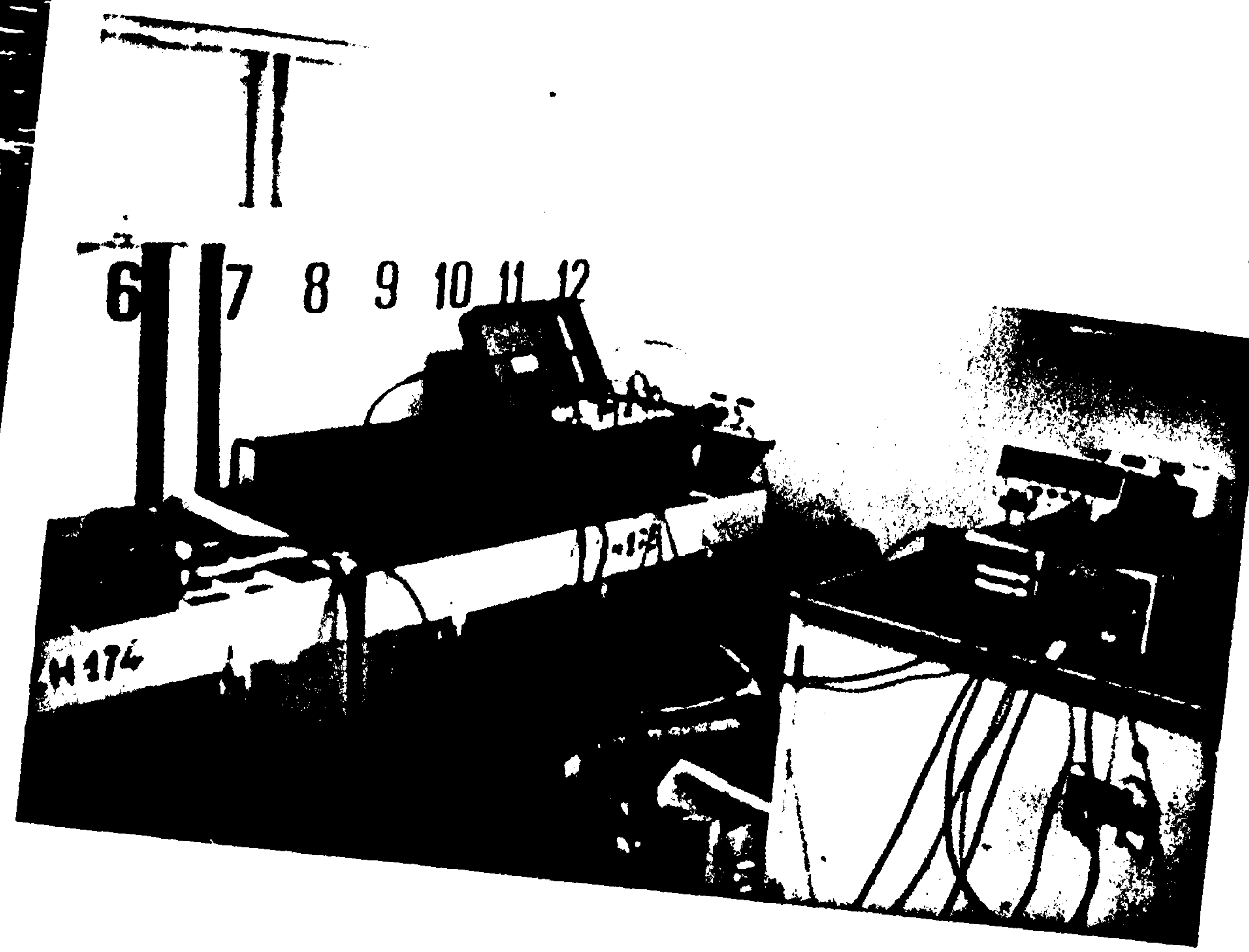
(a) Seismo-acoustic measurement probe



(b) Vibrator and pipe clamping mechanism

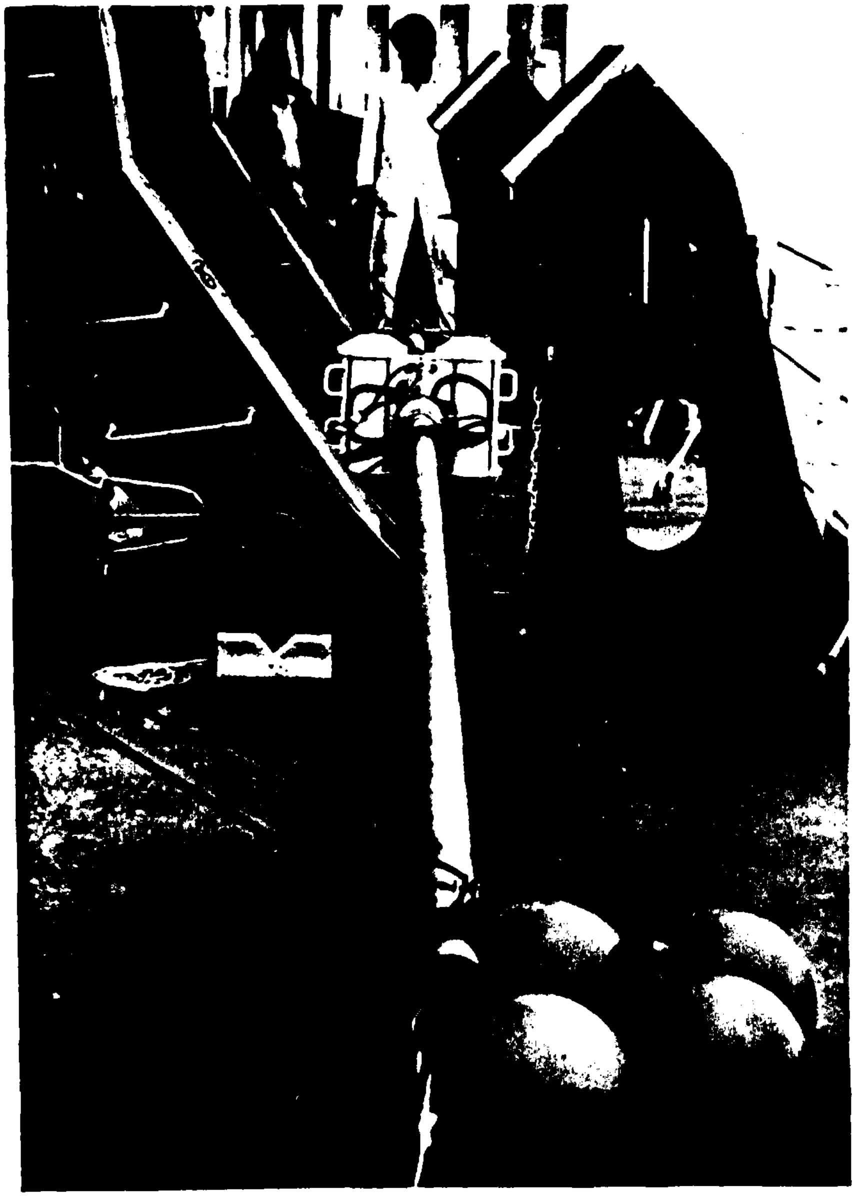
FIGURE 11. SEISMO-ACOUSTIC PROBE ASSEMBLED ABOARD *R/V ALLIANCE*

(a) Probe system being lowered to the seabed

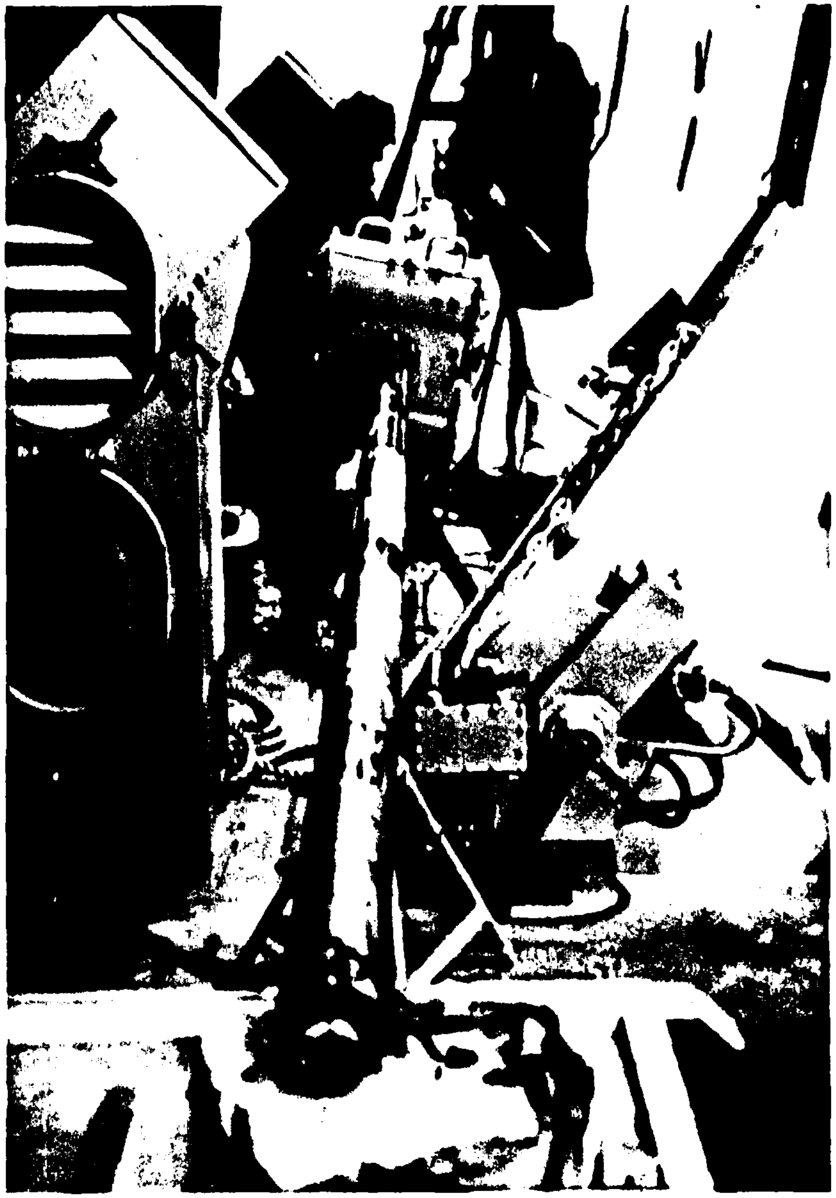


(b) Surface electronic equipment

FIGURE 12. SEISMO-ACOUSTIC PROBE SYSTEM DEPLOYMENT



(a) Probe assembly showing vibrator, riser pipe, and buoyancy floats



(b) Probe assembly showing measurement probe retrieval from seabed

FIGURE 13. SEISMO-ACOUSTIC PROBE SYSTEM DECK HANDLING

rings coated with silicone rubber thread locking compound and then securely reassembled. The riser pipe was inserted through the vibrator and pipe clamp and was then attached to the top of the probe and very securely tightened. Four plastic spherical floats having a total buoyancy of about 75 kg (165 lbs) were tied to a stainless steel clamp at the top end of the riser pipe to aid in maintaining the probe vertically oriented when submerged.

