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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

One problem normally associated with the use of low-frequency, high-power underwater acoustic sources is the ability to accurately monitor the generated sound pressure level. The USRD was tasked by the Office of Naval Research to design, fabricate, and install an acoustic monitoring system for a large hydraulically actuated source, the VIBROSEIS system. The monitoring transducers and the associated calibration system were designed to operate in the 5- to 225-Hz frequency range and to minimize several problems associated with the particular source. The system was installed, calibrated at sea, and performed satisfactorily during the ocean exercise.

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AN ACOUSTIC MONITORING SYSTEM FOR THE VIBROSEIS LOW-FREQUENCY UNDERWATER ACOUSTIC SOURCE

Introduction

The Long Range Acoustic Propagation Project (LRAPP) of the Office of Naval Research, in carrying out its mission, used a low frequency high power underwater acoustic source known as the VIBROSEIS System. The source consists of two 1.2-m diameter opposed air backed pistons driven by a hydraulic ram between them, and exists in both "shallow" (18.3 m depth) and "deep" (91.5 m depth) operating configurations. The source, its lifting structure, supply lines, and tow members are shown in Figure 1.

A requirement for operation of the system in the LRAPP exercises was a continuous knowledge of the generated sound pressure level, implying the necessity of an acoustic monitoring system. In an earlier monitoring system, the hydrophones were attached to the tow members, 3.7 m from the geometrical center of the source. The hydrophones were enclosed in foam-filled, open-ended, steel tubes in an attempt to provide some mechanical protection and vibration isolation. Results obtained with this system were unsatisfactory for several reasons: the distance from the acoustic center of the source (which was not known) to the hydrophone could vary as a function of tow angle; the foam surrounding the hydrophones acted as a pressure release material, yielding an erroneous measurement of the sound pressure level [1]; and large variations in the received signal level due to surface reflection were caused by the relatively large ratio of hydrophone spacing (3.7 m) to depth, especially in the case of the shallow source.

Because of its experience in the design of transducers and measurement methods to meet unusual requirements, the Underwater Sound Reference Division was requested to design, fabricate, and install a new VIBROSEIS acoustic monitoring system. The system would have to meet all acoustical and mechanical requirements, maintain a constant separation between the acoustic centers of the source and hydrophone, and minimize the effects of vibration and the surface boundary. An additional task required the USRD to devise an "at sea" method of calibrating the monitoring system.

Seven transducers designated USRD type F58 and all hardware needed to implement the system were built, tested, and installed aboard the source ship.

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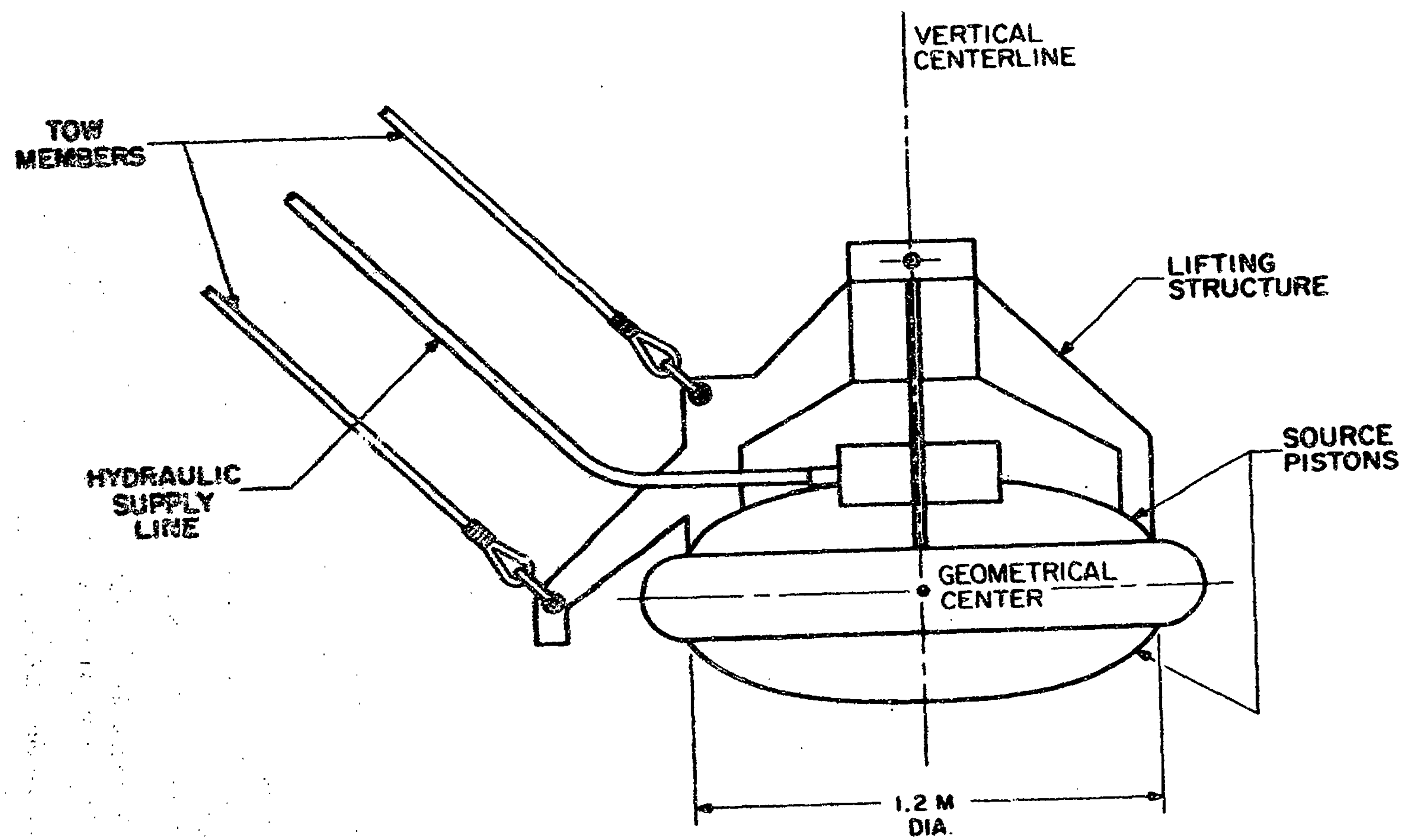

Fig. 1 — VIBROSEIS source schematic

Methods

The operating acoustical requirements of the monitoring system were not unusually stringent, i.e., measure sound pressure levels from 170 to 190 dB re 1 μPa in the frequency range 5 to 225 Hz, to maximum depths of 137 m. The operating environment, however, was extremely hostile. The hydrophones and their associated hardware must be impervious to hydraulic oil, are subjected to high amplitude vibrations, and must withstand the rough handling of system deployment and retrieval.

From Figure 1, it can be seen that to maintain a constant separation between the hydrophone and source, the hydrophone must be attached to the source structure itself. One question which naturally arises from such a suggestion is, how close to the source may the hydrophone be placed and yet remain in the "far field" (Fraunhofer diffraction zone). If standard criteria for a piston radiator are applied, the source dimensions and the frequency range of operation indicate the upper portion of the source lifting structure, a distance of approximately 0.6 m from the source, will provide a far field mounting point [2,3].

