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A HYDROPHONE FOR MEASURING ACOUSTIC AMBIENT NOISE IN THE OCEAN AT LOW FREQUENCIES (USRD TYPE H62)

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A low-frequency, pressure-sensitivity hydrophone with an open-circuit crystal voltage sensitivity of -178 dB re 1 V/μPa and a sensor capacitance of 2000 pF to provide low self noise has been developed for use at depths to 5516 m. The self-contained batteries and low-noise preamplifier are protected from high pressure and seawater by a vinyl-covered aluminum housing. Changes in the free-field voltage sensitivity are less than 1.5 dB at hydrostatic pressures to 55.16 MPa (8000 lb/in.^{2}) in the frequency range 10 to 2000 Hz.

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Introduction

Acoustical measurements made in the ocean depend upon the hydrophone for signal detection and accurate recording of events. If only detection of the signal is required and not the sound pressure levels or phase, a very simple sensor can be used. Most acoustical measurements, however, are concerned with the received sound-pressure level and possibly its phase. Then it is not sufficient merely to detect the signal. A calibrated sensor element whose electroacoustic characteristics are as nearly independent of time, temperature, or hydrostatic pressure as possible must be used. The sensitivity as a function of environmental conditions can be determined from calibration measurements made at hydrostatic pressures and temperatures that simulate the actual environment.

The hydrophone to be described was designed to meet the general specifications provided by the user. Quantitative values were not provided in all instances because the exact values were not known. High sensor capacitance was desired to obtain low self-noise. It was thought that a minimum value of 2000 pF would be adequate although a higher capacitance was requested. There were conflicting demands on the preamplifier pressure housing. An inside diameter of 5.0 cm was required for the preamplifier and batteries yet the housing was to be lightweight and strong enough to withstand 55 MPa (8000 psi) hydrostatic pressure. Because the hydrophone would be supported frequently by buoys, weight was an important design consideration. These hydrophones were to be used in varied problems in both shallow and deep water with different preamplifier and power requirements. Therefore, the pressure housing for the preamplifier and battery power source was designed to permit opening in the field, thus precluding a design that would completely seal the hydrophone in an elastomer covering to protect it from corrosive forces.

Other requirements for the sensor in addition to the low self-noise included a free-field voltage sensitivity greater than -179 dB re 1 V/μPa, with changes in sensitivity due to temperatures between 0 and 25°C and hydrostatic pressure at depths to 5516 m not to exceed 2 dB. The design includes a mount for the sensor to minimize the response to acceleration along the longitudinal axis and provisions for setting the low frequency cut-off of the sensor to predetermined values. The sensor must provide anomaly-free response characteristics over the passband 1 to 2000 Hz.

Most of these requirements have been met in the USRD type H62 hydrophone shown in Fig. 1. This general design can be used to satisfy other measurement requirements, such as different sensitivities and source capacitances, by enclosing the appropriate number of sensors in the same acoustic boot and combining their outputs in series or parallel as required to raise or lower the sensitivity and the self-noise of the hydrophone.

Fig. 1. USRD type H62 hydrophone.

Design Considerations

Accurate acoustical measurements in the ocean require hydrophones with the same stability and acoustical characteristics as those of laboratory standards. The type H62 hydrophone was designed to maintain these characteristics over wide ranges of temperature and hydrostatic pressure, and to be exceptionally rugged for the protection of the sensitive elements against the hazards of the ocean environment. Principal construction features that make this possible are shown in Fig. 2.

Sensor Design

Physical characteristics of the ferroelectric ceramic PZT-5H, particularly its high dielectric constant of 3400, appeared desirable for the design of high-capacitance, low-impedance sensor elements with the high sensitivity required for low equivalent noise pressure; however, data on its performance at high pressures were considered inadequate. Because most electromechanical parameters change in a logarithmic manner after the poling of the ceramic, a supply of PZT-5H cylinders that had been poled several years earlier provided a good source for a well-aged element for the capped-tube sensor.

The active element of the sensor is a 5-cm-o.d. by 5-cm-long by 3.18-mm-wall PZT-5H ceramic cylinder capped at each end with a stainless steel disk 5 cm in diameter and 6.25 mm thick. Steel was preferable to aluminum in