With the fully assembled probe system ready for submersion over the side, the hoisting winch was operated to raise the probe to an approximate vertical orientation suspended from the 'A'-frame while simultaneously being boomed outboard. A nylon tether line temporarily attached to the top end of the riser pipe was used to hold the probe assembly at a slight angle away from the side of the ship until it was ready to be lowered under water. In this position the vibrator module was briefly activated to confirm that it was ready for remote operation. Vibrations coupled to the hoisting cable gave a good indication of the vibrator module operation to later reveal its active operation when submerged.

The hoisting cable was marked at one-meter intervals to provide information on the location of the probe relative to the ship railing. These markers allowed observations of the probe depth and descent rate when the lifting cable was taut and a measure of bottom penetration of the probe when the lifting cable was slacked from the winch but held in vertical tension by hand. Calm waters during these initial tests imposed a ship heave of only about ±10 cm (±4 in.). A sounding line in contact with the bottom was also used to provide an absolute reference for probe penetration depth when compared with the lifting cable markers.

B. Vibration Probe Penetration Tests

With the vibrator module clamped at the lowest practical position on the riser pipe, the probe system would be able to penetrate to a depth of about 4.6 m (15 ft) into the bottom until the vibrator module rested on the bottom.

The vibrator was activated and the probe system was observed to sink into the sediment at a rate of about 2-3 cm/sec (0.8-1.2 in./sec) and the 4.6-meter penetration limit was achieved within a total time interval of approximately three minutes. The approximate penetration rate into the top 4.6 m of sediment was 1.5 m/min (4.9 ft/min). During this bottom-penetration operating time, the lifting cable winch was operated to payout cable at a rate faster than the penetration rate of the probe into the sediment also taking into account the heaving motions of the ship.

At the completion of this probe penetration test, divers examined the probe penetration and attitude of orientation. The vibrator module was found to be resting on the bottom and the riser pipe was vertical. After conducting a series of acoustic measurements in the sediment, the hydraulic clamping mechanism was released and the vibrator unit hoisted three meters upward on the riser pipe and reclamped using the manual hydraulic pump and control unit on the deck. The vibrator unit was then activated and the probe was allowed to penetrate into the bottom sediment until the vibrator again rested on the bottom. The penetration rate to the new total depth of approximately 7.6 meters (24.9 ft) was observed to be essentially the same [1.5 m/min (4.9 ft/min)] as observed earlier. Diver inspection of the probe revealed that the vibrator module was again resting on the bottom and the riser pipe was three meters deeper into the sediment and vertically oriented. After completing a second series of acoustic measurements, the probe was retrieved by means of the winch and hoisting cable. No difficulties were encountered in recovering the probe and returning it to the deck.

Inspection of the probe system and vibrator unit after recovery revealed that the vibrator aluminum frame was cracked at weldments on two gussets which provide reinforcement to the hub on the lower side of the vibrator module. Although repairs would be required, the vibrator unit was judged to be useable in additional tests until repairs could be made.

C. *Probe Acoustic Measurements*

Several series of measurements were conducted to determine the acoustical performance of the seismo-acoustic probe. The first measurements were conducted with the probe penetrated 4.6 m (15 ft) into the seabed. At this penetration depth, the source transducer was located at a depth of 2.1 m (82.7 in.) into the bottom and the two detectors were at 3.1 m (121 in.) and 4.1 m (161 in.) deeper than the source, respectively. The surface transformer unit was connected to provide a 2:1 step-up turns ratio and the probe transformer module was connected to provide a 2.74:1 step-up turns ratio resulting in an overall source excitation voltage step-up of 5.48:1 from the power amplifier to the piezoceramic element of the source transducer. The maximum rated output voltage of the source power amplifier is 70 VRMS before overload distortion occurs. The source excitation signal was a five-cycle sine-wave burst whose frequency could be adjusted in the range of 150-1,500 Hz. The fixed gains of the detector preamplifiers in the probe were 52 dB and the surface post amplifier gain in each detector channel was adjustable in 6-dB steps from zero to 42 dB. The post amplifiers are capable of delivering an output signal of ±15 V peak before being over driven.

The source excitation level was adjusted to produce post amplifier output signals of about ±10 V peak with the post amplifier gains set at 0 dB. With the probe first set to operate in the compressional (P) wave mode and next in the horizontally polarized shear (SH) wave mode, detector output signals were recorded for source pulse frequencies of 250, 500, 1,000, and 1,500 Hz. These detected signals were observed on a two-channel oscilloscope synchronized by the source signal pulse generator and were also recorded in digital form using a SACLANT Centre personal computer and an analog-to-digital converter system operating at a sampling rate of 10,000 samples/sec with 11-bit plus sign resolution. The source transducer was operated in water prior to penetrating the probe into the sediment and was observed and recorded using a broad bandwidth hydrophone having a sensitivity of -200 dBV re 1 μPa.

Figures 14 through 17 present copies of several representative detector output waveforms obtained during the initial seabed acoustic tests. Additional data were recorded for analysis and evaluation at a later time. Figure 14(a) shows the detected five-cycle pulse signal at 250 Hz radiated into the water before the probe penetrated into the bottom. The hydrophone was located at a distance of approximately 3 m (9.8 ft) away from the source. The 250-Hz pulse signal is identifiable in this record although the background noise is