Positioning the Monitor Hydrophone

Since the measured sound pressure level requires a reference distance to be meaningful, the problem requiring the most initial attention was developing a method to measure the fixed distance between the acoustic centers of the hydrophone and source. Complicating the problem was the fact that the location of the source's acoustic center was also unknown. However, some conclusions as to the probable location of the acoustic center were drawn from general considerations about the source and how it operates. The source is reasonably symmetrical so there was reason to believe the acoustic center lies somewhere along the vertical centerline of the two pistons. Additionally, the upper piston is somewhat clamped by the added mass of the lifting structure and hydraulic accumulators, the tension of the tow cables, and the force of the water flow due to the tow angle. This led to the conclusion that the acoustic center lies on the vertical centerline of the source somewhere between the geometrical center and the surface of the lower piston (Figure 1).

Assuming this conclusion to be correct, a method of measuring acoustic path length differences was used to determine the distance between the acoustic center of the source and a fixed hydrophone. Two in-line hydrophones H_1 and H_2, shown in Figure 2, are positioned a known fixed distance apart, and can be towed about a horizontal line passing through the geometrical center of the source and perpendicular to the tow direction. Since the acoustic pressure is inversely proportional to the distance from the source, the ratio of the simultaneously measured pressures at each of the two hydrophones is given by

$$\frac{P_2}{P_1} = \frac{X_1}{X_2} ,$$

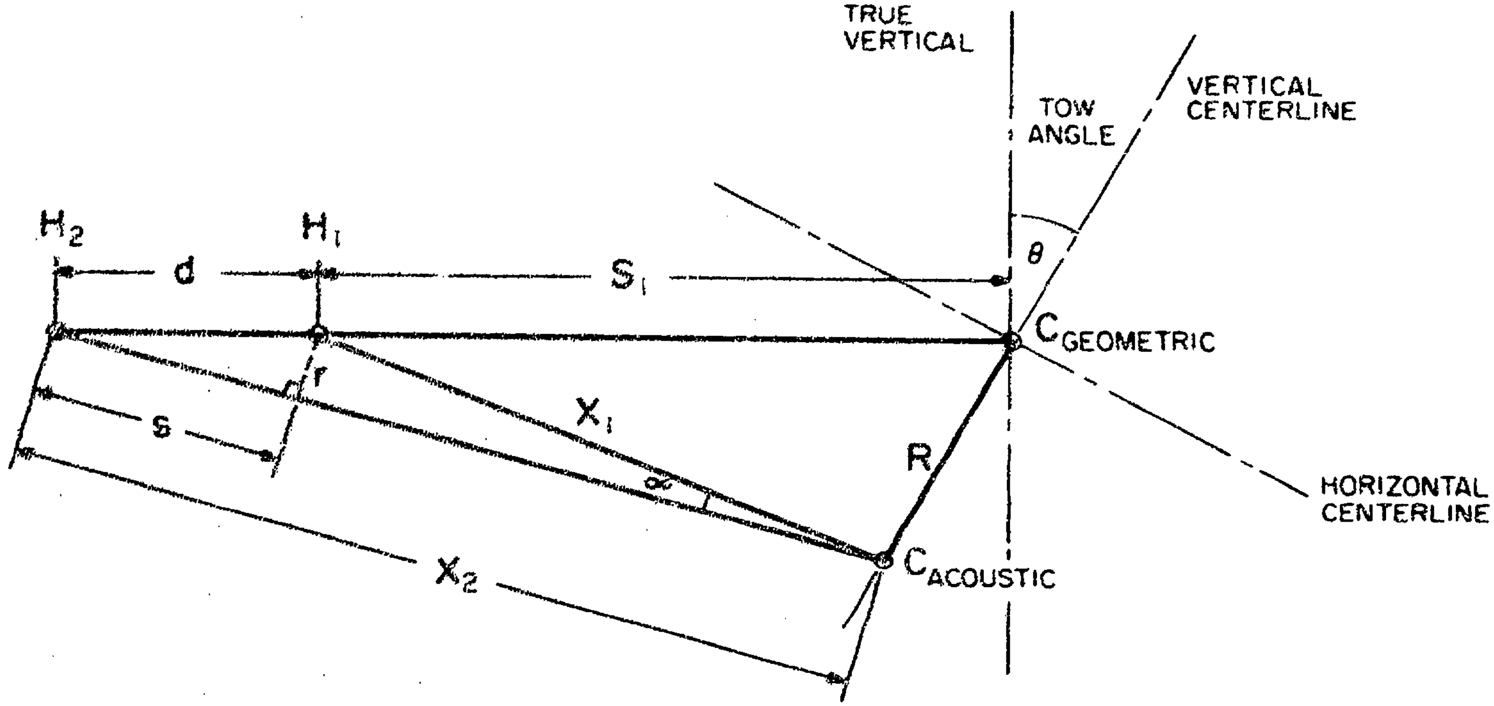

Fig. 2 — Geometry, two towed hydrophones

where P_1 and P_2 are the sound pressures at hydrophone positions 1 and 2, and X_1 and X_2 are the distances from the acoustic center to each of the hydrophone positions. Rewriting the equation in terms of the output voltages, E, and the free field voltage sensitivities, M, of the two hydrophones

$$\frac{E_2M_1}{M_2E_1} = \frac{X_1}{X_2} \text{ or } X_1 = X_2t, \qquad (1)$$

$$\text{where } t = \frac{E_2M_1}{M_2E_1}.$$

From the geometry shown in Figure 2, $d^2 = S^2 + r^2$ and $X_1{}^2 - (X_2 - S)^2 + r^2$. Solving one equation for r^2 and substituting gives $d^2 = X_1{}^2 - X_2{}^2 + 2sX_2$. However, for small values of the angle α, such that $\sin\alpha \approx \alpha$, $s = X_2 - X_1$, and therefore,

$$d^2 = X_2{}^2 - 2X_1X_2 + Y_1{}^2, \text{ or}$$

$$d = X_2 - X_1.$$

Solving equations (1) and (2) simultaneously, yields

$$X_1 = \frac{td}{(1-t)} \text{ and} \qquad (3)$$

$$X_2 = \frac{d}{(1-t)} \qquad (4)$$

So the fixed separation between the two hydrophones, d, becomes the only "reference" distance needed to determine the distance from each of the hydrophones to the acoustic center of the source. To insure the validity of the method, it is only necessary to choose s_1 and d so that α approximates $\sin\alpha$ to within an acceptable error. This may be accomplished by choosing S_1 to be large compared to R (the distance from the geometric to the acoustic center of the source) and by choosing d to be small compared to S_1. The separation, d, should not, however, be made so small that very little path length difference (s) exists between the hydrophones as measurement resolution will suffer. It would be convenient to choose S_1 = 50.9 inches (1.29 m) and d = 21.0 inches (0.53 m) simply because the hydrophones would then be at +3 dB re 1 yard (+2.2 dB re 1 m) and +6 dB re 1 yard (5.2 dB re 1 m) from the geometrical center of the source. If S_1 and d are thusly chosen and the original assumption about the probable location of the acoustic center is correct, it can be shown from the geometry of Figure 2 that when α and R are at their maximum, the path length difference method of determining X_1 and X_2 is in error by approximately 0.2 dB.

However, we still have not satisfied the original requirement of fixing the position of the monitor hydrophone relative to the acoustic center of the source. Figure 3 shows the initial geometry modified by moving the hydrophone farthest from the source H_2 to a point on the lifting structure H_3, while retaining the hydrophone closest to the source in the towed configuration. If the hydrophone outputs are simultaneously sampled in this configuration, the ratio of the pressures at the two positions may be represented by

$$\frac{P_3}{P_1} = \frac{X_1}{X_3} .$$

As before, this can be rewritten in terms of the output voltages, E, and the free-field voltage sensitivities, M,

$$\frac{E_3 M_1}{M_2 E_1} = \frac{X_1}{X_3} \text{, or}$$

$$X_3 = \frac{X_1}{t'}, \tag{5}$$

where $t' = \dfrac{E_3 M_1}{M_2 E_1}$.