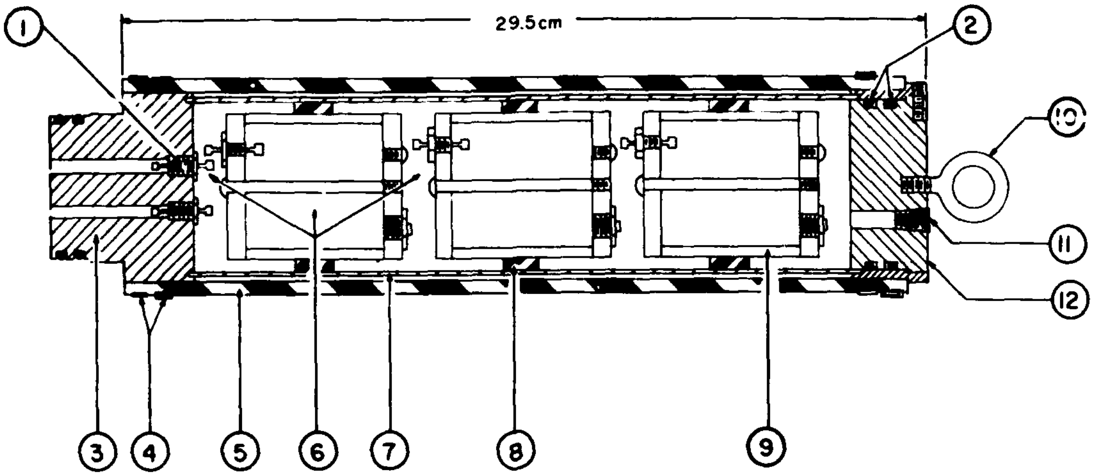


Fig. 2. Principal design features of H62 hydrophone: (1) glass-to-metal seal, Fusite 105 TB-FP; (2) O-rings; (3) anodized aluminum; (4) punch-lok clamp, SST 316; (5) butyl rubber boot; (6) Baker's DB grade castor oil; (7) expanded aluminum; (8) rubber mount; (9) ceramic sensor element; (10) eyebolt, SST 304; (11) oil filler plug; (12) anodized aluminum end plate.

the end caps because of its higher Young's modulus and lower coefficient of linear thermal expansion. The capped cylinder has maximum sensitivity when the end caps are very rigid [1] and the likelihood of a fracture at the bond between the end caps and the ceramic cylinder, or of the ceramic itself, is reduced by selecting the materials to be bonded so that their coefficients of linear thermal expansion are very nearly the same [2].

Preliminary acoustical and electrical measurements made on an early design of a capped, oil-filled PZT-5H ceramic cylinder revealed that its sensitivity changed no more than 1.5 dB when subjected to hydrostatic pressures to 55.16 MPa (8000 lb/in.^{2}). This design proved to be stable in the temperature range 0 to 25°C despite changes in capacitance with changes in temperature.

To achieve maximum stability, the sensor was designed with an orifice to permit equalization of the internal hydrostatic pressure with that of the external seawater [3]. The orifice is a drilled hole in one of the end caps to provide a passageway for the coupling fluid. Maximum sensitivity of a capped ceramic cylinder is obtained when the end caps are very rigid, the ceramic cylinder is not restrained by the caps, and the cylinder is filled with air. When the cylinder is filled with castor oil, the sensitivity of the element decreases 3.5 dB.

The orifice serves as a high-pass acoustic filter; its size determines the low-frequency characteristics of the sensor element. When a lower cutoff frequency is required (in this case, the frequency at which the sensitivity decreases 3 dB), the diameter of the orifice is reduced to increase the acoustic resistance. Because this resistance is a function of the coupling fluid viscosity, as well as a function of the length and radius of the orifice, the cutoff frequency is a function of the oil temperature. Effects of temperature on cutoff frequency caused by changes in the viscosity of castor oil are shown in Fig. 3.

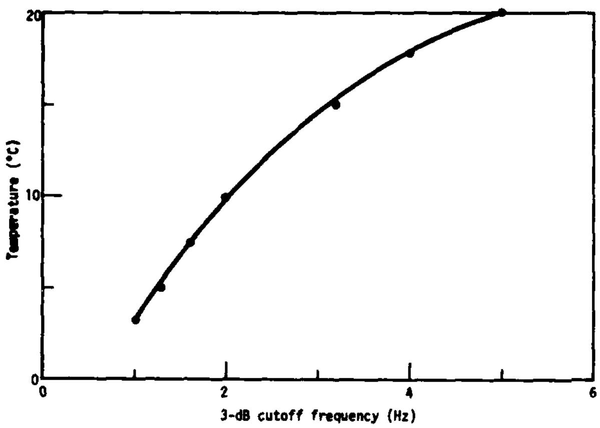


Fig. 3. Change in cutoff frequency caused by change in viscosity of castor oil.

The effects of both hydrostatic pressure and temperature on viscosity must be considered in computing the cutoff frequency. Figure 4 shows the change in cutoff frequency produced by the combined effects of temperature and pressure. It is evident that the ranges of environmental temperature and hydrostatic pressure must be known when designing a sensor for a specific cutoff frequency.