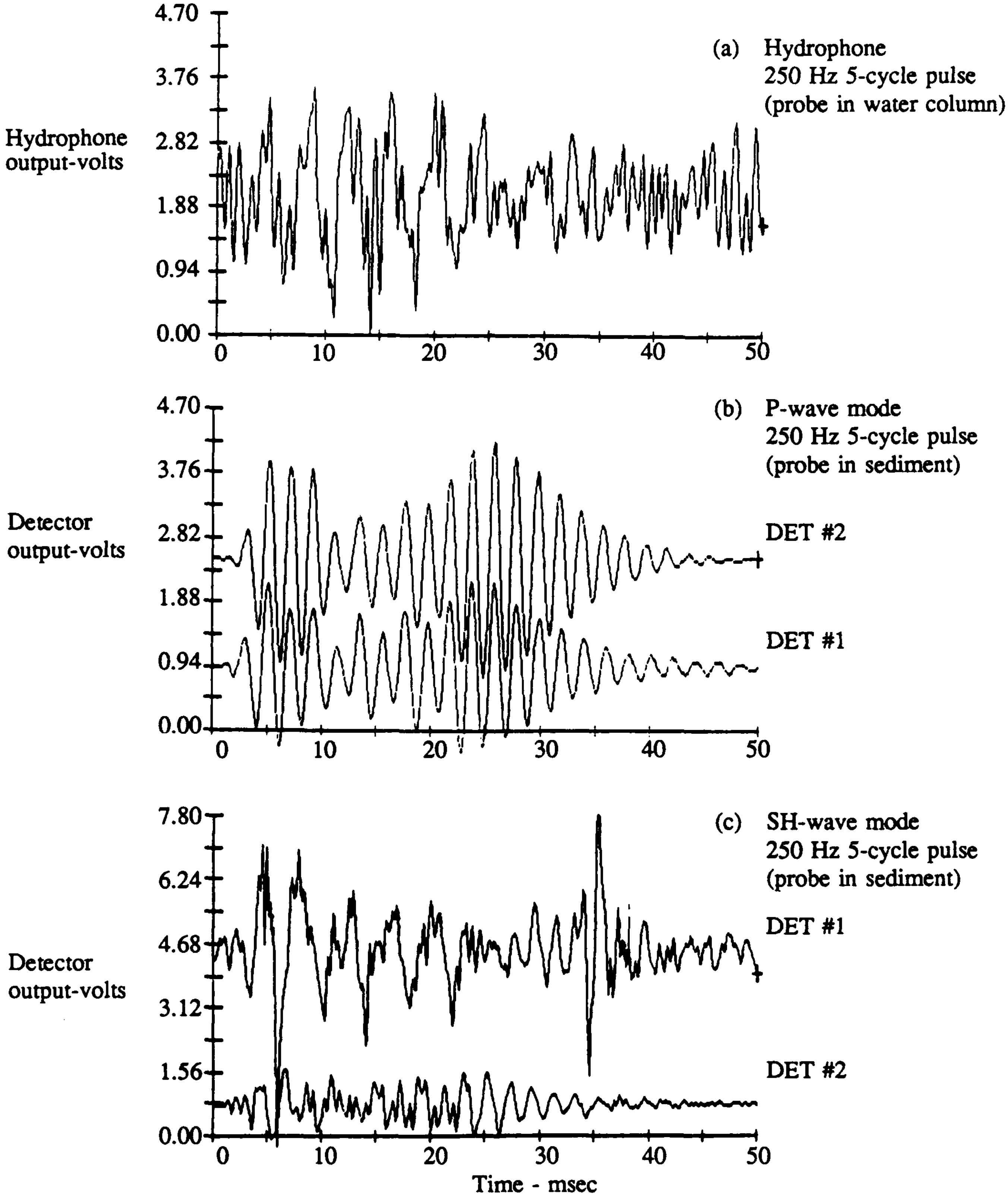


FIGURE 14. SEABED ACOUSTIC MEASUREMENTS - 250 Hz

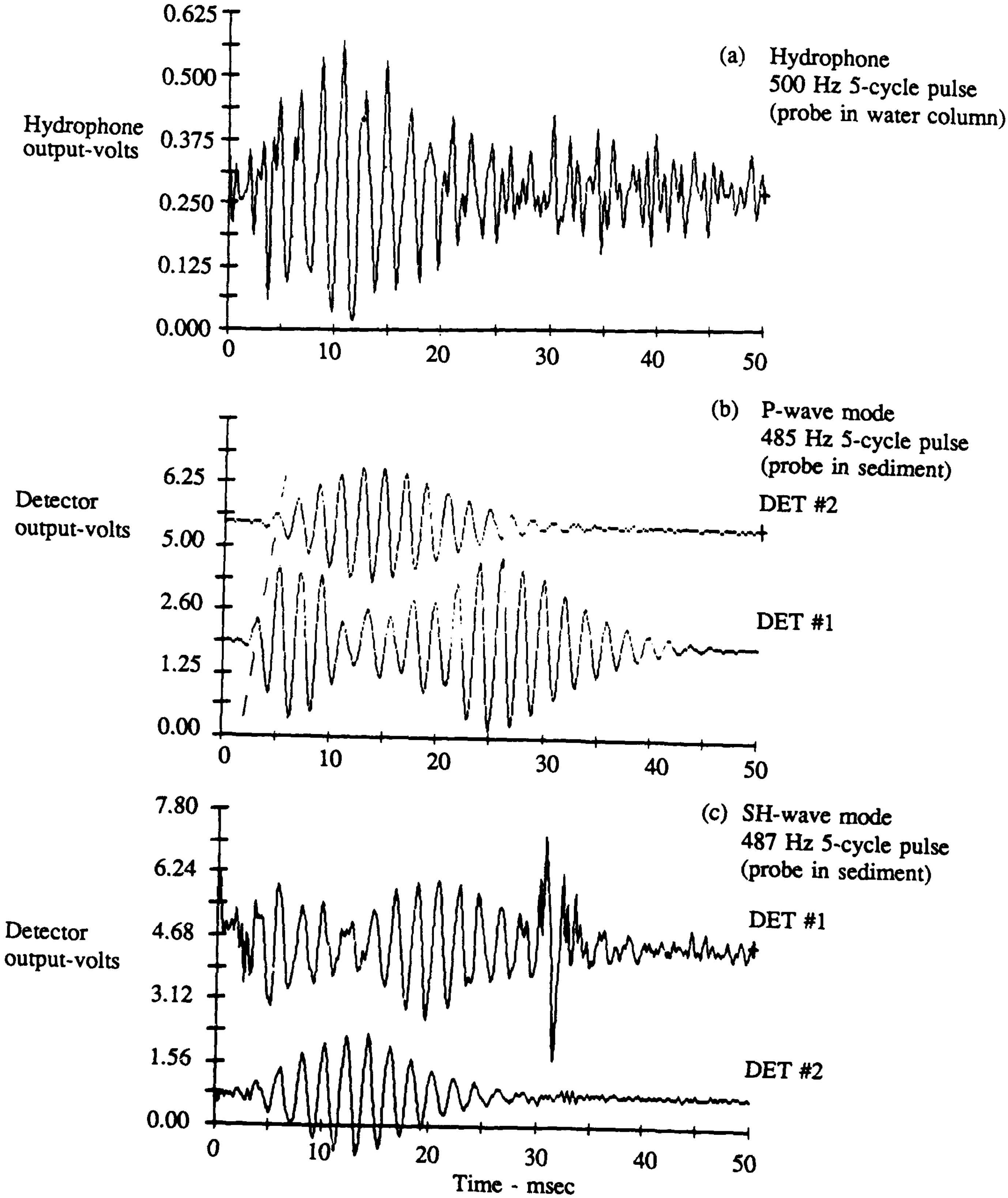


FIGURE 15. SEABED ACOUSTIC MEASUREMENTS - 500 Hz

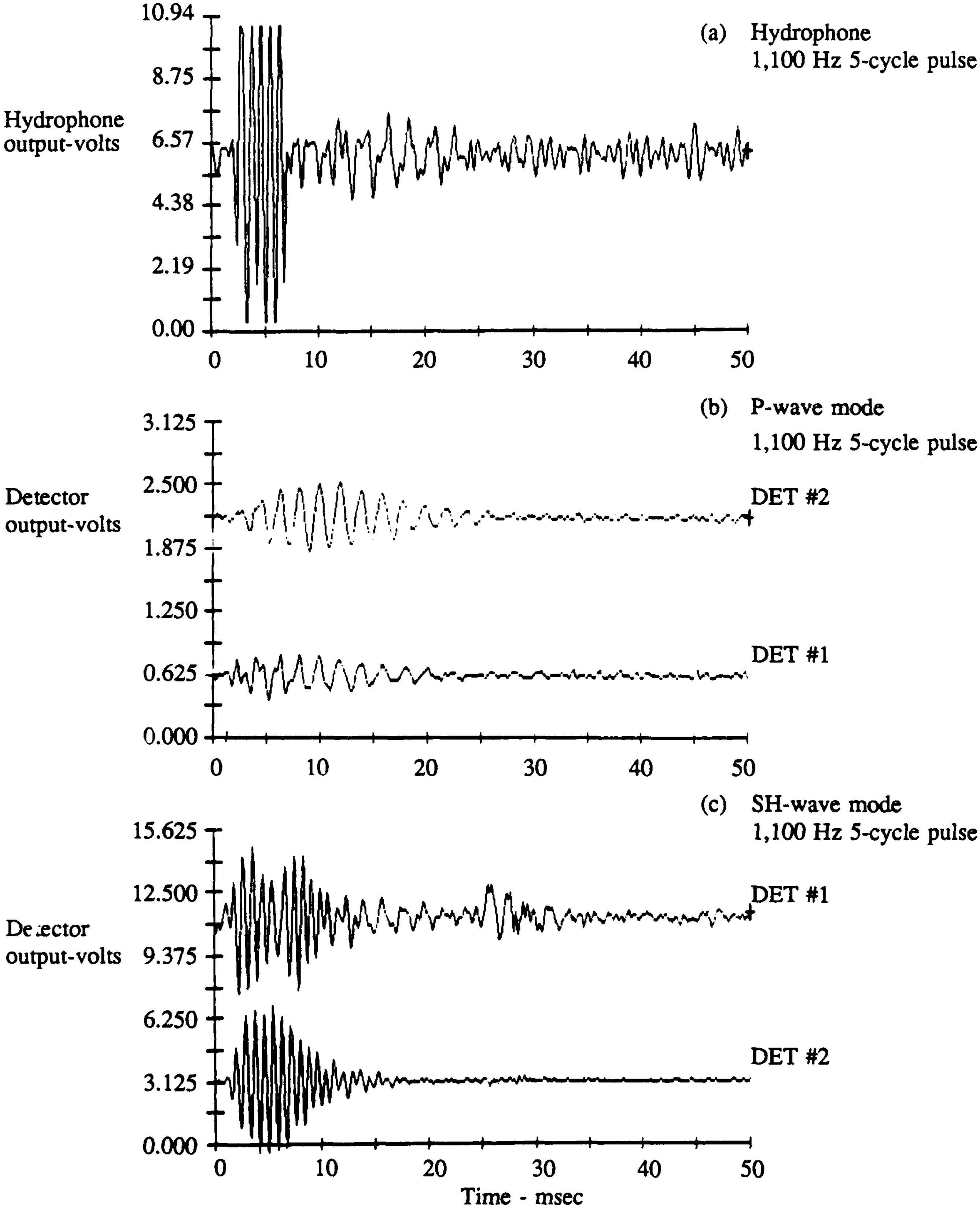


FIGURE 16. SEABED ACOUSTIC MEASUREMENTS - 1,100 HZ

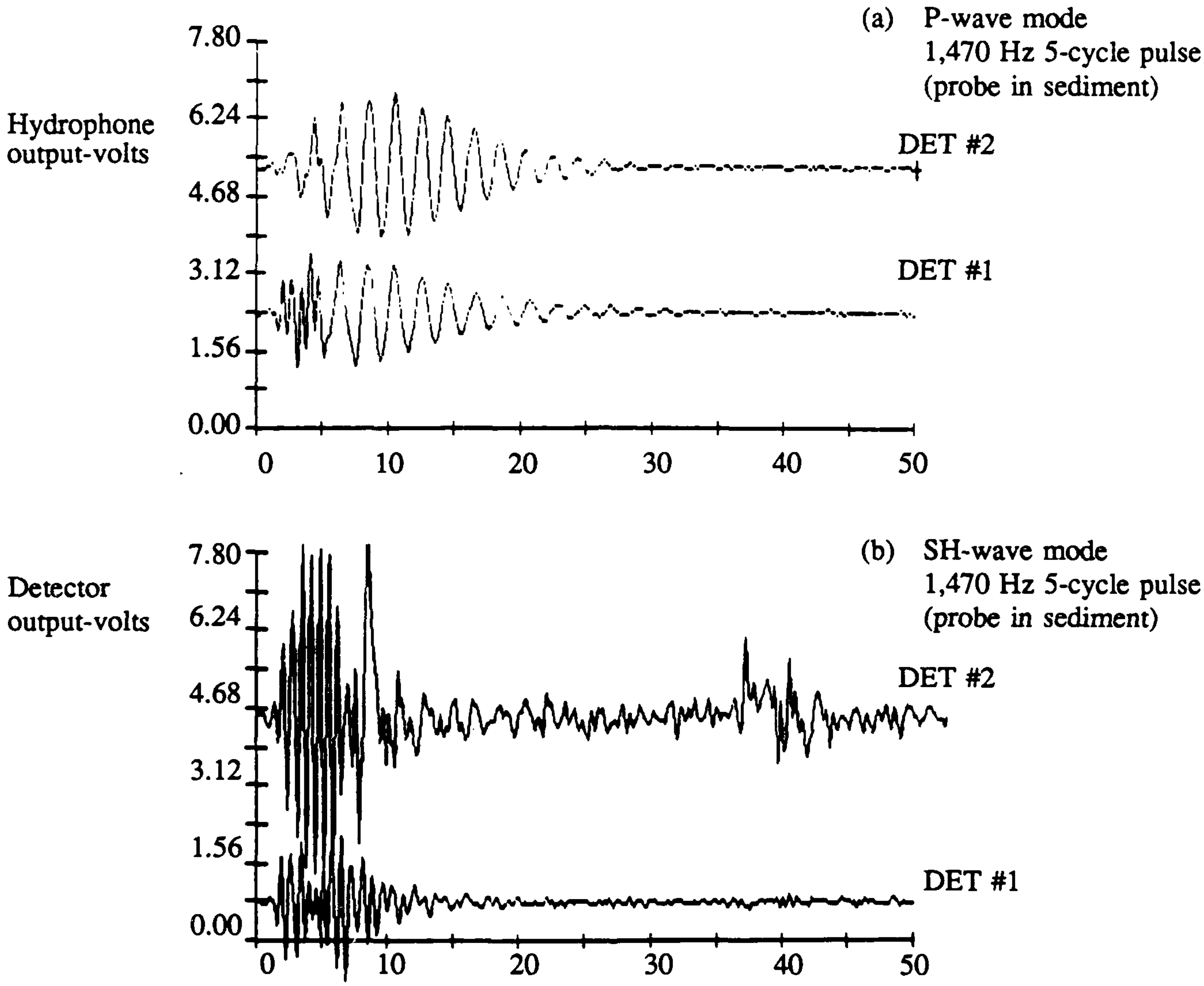


FIGURE 17. SEABED ACOUSTIC MEASUREMENTS - 1,470 Hz

relatively high. One reason for this poor signal-to-noise ratio is that the probe source level was set low enough to prevent the detector output signals from being overdriven and distorted.

Figures 14(b) and 14(c) show the response of the probe when embedded in the sediment and excited by a five-cycle pulse at 250 Hz. The compressional wave response illustrated in Figure 14(b) shows only a ringing effect in both detector channels at a frequency of about 490 Hz which is apparently associated with the probe body structure and/or the source transducer electrical excitation circuit. As indicated earlier in Figure 9, the excitation