So now we have the desired fixed distance, X_3, from the acoustic center in terms of the "reference" distance X_1, but from equation (3) $X_1 = \frac{td}{(1-t)}$ and therefore

$$X_3 = \frac{td}{t'(1-t)} . \tag{6}$$

That is, the distance from the acoustic center of the source to the fixed hydrophone can be obtained from the initial hydrophone spacing, d, the free-field voltage sensitivities of the hydrophones, and the hydrophone output voltage ratios measured in each of the two configurations. Both sets of measurements require that the source be in a stable towed condition and that all other system parameters remain unchanged.

Minimizing the Effects of the Surface Boundary and Acceleration

Placing the hydrophone on the source lifting structure reduces the ratio of hydrophone spacing to depth to near minimum, thereby minimizing the interference effect between the surface reflected and direct signals.

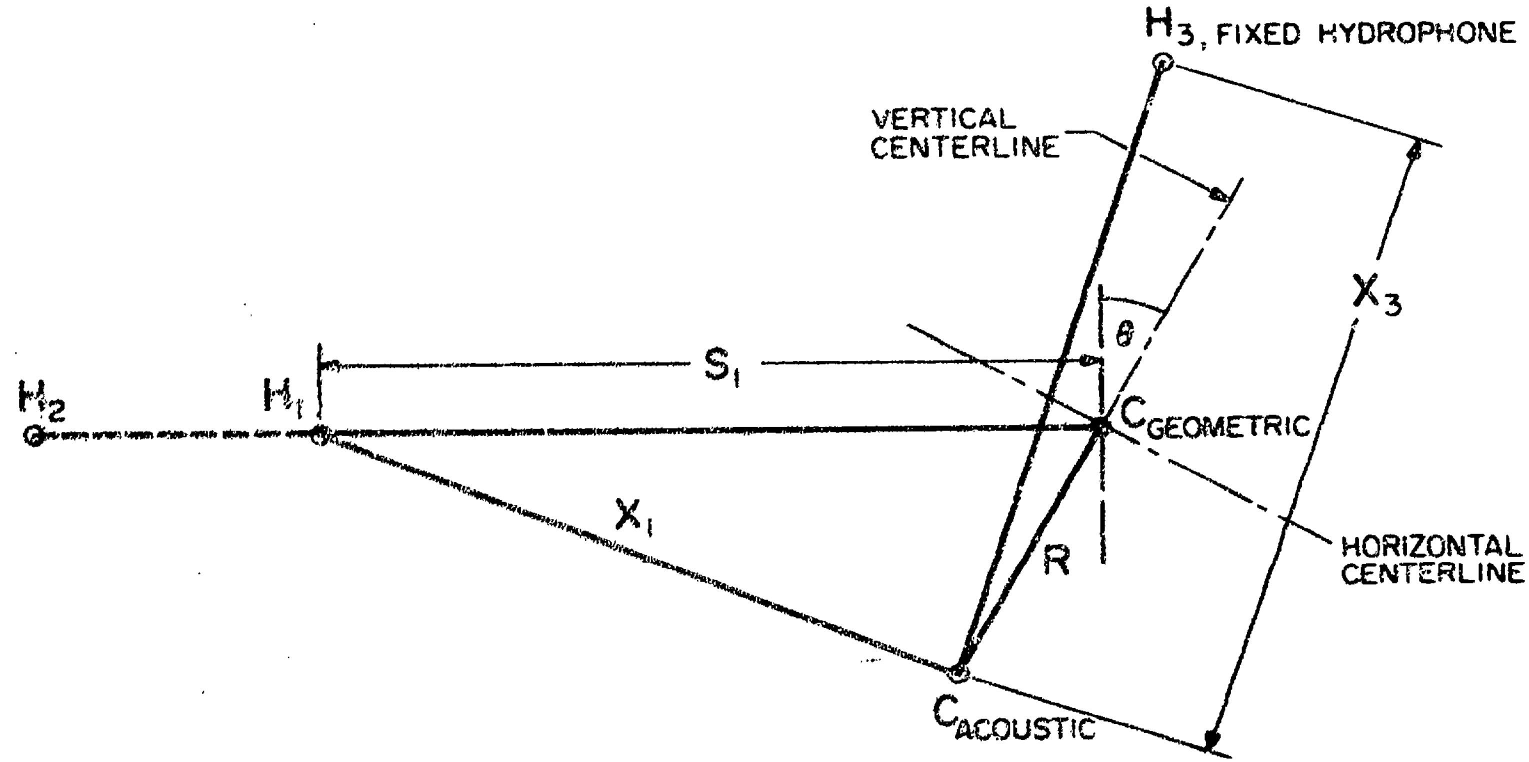

Fig. 3 — Geometry, one towed, one fixed hydrophone

Compared to the 3.7 m hydrophone spacing of the original monitoring system, the closer spacing will increase the separation between the levels of the direct and surface reflected signals by approximately 10 dB in the case of the shallow source. The effects of the surface reflected signal are reduced to insignificance in the case of the deep source.

Attaching the monitor hydrophone to the source helps to solve the problems of fixing the hydrophone spacing and reducing the effects of the surface boundary, but substantially adds to the acceleration magnitude experienced by the device. Acceleration canceling configurations of the sensor were eliminated from consideration because it was felt it would not withstand a rigid or semi-rigid mounting. Instead, it was decided the problem could be solved by providing sufficient vibration isolation for the hydrophone. That is, the acceleration of the piston surface is proportional to the generated sound pressure level, so if sufficient isolation is provided, there exists a large difference between the hydrophone's acceleration sensitivity and its sensitivity to acoustic pressure. This, then, would be analogous to a large signal to noise ratio (hydrophone voltage output due to acoustic signal/voltage output due to acceleration) and therefore minimize the effects of acceleration.

The vibration mount must meet several requirements to provide the necessary isolation. The compliance in the plane of the vibration must be large to achieve the necessary low frequency of mechanical resonance, yet the compliance in the plane perpendicular to the vibration must be small to prevent appreciable displacement of the hydrophone by the force of the water flow. The mount must also counteract any torque applied to the hydrophone.

These requirements were satisfied by fabricating and attaching a webbed neoprene rubber mount to each end of the hydrophone. The acceleration responses of the hydrophone in air with the mount "blocked" and with the mount free to move are shown in the curves of Figure 4. The mount provides the poorest isolation at the frequency where its compliance resonates with the mass of the hydrophone, 12 Hz, but even at this frequency it can be shown from the maximum displacement of the pistons that the voltage generated by acceleration will be approximately 40 dB below the acoustically generated signal.

At Sea Calibration

A comparison calibration of an unknown hydrophone can be made by measuring the difference in output between the unknown hydrophone and a hydrophone of known receiving sensitivity when both are exposed to the same sound pressure level. This simple technique may be applied in satisfying the requirement of an "at sea" calibration capability for the monitoring system. The calibration system to be used employs a USRD type G40 shipboard calibrator and is shown in the block diagram of Figure 5 [4].