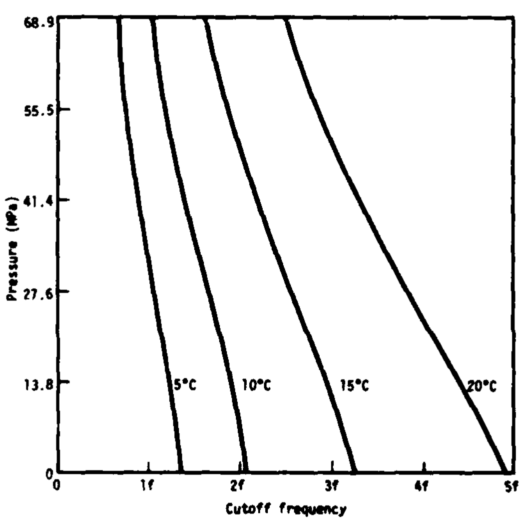


Fig. 4. Cutoff frequency of H62 hydrophone as a function of temperature and pressure (f is cutoff frequency, 3-dB-down point, set at 5°C and 34.5 MPa).

Radius a of the orifice is determined from the following equations:

$$RC_v = 1/2\pi f, \tag{1}$$

$$R = 8\eta \ell_0/\pi a^4, \tag{2}$$

where R is the acoustic resistance of a small orifice [4], C_v is the acoustic compliance of the oil volume inside the ceramic element ($C_v = V/\beta$), f is the desired cutoff frequency (3 dB down), V is the internal volume of the sensor element, β is the bulk modulus of the castor oil, η is the viscosity of the oil, and ℓ_0 is the length of the orifice.

Combining Eqs. (1) and (2) and solving for a gives

$$a = 2(f\eta\ell_0 V/\beta)^{\frac{1}{4}}. \tag{3}$$

One of the stainless steel end caps was drilled and tapped to receive interchangeable threaded plugs, in each of which was drilled a different size precision orifice to permit installation of any required orifice after the cylinders were filled with oil. Orifice size computations are presented in Appendix A.

Acceleration Sensitivity

The manner of mounting the ferroelectric ceramic cylinders largely determines their sensitivity to axial acceleration [5]. Figure 5 shows the results of acceleration measurements made on an H62 hydrophone in which three capped PZT-5H sensor elements were mounted in the expanded

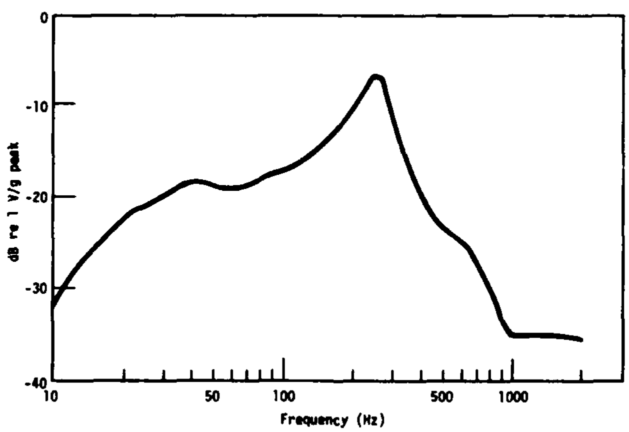


Fig. 5. Acceleration sensitivity of the type H62 hydrophone, measured parallel to the longitudinal axis (sensitivity of sensor, -177 dB re 1 V/μPa).

metal frame. Each element was supported by a single rubber ring positioned at the center of the outer surface of the ceramic cylinder and cemented to both this surface and the inner side of the frame. This is one of the simplest possible designs for mounting the sensitive elements, and it greatly facilitates construction.

Hydrophone Sensitivity

This type of hydrophone can be assembled with one, two, or three sensor elements connected electrically in series to produce sensitivities ranging from -194 to -184.5 dB re 1 V/μPa. To obtain the higher sensitivity that was required of the H62, the electrodes were divided into three equal pairs of cylindrical bands by removing two thin rings of the inner and outer electrodes as shown in Fig. 6. When the nine pairs of electrodes of three sensor elements are connected in series, the theoretical increase in sensitivity is 19 dB; however, this increase usually is not realized in practice because of the physical limitations such as shunt capacitances between adjacent sections and between each section and the metal frame. The capacitance of the nine series-connected sections seen by the preamplifier is 2000 pF, which is adequate for low self-noise performance.

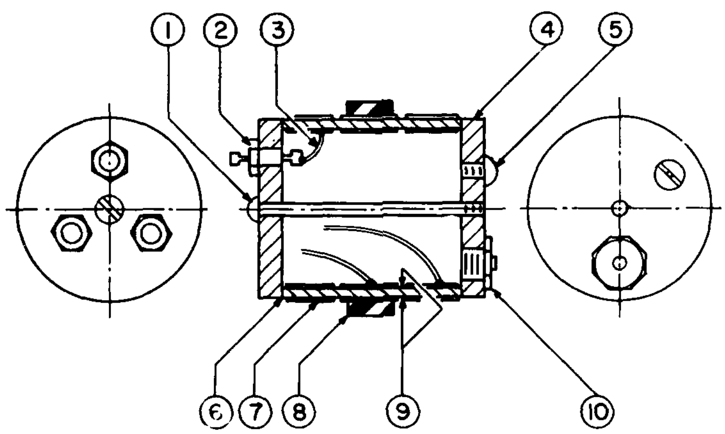


Fig. 6. Construction details for the capped ceramic cylinder used as a sensor element in the H62 hydrophone: (1) tie bolt; (2) glass-to-metal seal; (3) hookup wire; (4) end cap, SST 303; (5) orifice plug; (6) Epon VI epoxy cement; (7) silver electrode; (8) rubber mount, type W neoprene; (9) electrode removed inside and outside; (10) relief valve, Alemite No. 47640.