sensitivity of the compressional wave source mode is relatively low in comparison with the shear wave sensitivity. The shear wave mode response illustrated in Figure 14(c) shows a five-cycle pulse in Detector #1 followed by a later transient impulse wavelet at a frequency of about 400 Hz (time of occurrence:33 msec). Repeat observations of this signal showed that the transient impulse was incoherent with respect to the acoustic pulse synchronization and probably was caused by powerline transients aboard the ship. The 250-Hz shear wave response of Detector #2 is too low in signal-to-noise ratio to be clearly observed, implying either very high attenuation in the sediment or possibly a limitation in the low-frequency response of the shear wave detector. Subsequent measurements of the source excitation voltage from the power amplifier revealed that low-frequency pulse signals below about 300 Hz were reduced in amplitude in comparison with higher frequency signals. This problem was later corrected by changing the winding connections on the surface transformer unit to provide uniform excitation at frequencies as low as 100 Hz.

Figure 15(a) shows the hydrophone response to a five-cycle sinusoidal source excitation pulse at a frequency of 500 Hz. This water-borne signal has a poor signal-to-noise ratio for the same reasons mentioned for the signal shown in Figure 14(a). Bandpass filters were used to improve the signal-to-noise ratio. Close examination of this signal shows a subtle transient effect after the fifth cycle indicating the presence of the 490-Hz resonance effect in the probe when excited near its resonance. This signal characteristic implies that the source ringing was, at least in part, associated directly with the transducer electrical excitation circuit. This effect was later reduced by changing the winding connections on the surface line matching transformer or otherwise adjusting the excitation circuit output impedance to better match the impedance of the source transducer.