Two hydrophones, one the calibration "standard" and one the unknown, are placed at the same depth in the calibrator. The generated sound pressure

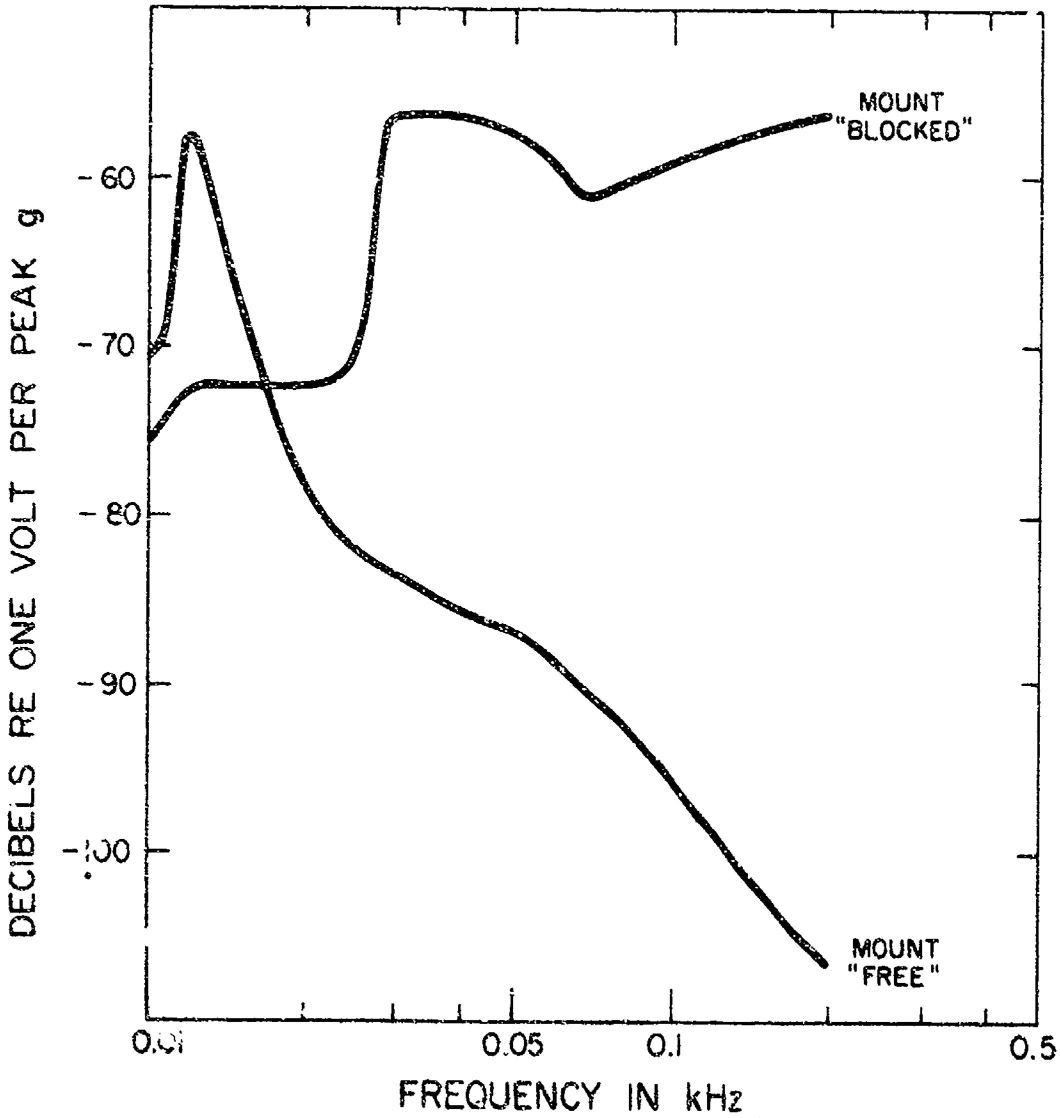

Fig. 4 — Hydrophone acceleration sensitivity

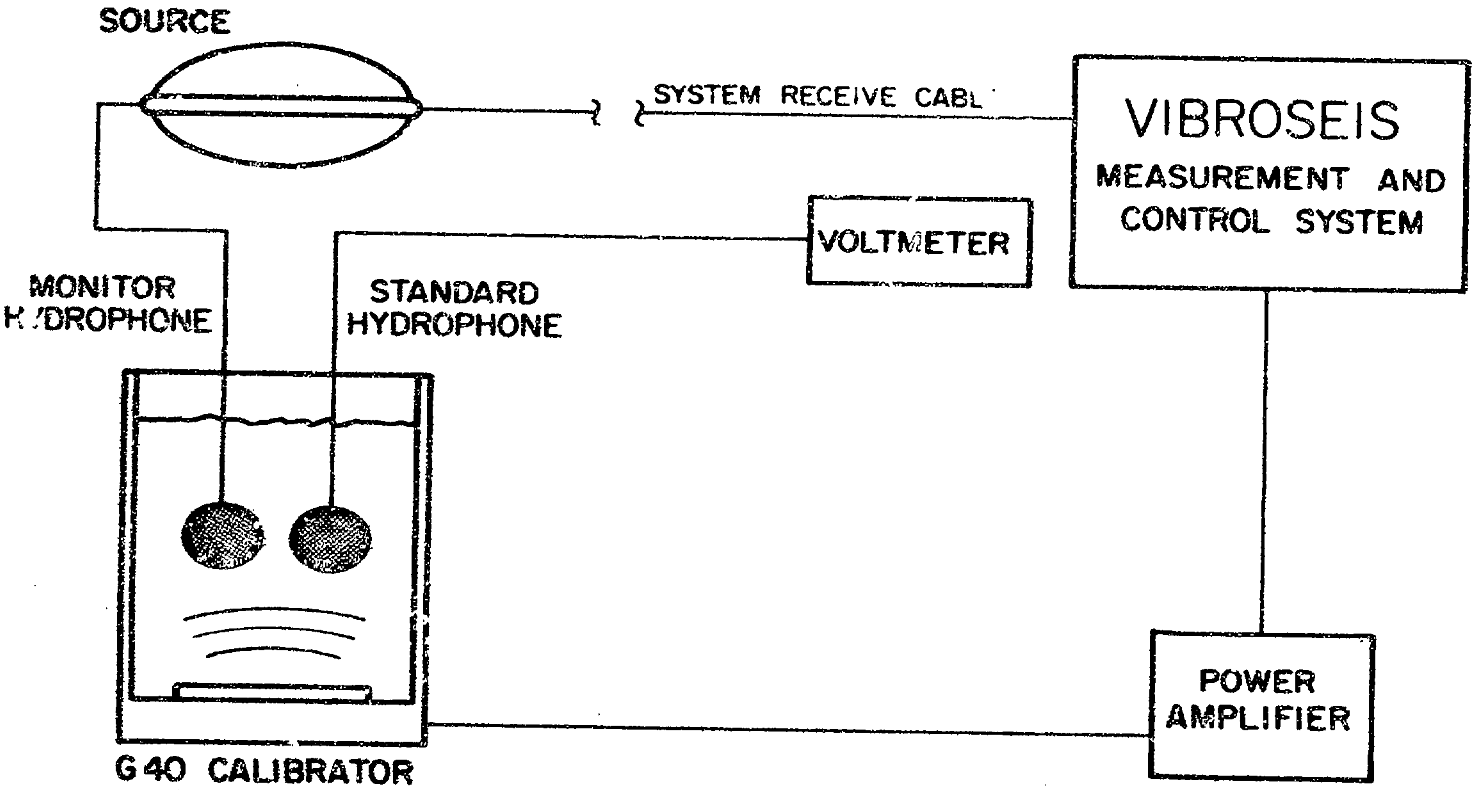

Fig. 5 — Calibration system block diagram

level at that point is established by the output of the standard hydrophone. The gain of the system monitoring the unknown hydrophone may then be varied until it indicates the same sound pressure level as the standard. The procedure should be repeated over a range of sound pressure levels in the frequency range of interest to insure system linearity. Thus, the system can be calibrated for each hydrophone/receive cable pair by noting the system gain required to match the signal level of the unknown hydrophone with that of the standard.