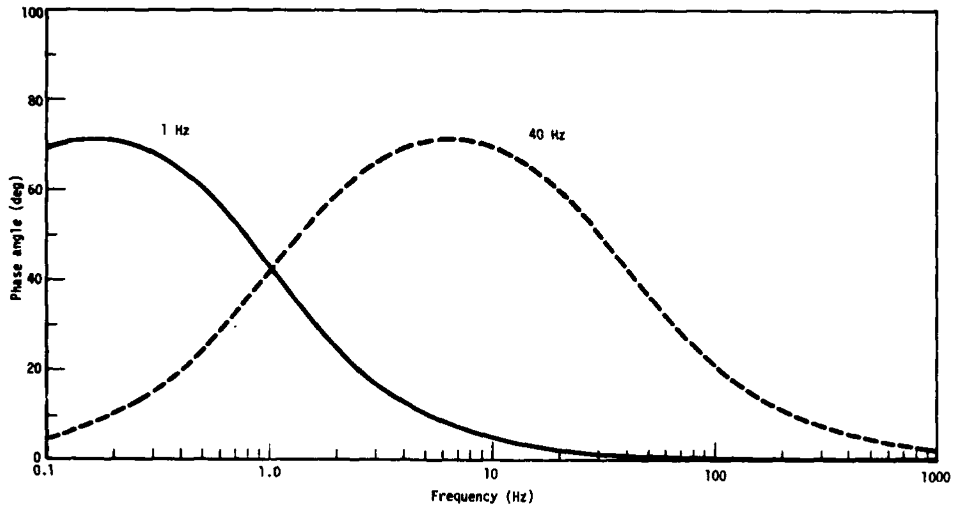


Fig. 7. Phase difference between H62 hydrophone output voltage and the sound pressure at the hydrophone with sensor elements compensated by small orifice to give 1- and 40-Hz cutoff.

Phase Angle

When measurements are to be made with an array of two or more hydrophones, the hydrophones should be designed to have the same cutoff frequency to preclude the appearance of out-of-phase signals near the cutoff frequency. Figure 7 illustrates the phase angle differences between the signals of two H62 hydrophones whose cutoff frequencies are 1 Hz and 40 Hz.

If hydrophones with different cutoff frequencies must be used, an alternate method would be to use an orifice small enough to place the cutoff frequency for all of the hydrophones initially much lower than that required for the measurements and then adjust the cutoff frequencies for each hydrophone with a suitable shunt resistor. A higher noise level may result for the combined RC network, but in some circumstances it is the best alternative. Because large voltages can be produced by changes in temperature and pressure as a transducer is lowered into or raised from the ocean, a resistor or some other protective device usually is required to prevent damaging the preamplifier input transistor. This resistor can be used also to change the cutoff frequency.

Self-Noise Considerations

Every electrical component is a potential noise source. The list includes passive components as well as transistors, tubes, and the like. The three main types of noise usually considered in the design of electronic devices are thermal noise, low-frequency (1/f) noise, and shot

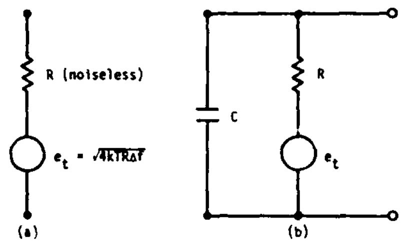


Fig. 8. Equivalent circuits: (a) thermal noise element; (b) parallel RC network.

noise. Only thermal noise will be discussed here, but it should be noted that the 1/f noise of tubes, transistors, diodes, and resistors is important at low frequencies.

For analytical purposes every element that generates thermal noise is represented by an equivalent circuit composed of a noise voltage generator in series with a noiseless resistance as shown in Fig. 8a. The noise generator has an rms voltage e_t equal to $(4kTR\Delta f)^{1/2}$, where R is the resistance of the real part of a conductor's impedance, k is Boltzmann's constant, T is the temperature of the conductor in Kelvin, and Δf is the noise bandwidth of the measuring system in hertz.

It is evident from the expression above that noise voltage is proportional to the square root of the absolute temperature and the frequency bandwidth, but is independent of the band center location. Reactive components do not generate thermal noise but the resistance is defined as the real part of their complex impedance.