The compressional wave and shear wave responses for Detector #1 shown in Figures 15(b) and (c) confirm the above observations by the fact that the leading and trailing edges of the five-cycle pulse produce distinct transients which distort the source excitation waveform. These signals and the compressional and shear wave responses for Detector #2 are essentially identical and are closely similar to the hydrophone signal shown in Figure 15(a). They are also identically delayed in time from the responses in Detector #1 by about 1.8 msec, corresponding to an apparent travel speed of 550 m/sec; a velocity too slow for compressional waves and too fast for shear waves in the sediment. Therefore, these signals must be assumed to travel through the body of the probe in the form of a flexural wave which is equally excited by the compressional or shear operating modes of the source transducer. The transient impulse shown in Figure 15(c) is a powerline disturbance unrelated to the acoustic signals.

Figure 16(a) shows the hydrophone response to a five-cycle sinusoidal excitation pulse at 1,100 Hz. The pulse envelope of this signal is very well defined, indicating that the source transducer exhibits a relatively wide bandwidth and a uniform phase response at this frequency. The compressional wave mode responses of Detector #1 and Detector #2 in Figure 16(b) show that the 1,100-Hz source pulse excites the probe body resonance at about 500 Hz with the practical exclusion of any useful response to the 1,100-Hz source signal. The shear wave mode responses of Detector #1 and Detector #2 shown in Figure 16(c) follow the 1,100-Hz source signal but are again noted to have travel times that are too slow for compressional waves and too fast for shear waves in the sediment. Similar compressional and shear wave test results are shown in Figure 17 for an excitation pulse at 1,470 Hz.

The results of these initial acoustic tests clearly indicate that the source transducer is not adequately isolated from the structural body of the probe. The isolator mass sections of the probe and the 'O'-ring suspensions of the cylindrical bender transducer elements are only partially effective in isolating the source vibrations to the degree necessary for observing the sediment-borne pulse signals. This problem is aggravated by the fact that the principal mode of propagation in the probe body is one of flexural vibration whose velocity is sufficiently slow to interfere with both the compressional and the shear waves that travel in the sediment. The additional data recorded as part of these field tests are expected to support this conclusion; even though modifications to the electrical excitation circuit were made in those tests which improved other aspects of the probe system acoustic response.

A secondary problem associated with the system was found to be its limited low frequency response. However, tests were performed in which the surface transformer windings and impedance levels were changed from the initial 1:2 turns ratio to a turns ration of 1:5 which was sufficient to provide uniform excitation drive voltage at frequencies down to about 100 Hz; a frequency limit lower than the low-frequency operating range of the cylindrical bender transducer. The electrical resonance of the initial source excitation system was damped by increasing the power amplifier output impedance by means of a 20-ohm series resistor. This arrangement made a substantial improvement in the subtle electrical transients caused by the abrupt leading and trailing edges of the excitation pulse signals. However, a thorough evaluation of this source excitation circuit change was not possible in the presence of the stronger probe body interference signals.

V. CONCLUSIONS AND RECOMMENDATIONS

A. *Summary Results and Conclusions*

(1) The prototype seismo-acoustic probe developed and tested under Contract No. N00014-89-C-0098 represents the first version of a self-penetrating seabed probe system designed to measure the compressional and shear wave parameters of the seabed sediment. Several new and untried technical features and operating concepts were incorporated in this design to achieve the desired measurement objectives. Taking these broad factors into account, the basic probe system design has good technical merit and a very good potential for becoming a practical and productive seabed probe which can be improved and developed for widespread use. The initial shipboard and seabed tests revealed that certain physical design features of the prototype model should be modified to improve the ruggedness and reliability of assembly and operation. Other design features associated with the acoustical performance of the probe must undergo revision in order to achieve productive seismo-acoustic measurement results.

(2) The prototype probe system has provided an excellent test bed by which the overall application concept could be tested and evaluated. Based upon the test results from the first sea trials, this equipment has the potential to be modified to incorporate certain necessary and desirable changes and to be used as the basis for further tests and perfection of the self-penetrating seabed measurement technique.

(3) The prototype probe system was designed with the anticipation of certain versatilities in the seismo-acoustic measurement objectives. These design features include the modular form of construction employed in the acoustic measurement probe so that these subsections of the system may be replaced or interchanged with alternate modules to provide other operating features and to facilitate the of other supplemental modular sections for expanding the probe operating functions.

(4) The vibration scheme by which probe penetration into the sediment is achieved functioned very successfully and efficiently. The 4-hp electrically operated vibrator unit had sufficient size and power to produce dynamic displacements of the probe of ±2 mm (±0.08 in.) which were sufficient to liquify the sediment around the nose cone and to break the contact friction between the cylindrical probe surface and the sediment. The submerged weight of the probe was sufficient to allow the probe to sink into the sediment at a rate of 1.5 m/min (4.9 ft/min). The undersize 89 mm (3.5 in.) diameter of the probe riser pipe relative to the 101.6 mm (4.0 in.) diameter of the measurement probe significantly reduces the friction on the riser pipe and, therefore, the penetration resistance of the probe is essentially governed the 4.5 m (14.8 ft) length of the measurement probe independent of

its penetration depth. The results of the recent field tests confirm the general viability of the probe self-penetration technique and the equipment characteristics by which it is accomplished.

(5) Structural failures occurred in two welded gusset joints on the hub of the vibrator module. A third nearby identical gusset joint did not fail. Stresses which caused these failures were apparently the result of the transient torque which occurs when the vibrator is initially started and while the two separate eccentric rotors are seeking their natural (not physically linked) synchronization. The inertial reaction mass of the probe against the torsional force acts exceeds that of the lighter weight core tubes for which the vibrator was designed. This failure problem can be corrected by modifying the reinforcing gussets to provide more uniform stress distribution in the hub assembly. No other vibration-induced failures occurred in either the vibrator unit or the measurement probe.