Hardware and Instrumentation

The VIBROSEIS monitoring system designed and constructed by the USRD consists of three main components: the monitoring hydrophones, a specially designed transducer vibration mount and tow cable assembly, and the calibration system.

Monitoring Hydrophones

The monitoring hydrophones were USRD type F58. The transducer sensor element is a 38 mm (1.5 in.) diameter radially poled piezoelectric, lead zirconate-titanate sphere with a wall thickness of 3.2 mm (0.125 in.). This sensor is encapsulated in B. F. Goodrich "Rho C" compound 35075 inside a steel expanded metal frame, strengthened at each end with steel rings. Each ring has two threaded mounting studs. Figure 6 is a photograph of the F58.

Seven of these transducers were constructed, one as the calibration standard hydrophone and six as VIBROSEIS monitoring hydrophones. The monitoring hydrophone open circuit free field voltage sensitivities varied from -194.0 to -194.5 dB re 1 V/μPa from unit to unit in the frequency range 2 to 250 Hz, measured at the end of 6.1 m of cable. There is no change in sensitivity with pressures up to 2.068 MPa (207 m depth), and the hydrophones are omni-directional in this frequency range.

Each of the six monitoring hydrophones were constructed with 6.1 m of cable terminated by underwater connectors to be compatible with the VIBROSEIS receive system.

The durability of the hydrophone design was proven by their successful use without failure during ten months of sea exercises. Several failures of the hydrophone female cable connector resulted because it is mated to a bulkhead connector mounted on one leg of the lifting structure. This exposes the connector to the full alternating acceleration of the top piston of the VIBROSEIS source, estimated to be up to 4 g's peak, causing fatigue failure of the cable leads where they are soldered to the pin sockets inside the molded female connector. The problem was solved by eliminating the relative motion between the cable and the connector.

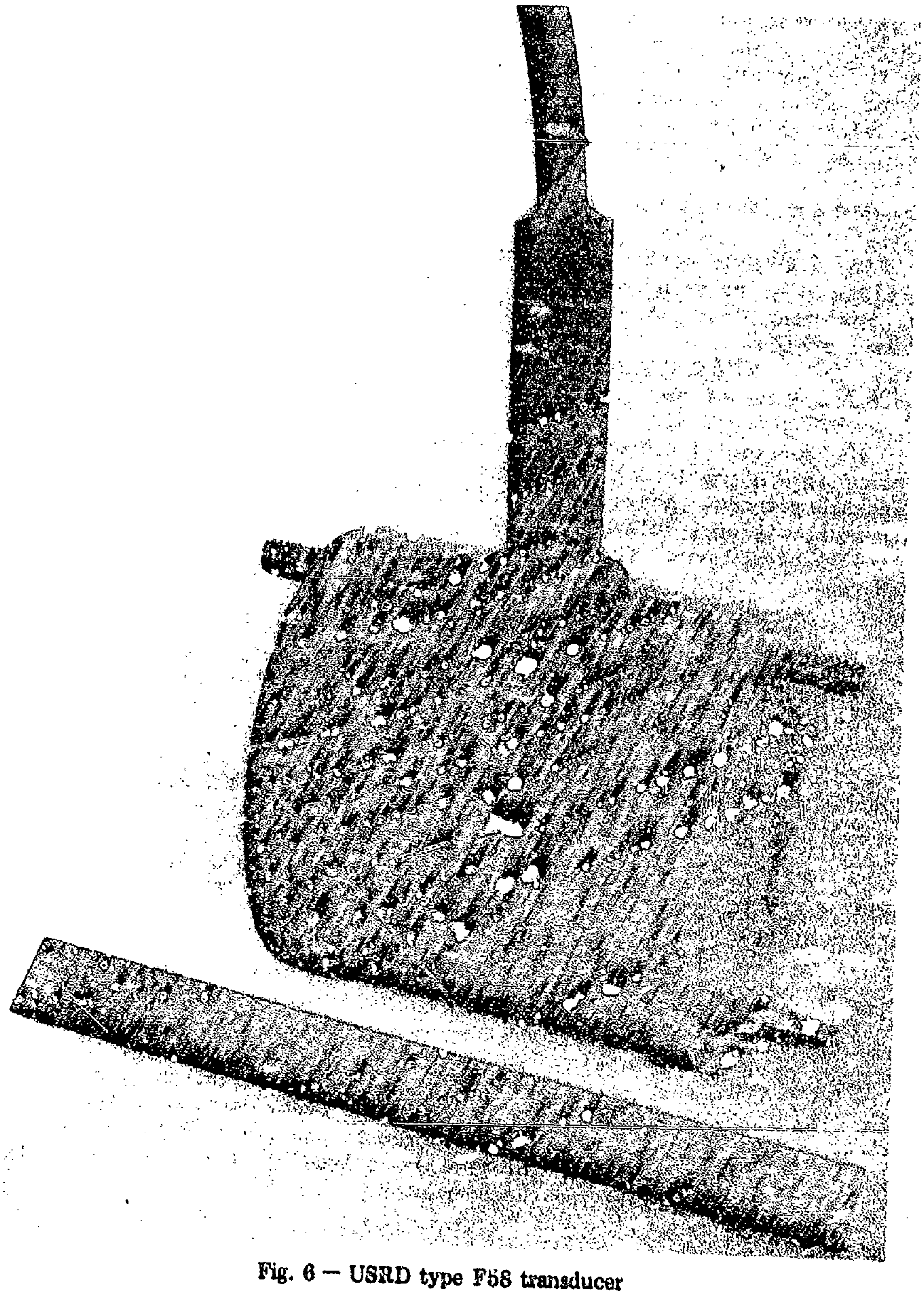

Fig. 6 — USRD type F58 transducer

Vibration Mounts and Tow Cable Assembly

To obtain the best isolation of mechanical vibration from the VIBROSEIS source to the mounted hydrophone, a high compliance vibration mount was designed. This vibration mount consists of two neoprene webs each molded to an inner and outer stainless steel ring. The hydrophone is attached to the inner rings at the top and bottom by the hydrophone mounting studs with wingnuts for easy installation. Figure 7 shows the hydrophone as attached to the vibration mount. Figure 8 shows the hydrophone vibration mount assembly with its outer rings bolted to a mounting bracket to be attached to the rear leg of the VIBROSEIS source lifting structure leg. The position of the hydrophone vibration mount assembly was chosen from a structural standpoint to be protected from damage during deployment and retrieval of the source.

To perform the hydrophone tow tests previously described and shown in Figure 2, a tow cable assembly was devised. This assembly consisted of two "L" shaped outriggers bolted to the VIBROSEIS source at the bottom of the port and starboard lifting structure legs. This provided tow points on a line perpendicular to the VIBROSEIS source centerline and assured a constant distance between the hydrophones and the source geometric center (S_1 in Figures 2 and 3). Figure 9 shows the starboard outrigger (A), tow cable (B), and hydrophone H_1 (C), which is attached to the tow cable end straps by its mounting studs. The tow points and the tow cable lengths were chosen from the viewpoint of deployment and retrieval so that the tow assembly would freely trail behind the source in the water and not become fouled in the source structure. Several tow tests were effectively carried out using the tow cable assembly. From the resulting hydrophone output data, the tow geometry was effectively maintained.

Calibration System

The calibration system provides the capability of shipboard calibration of the VIBROSEIS monitoring hydrophones, receive cable, and measurement and control system as an operating system at sea.