Crystal and capacitor hydrophones can be represented by an equivalent parallel resistor-capacitor circuit as shown in Fig. 8b. In shunting the resistor, the capacitor limits the noise voltage, especially that of the higher frequency components. The volume resistivity and the leakage resistance of the ferroelectric ceramic are relatively high and may be of the order of 10^{12} Ω or higher. In most practical circuits the controlling resistance is attributed to the input impedance of the associated amplifier or to a resistor introduced to adjust the lower cutoff frequency of the circuit. This resistance can be used also to limit the voltage buildup that may be produced across the sensor by changes in temperature or pressure. Practical resistance values usually range from 10^5 Ω to 10^{10} Ω and capacitance values range from as low as 100 pF to as high as 75 nF.

The self-noise produced by the piezoelectric hydrophone is given by

$$e_{tot} = \left[4kT \int_{f_1}^{f_2} R(f)df\right]^{1/2}, \tag{4}$$

where f_1 and f_2 are the limiting frequencies of the passband, and T is the temperature in Kelvin. In the parallel RC circuit,

$$R(f) = \frac{R}{1 + (\omega CR)^2} , \qquad (5)$$

where $\omega = 2\pi f$, C is the capacitance, and R is the parallel resistive component.

The self-noise produced by a crystal or capacitor hydrophone can be obtained by substituting Eq. (5) in Eq. (4) and integrating between the limits f_1 and f_2 to obtain

$$e_{tot} = (2kT/\pi C)^{\frac{1}{2}} \left[\tan^{-1}(\omega_2 CR) - \tan^{-1}(\omega_1 CR)\right]^{\frac{1}{2}} , \qquad (6)$$

where e_{tot} is the rms open-circuit voltage in the total band between f_1 and f_2, k is the Boltzmann gas constant (1.37×10^{-23} J/K), and $\omega_1 = 2\pi f_1$, $\omega_2 = 2\pi f_2$.

Figure 9 shows the noise voltage for a 1-Hz bandwidth when the resistance is 0.8, 100, and 2000 MΩ and the capacitance in parallel with the resistor is 2000 pF. Lower resistance values can produce lower noise voltage at frequencies below that at which the capacitive reactance equals the resistance; however, the sensitivity of the sensor element will decrease by 6 dB per octave below this frequency also. When low-frequency information is not required, it usually is better to use a high-pass filter

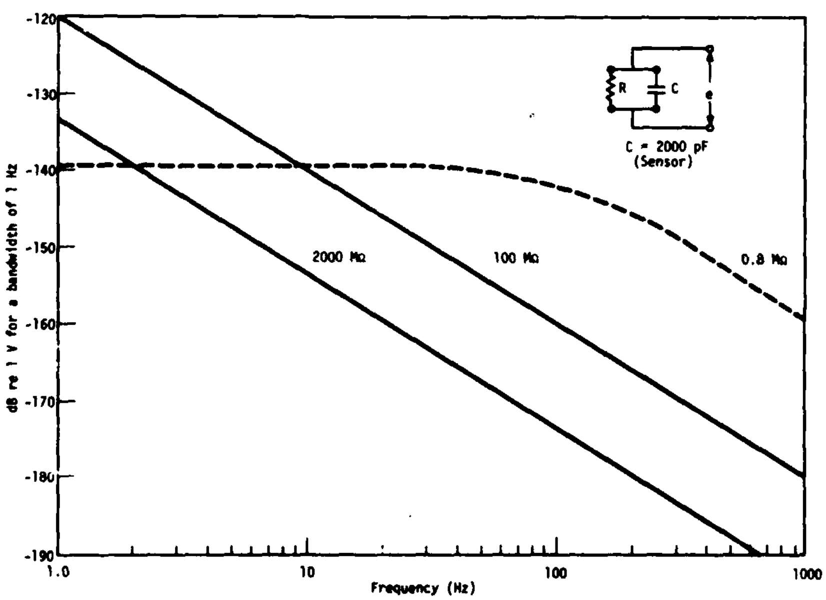


Fig. 9. Noise voltage produced in a 1-Hz bandwidth by a parallel resistance-capacitance combination equivalent to the ceramic sensor shunted by a resistor.

or a preamplifier designed to roll off at the low frequencies. When a hydrophone is designed to operate at frequencies much lower than is required for the measurements, the preamplifier may be overloaded by low-frequency ambient noise or other sources of sound.

Preamplifier

Several different preamplifier designs have been developed for use in the H62 hydrophone. Preamplifiers and battery packs were provided by NRL Code 8108 to be used in hydrophones constructed for their requirements. The USRD has developed one preamplifier that affords a gain of +10, 0, or -10 dB at the user's option. It has a high input impedance, requires a low current of 0.5 mA (for long battery life), and has an output impedance