(6) Compressional-wave acoustical operation of the measurement probe in the water column revealed that the sound pressure level of the source transducer as measured by a nearby hydrophone was relatively low when the source excitation level was adjusted to maintain the output signals from the probe detectors within their linear range. The detector output waveforms were indicative of source vibrations transmitted through the structural body of the probe at an amplitude too high to allow the water-borne sound signals to be observed. Acoustical operation of the probe in both the compressional- and shear-wave modes when embedded in the sediment produced similar masking effects of the sediment-borne signals. From these results, the source transducer element is obviously not adequately isolated from the probe housing to allow sediment-borne signals to be detectable. Tests at several source excitation frequencies were analyzed to indicate that the interference signals traveled through the probe body as flexural vibrations having a velocity of approximately 550 m/sec (1,800 ft/sec) in both the compressional- and shear-wave operating modes. Modification of the source transducer element suspension will be required in order to reduce the excitation of these interfering flexural waves transmitted through the probe body.

(7) The electrical impedance of the source transducer excitation circuit exhibited a resonance effect in the initial arrangement of the probe system. Brief tests in which the power amplifier output resistance was increased showed that the sharpness of this resonance could be significantly reduced by this method. Changes in the surface matching transformer inductance and turns ratio also reduced the effects of this resonance. However, because of the interference signal coupled through the mechanical structure of the probe, the electrical operation of the source transducer could not be evaluated in detail.

B. Recommended Probe System Modifications

The prototype seismo-acoustic probe was found to be a workable self-penetrating seabed probe which has a very good potential for successful development and practical application in the future. Modifications to the source transducer to decouple its vibrations from the structural body of the probe represent the primary design changes needed to correct the deficiencies in the probe acoustic operation. Technical concepts for this change and other modifications and tests which could improve the probe assembly and operation are recommended below.

1. Acoustical Operation

- Modify the source transducer cylindrical bender end supports to reduce mechanical coupling to the structural body of the probe. Tentative modifications appear practical using a combination of metallic end mass rings to maintain the bender operating frequency range and composition rubber sleeves on each end of the bender cylinder to provide a high-compliance suspension. Omit the use of oil filling in the transducer cylinder cavity to further reduce the bender cylinder coupling to the probe body.

- Adjust and optimize the electrical excitation circuit of the source transducer to properly match the source transducer load when physically embedded in seabed sediment material.

- Conduct separate geotechnical investigation of seabed sediments under representative *in situ* conditions to determine the significance of changes, if any, in the elastic moduli and/or compressional- and shear-wave velocities caused by compaction and localized liquefaction of the sediment when the probe is penetrated into the seabed. Results of these tests will provide valuable guidance in future probe design and in interpretation of measurement data.

- Conduct separate design investigation of alternative seismo-acoustic probe transducers for generating and detecting compressional and shear waves in seabed sediments using the self-penetrating probe configuration. Design objectives include reduction of physical size of the transducer devices to better represent point source and point detection measurements without penalizing low frequency operation and to preferentially generate and respond to compressional waves and shear waves in separate measurement modes. Advantages of such alternative transducers will be improved acoustical performance of the probe and a desirable reduction in the probe size and weight.

2. *Probe Components, Assembly, and Handling*

- Modify vibration module and pipe clamping mechanism hub section by adding larger reinforcing gussets to increase resistance to torsional stresses produced by transient start-up of the vibrator.

- Revise recessed jumper cable connector arrangement on the measurement probe and on the cable junction module to allow more convenient and reliable cable assembly.

- Provide storage and handling reels for the three electrical cables and two hoses connecting the submerged probe system to the survey vessel.

- Develop a sensor collar to be attached to the probe to provide a direct readout of probe penetration depth in the sediment relative to the seabed surface.

- Construct module end adapters which will allow the acoustic source and detector modules of the probe system to be assembled and operated separately in the seabed. This arrangement, which will require additional riser pipe joints and a second vibrator module, will permit lateral measurements of compressional waves, shear waves, and interface waves in the seabed sediments. Source transducer excitation power capability is already provided in the system for measurements at lateral separation distances up to 40-50 meters and at sediment penetration depth offsets of 28 meters.

3. *Supplemental Probe System Tests*

- Conduct acoustic calibration tests in free field water to establish source transducer transmitting sensitivity and detector transducer receiving sensitivity versus frequency. These tests should be performed before and after applying modifications to improve source transducer element isolation from the probe body.

- Conduct acoustic radiation pattern tests in free field water to determine source transducer directivity characteristics. These tests should be performed before and after applying modifications to improve source transducer isolation from the probe body.

- Conduct seabed probe penetration tests to the maximum depth capability (28 meters) presently provided in the system. Tests should include operation of the water-jet-assist capability to evaluate this aid to penetration and recovery of the probe.

REFERENCES

1. Shirley, D.J. and Owen, T.E., U.S. Patent No. 4,525,645, June 1985.

2. Balogh, W.T. and Owen, T.E., "A New Piezoelectric Transducer for Hole-to-Hole Seismic Applications," Paper DEV 2.5, *Abstracts*, 58th Annual International Meeting, Soc. Expl. Geophys., Anaheim, CA, Oct. 30-Nov. 3, 1988.

3. Owen T.E. and Karisch, E.P., "Design Improvements to the Piezoelectric Cylindrical Bender Seismic Source," Third International Symposium on Borehole Geophysics, Minerals and Geotechnical Logging Society, SPWLA, Las Vegas, NV, Oct. 2-5, 1989.