The primary component of this system is the USRD type G40 shipboard calibrator. This device consists of a water-filled cylinder, open at the top, with a moving coil type projector at the bottom. The water-filled tube provides a calibration chamber into which the standard hydrophone and monitor hydrophone can be placed for system calibration. The calibrator provides for isolation from ship deck vibration and the effects of roll and pitch. It also has the capability of reproducing sound pressure levels up to 190 dB re 1 μPa, simulating actual high levels to which the monitor hydrophones and receive system will be subjected. Figure 10 shows the G40 calibrator as used with the calibration system.

To provide mobility on deck and allow placement near the VIBROSEIS source monitor hydrophone to be calibrated, the G40 calibrator was fitted with large casters and foot operated jacks to secure it in place.

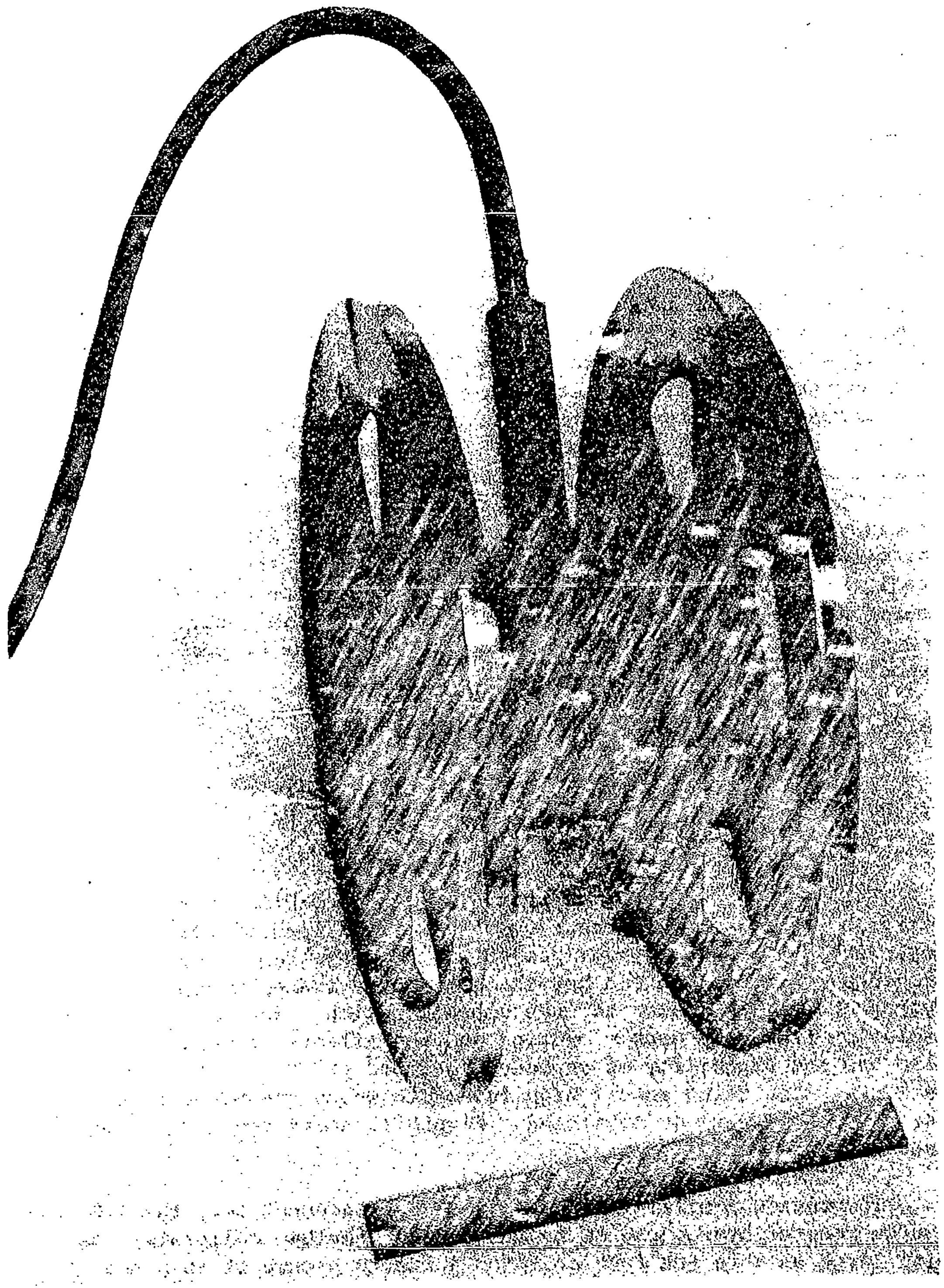

Fig. 7 — USRD type F58 transducer in vibration mounts

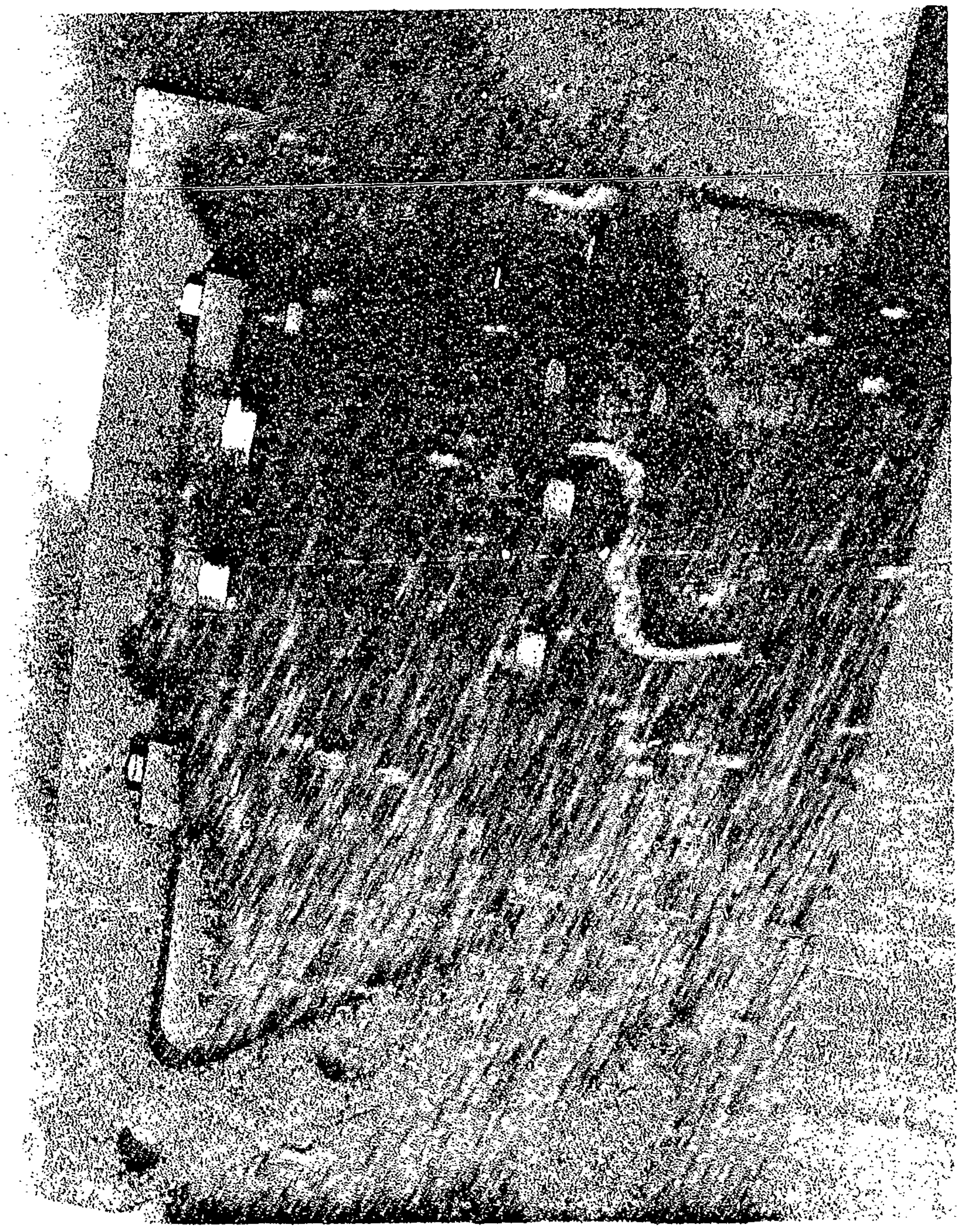

Fig. 8 — USRD type F58 transducer mounted in support bracket

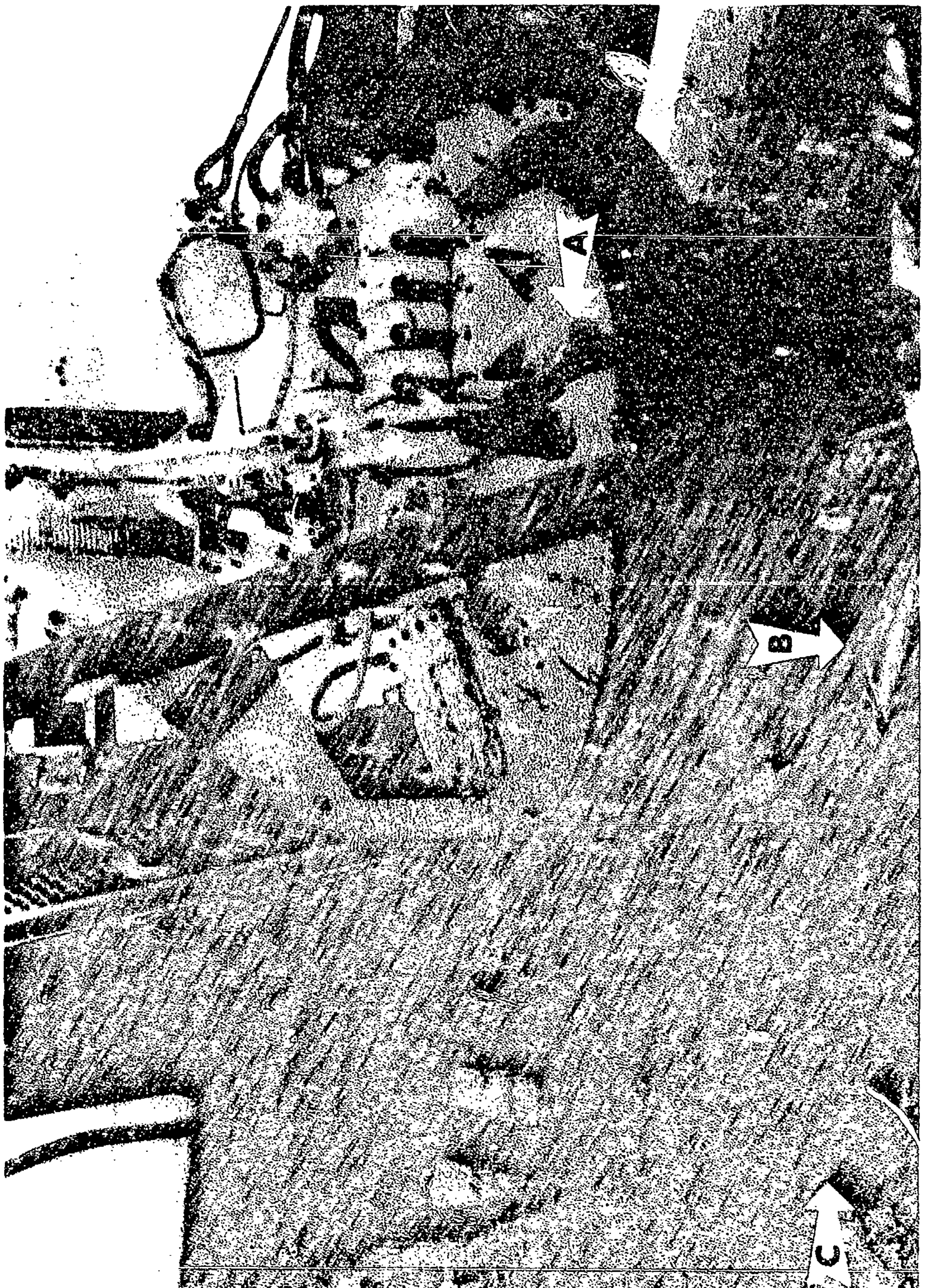

Fig. 9 — VIBROSEIS source with outrigger (A), tow cable (B), and hydrophone H_1 (C)