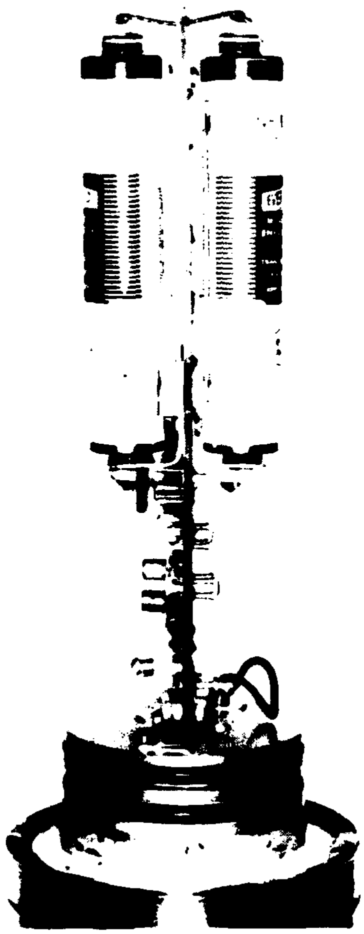


Fig. 10. USRD preamplifier used with the H62 hydrophone.

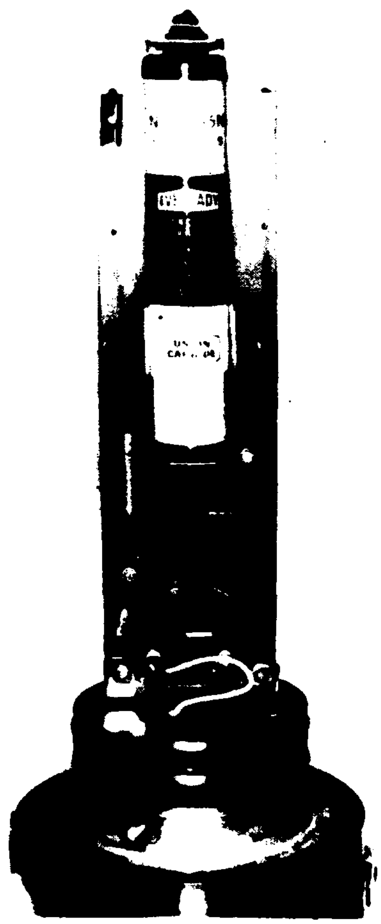
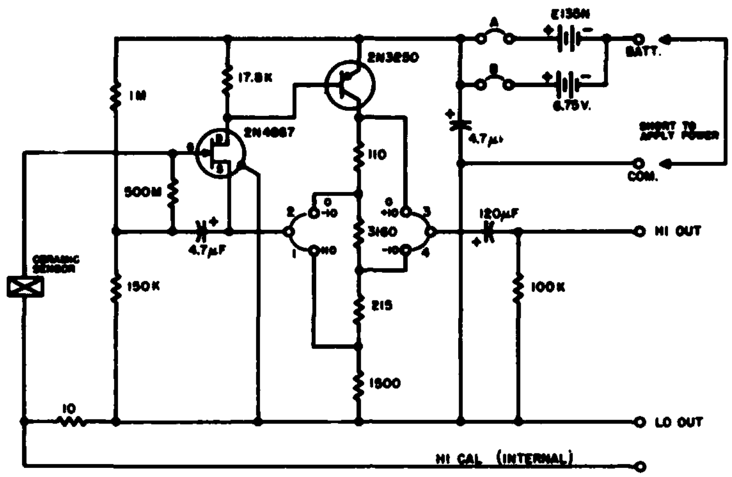


Fig. 11. USRD preamplifier viewed from circuit board component side.

of less than 10 kΩ, which is suitable for operation into a line driver or multiplexer unit. Figures 10 and 11 show the USRD preamplifier and batteries; Fig. 12 is a diagram of the electronic circuit. Only one battery is required for operation; the second battery can be used as a spare or can be connected in parallel with the other battery.



Notes:
1. Jumpers "A" and "B" activate one or both batteries.
2. Jumpers "1" and "3" cause gain of +10 dB.
3. Jumpers "2" and "3" cause gain of zero dB.
4. Jumpers "2" and "4" cause gain of -10 dB.
5. Important: Turn off battery power before moving jumpers.

Fig. 12. Electronic circuit used to provide +10, 0, and -10 dB voltage gain in USRD preamplifier.

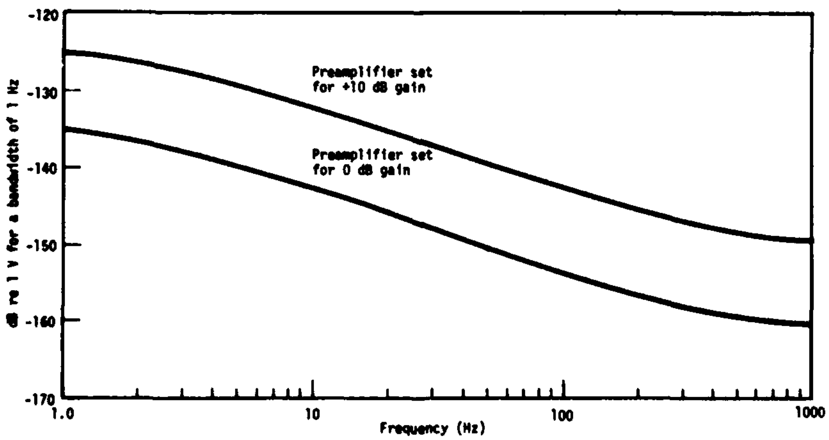


Fig. 13. Noise voltage measured at the output of the H62 hydrophone preamplifier with a source capacitance of 3300 pF and a resistance greater than 500 MΩ.