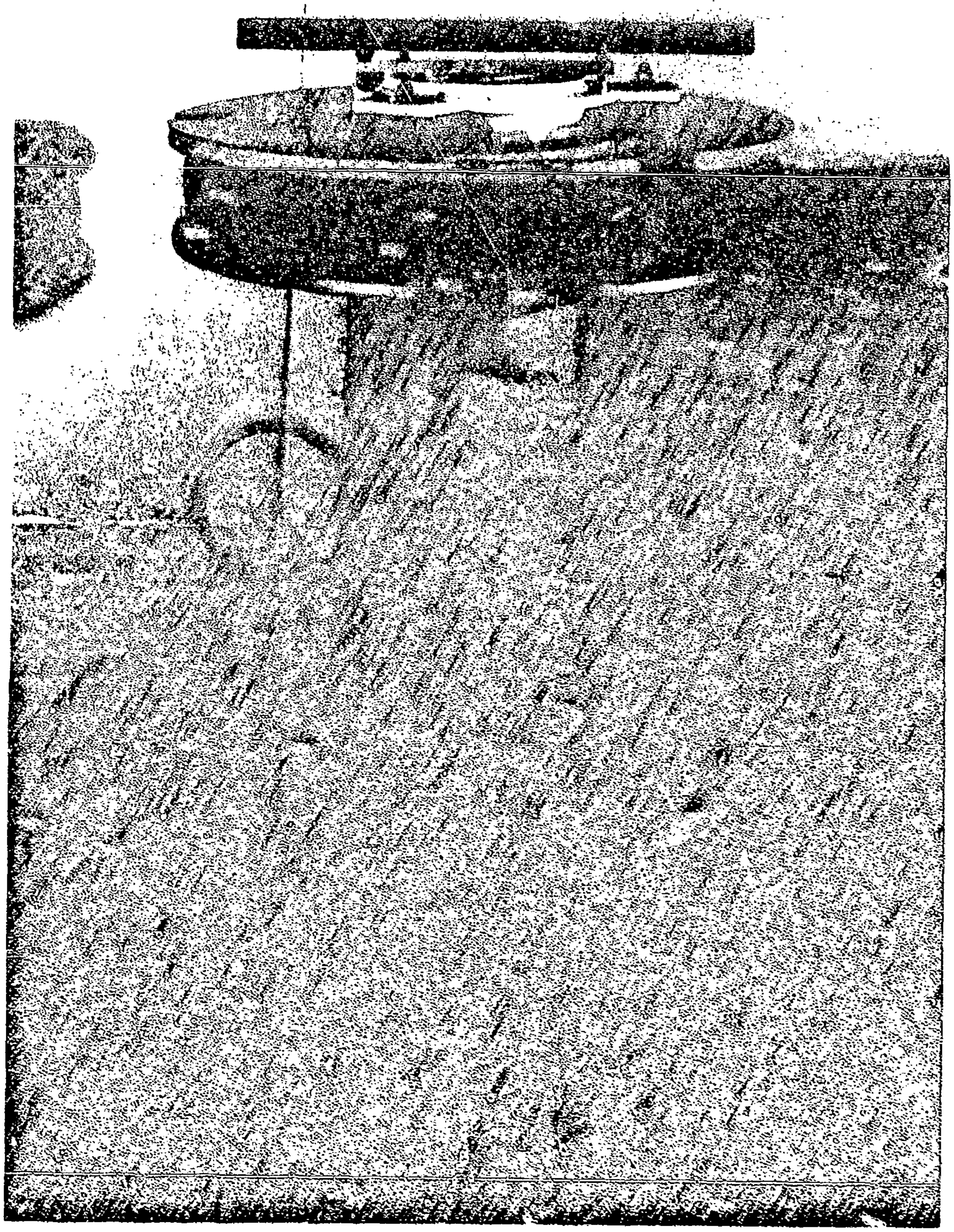

Fig. 10 — USRD type G40 snipboard calibrator

Successful calibrations of the monitor hydrophones and associated system were carried out at sea in the frequency range of 10 Hz to 250 Hz. The calibration system provided a unique advantage in that recalibrations of the monitor hydrophones were readily accomplished when modifications to the measurement and control system were made affecting system gain.

Results

The hydrophones, vibration mounts, receive cables, and the calibrator were installed aboard the source ship, the MV AMERICAN DELTA II, and the measurements required to meet the problem objectives were made.

To obtain data for the determination of the hydrophone spacing, the hydrophone outputs were sampled several times at chosen frequencies between 5 and 250 Hz so that mean and standard deviation values for t and t' could be obtained at each frequency point. Taking a minimum of eight samples at each frequency, mean values for t and t' were 0.734 and 1.207, respectively with corresponding standard deviations of 0.036 and 0.055. Using equation (6), these values yield a separation, X_3, of 1.26 m (49.72 inches) or 2.0 dB re 1 m (2.8 dB re 1 yard).

One requirement of the method used was that the outputs of the tow hydrophones be sampled simultaneously in each of the two towed configurations. In practice, this reqirement could not be met by the measurement system in use, and it is uncertain how much this affected the somewhat larger than expected deviations.

It can be shown (from the physical dimensions of the source and the geometry of Figure 3) that in order to meet the original assumption about the probable location of the source's acoustic center, the fixed separation between the hydrophone and the acoustic center, X_3 must be between 1.04 m (40.8 inches), the distance from the hydrophone to the geometric center C_G, and 1.3 m (51.4 inches), the distance from the hydrophone to the outer surface of the lower piston. Our measured value of 2.0 dB re 1 m would tend to indicate that the acoustic center is very near the surface of the lower piston; that is, the upper piston is approaching a "clamped" condition. In practice this does, in fact, seem to be true.

Conclusions

A system has been designed and implemented to accurately monitor source level and calibrate a low audio frequency sound source such as the VIBROSEIS system at sea. This system has effectively measured the position of the acoustic center of the source, minimized the effects on source level measurement by the sea surface boundary, and provided vibration isolation to the source mounted hydrophone.

Acknowledgement

Thanks go to Mr. Lloyd Hill for constructing the hydrophones and vibration mounts for this system.

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[4] G. D. Hugus and I. D. Groves, "Hydrophone Calibrator for Shipboard Use," J. Acoust. Soc. Am. 56, 70-74 (1974).

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55	Weinstein, M. S., et al.	SUS QUALITY ASSESSMENT, SQUARE DEAL	Undersea Systems, Inc.	750207	ADA007559; ND	U
BKD2380	Unavailable	WESTLANT 74 PHASE 1 DATA SUMMARY (U)	B-K Dyanmics, Inc.	750301	NS; ND	U
TM-SA23-C44-75	Wilcox, J. D.	MOTION MODEL VALIDATION FROM LRAPP ATLANTIC TEST BED DATA	Naval Underwater Systems Center	750317	ND	U
RAFF7412; 74-482	Scheu, J. E.	SQUARE DEAL SHIPPING DENSITIES (U)	Raff Associates, Inc.	750401	ADC003198; NS; ND	U
PSI TR-004018	Barnes, A. E., et al.	ON THE ESTIMATION OF SHIPPING DENSITIES FROM OBSERVED DATA	Planning Systems Inc.	750401	~~ND~~ AD 096582	U
NUSC TD No.4937	LaPlante, R. F., et al.	THE MOORED ACOUSTIC BUOY SYSTEM (MABS)	Naval Underwater Systems Center	750404	ADB003783; ND	U
USI 460-1-75	Weinstein, M. S., et al.	SUS SIGNAL DATA PROCESSING (U) INVESTIGATIONS CONDUCTED UNDER THE DIAGNOSTIC PLAN FOR CHURCH ANCHOR AND SQUARE DEAL SHOT DATA (U)	Underwater Systems, Inc.	750414	ADC002353; ND	U
Unavailable	Ellis, G. E.	SUMMARY OF ENVIRONMENTAL ACOUSTIC DATA PROCESSING	University of Texas, Applied Research Laboratories	750618	ADA011836	U
Unavailable	Edelblute, D. J.	OCEANOGRAPHIC MEASUREMENT SYSTEM TEST AT SANTA CRUZ ACOUSTIC RANGE FACILITY (SCARF)	Lockheed Missiles and Space Co., Inc.	751015	ADB007190	U
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Unavailable	Hampton, L. D.	ACOUSTIC BOTTOM INTERACTION EXPERIMENT DESCRIPTION	University of Texas, Applied Research Laboratories	760102	ADA021330	U
PSI-TR-036030	Turk, L. A., et al.	CHURCH ANCHOR: AREA ASSESSMENT FOR TOWED ARRAYS (U)	Planning Systems Inc.	760301	ND	U
NUC TP 419	Wagstaff, R. A., et al.	HORIZONTAL DIRECTIONALITY OF AMBIENT SEA NOISE IN THE NORTH PACIFIC OCEAN (U)	Naval Undersea Center	760501	ADC007023; NS; ND	U
NRL-MR-3316	Young, A. M., et al.	AN ACOUSTIC MONITORING SYSTEMS FOR THE VIBROSEIS LOW-FREQUENCY UNDERWATER ACOUSTIC SOURCE	Naval Research Laboratory	760601	ADA028239; ND	U
ARL-TR-75-32	Ellis, G. E.	SUMMARY OF ENVIRONMENTAL ACOUSTIC DATA PROCESSING	University of Texas, Applied Research Laboratories	760705	ADA028084; ND	U
Unavailable	Unavailable	SUMMARY OF ENVIRONMENTAL ACOUSTIC DATA PROCESSING	University of Texas, Computer Science Division	761013	ADA032562	U
TTA83676285	Unavailable	ANALYSIS PLAN FOR NARROWBAND/ NARROWBEAM AMBIENT NOISE (U)	Tetra Tech, Inc.	761112	ADC008275; NS; ND	U
USI 564-1-77	Wallace, W. E., et al.	REPORT OF CW WORKSHOP. NORDA, BAY ST. LOUIS, MISS., 28-29 SEPT 1976	Underwater Systems, Inc.	770124	ND	U