The self-noise voltage was measured at the output of the USRD preamplifier for each of the three gain settings with a 3300-pF sensor element connected to the input. Typical values of the noise voltage in a 1-Hz bandwidth for the gain settings of +10 and 0 dB are shown in Fig. 13. Noise could not be measured accurately with the -10-dB gain setting because this level was nearly the same as that of the electronic equipment used to make the measurements.

Figure 14 shows the equivalent noise pressure of a type H62 hydrophone (with USRD preamplifier) whose sensor element capacitance is 3300 pF and whose open-circuit crystal sensitivity is -180 dB re 1 V/μPa. The lower limit of ambient noise in the ocean as given by Wenz [6] is considerably higher than the curve for the hydrophone; thus, the hydrophone is not the limiting factor in ocean noise measurements. The ambient noise at Knudsen sea state zero is included to show its relative level.

Mechanical Design

All metal components, including the expanded metal that encloses the sensors, were made of aluminum to minimize weight and galvanic action. Figure 15 shows the sensors in an expanded metal frame made from 0.040-in.-thick aluminum stock. If greater strength and easier welding are desired, 0.060-in.-thick stock can be used. Types 6061-T6 and 7075-T6 anodized aluminum are used for all parts that will contact water. Additional protection against corrosion for the preamplifier housing is provided by covering it with shrinkable vinyl tubing that prevents nicks and scrapes in the anodized surface.

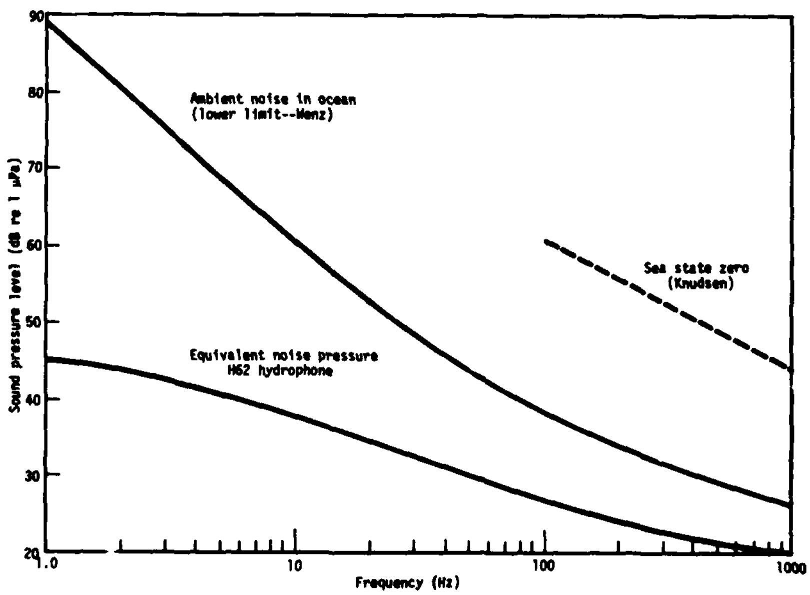


Fig. 14. Equivalent noise pressure of the H62 hydrophone when equipped with a USRD preamplifier and a sensor whose open-circuit crystal sensitivity is -180 dB re 1 V/μPa with a capacitance of 3300 pF.

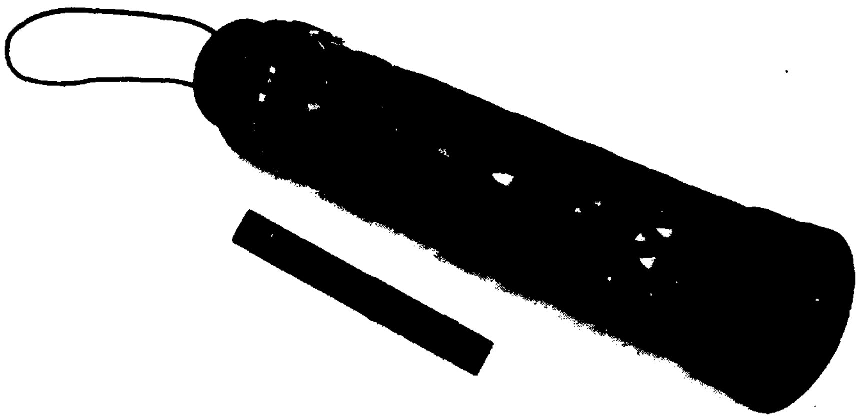


Fig. 15. Sensor head with the three ceramic cylinders mounted in the expanded aluminum tube.

Each end of the preamplifier housing is sealed by two O-rings, one of which is redundant to prolong the life of the hydrophone in case crevice corrosion occurs at the groove of the outer O-ring. In early models of the H62 hydrophone, three stainless-steel cap screws were used at each end of the housing to secure the cable gland assembly and sensor head; in newer models, the cap screws are made of nylon to eliminate a potential source of corrosion and to facilitate opening the hydrophone.

Oil-Filling the Sensor Elements

When two or three ceramic cylinders are mounted in the same sensor head, their proximity necessitates filling the cylinders with oil before cementing them in place in the support frame. The cylinders are individually filled in the conventional manner, which consists of immersing them in an open pan of castor oil in a vacuum chamber. After all the air in the cylinders is displaced by oil, special care is required to prevent the intrusion of any air during subsequent assembly and mounting operations. Orifices and relief valves are installed after releasing the vacuum but while the cylinders are still submerged in the oil. Then the pan and its contents are placed in a freezer and cooled to 15°C. When the oil-filled cylinders are removed from the pan at this temperature, it takes an hour or so for them to warm up to room temperature. During this time the oil expands and some of it bleeds slowly from the orifice, preventing air from entering the sensor while it is being cleaned, wired, mounted in the support frame, and sealed in an oil-filled butyl rubber boot. This technique was extremely effective in the preparation of 42 hydrophones that contained a total of 126 individual cylinders, all of which were successfully calibrated without any evidence of trapped air.

Hydrophone Characteristics

Two groups of H62 hydrophones were designed with two different specific cutoff frequencies to meet program requirements of NRL Code 8108. Eight hydrophones were constructed with 0.132-cm-diameter orifices (made with a No. 55 drill) to provide a 10-Hz cutoff at 0°C and 0 Pa. Thirty-two units were constructed with 0.081-cm-diameter orifices (made with a No. 67 drill) to provide a 1-Hz cutoff at 0°C and 34.5 MPa (5000 lb/in.^{2}).

Average free-field voltage sensitivities for these two groups of hydrophones are shown in Figs. 16 and 17. Average free-field voltage sensitivity of 10 hydrophones with 1-Hz cutoff frequency that were calibrated

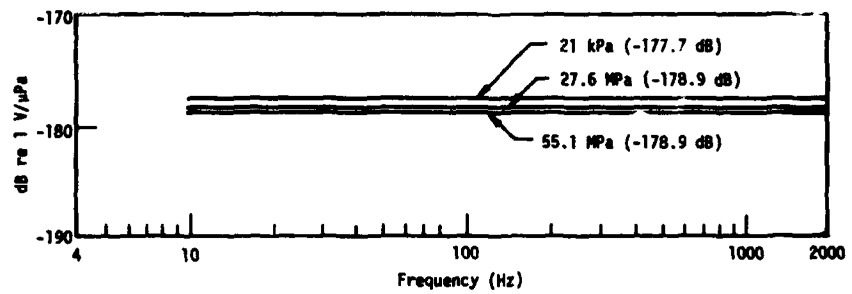


Fig. 16. Free-field voltage sensitivity of H62 hydrophone with 1-Hz cutoff at 3°C.

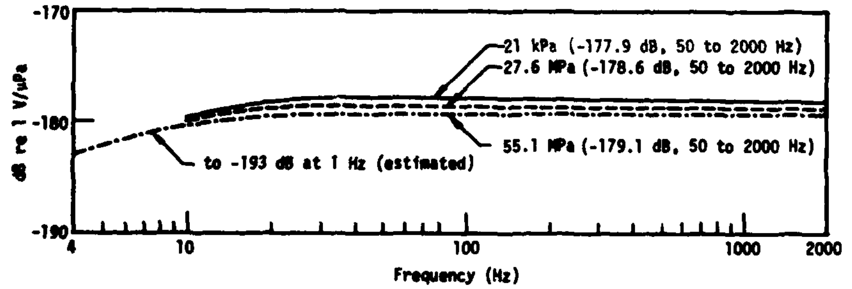


Fig. 17. Free-field voltage sensitivity of H62 hydrophone with 10-Hz cutoff at 3°C (average of serials 1Y through 8Y).

to 1 Hz is shown in Fig. 18. Figure 19 shows the effect of temperature on cutoff frequency of the hydrophones whose cutoff frequency was designed to be 10 Hz at 3°C, but which becomes 30 Hz at 20°C. Performance characteristics were relatively independent of hydrostatic pressure up to 55.1 MPa at the temperatures 3° and 20°C. Calibration measurements at frequencies below 10 Hz are limited to a maximum pressure of 6895 kPa (1000 lb/in.^{2}) by the USRD Low Frequency Facility equipment. Measurements can be made to a pressure of 68.95 MPa (10,000 lb/in.^{2}) in the frequency range 10 to 4000 Hz. Sensitivities of the individual hydrophones serials 1Y through 42Y have been published in a USRD Calibration Report [7].

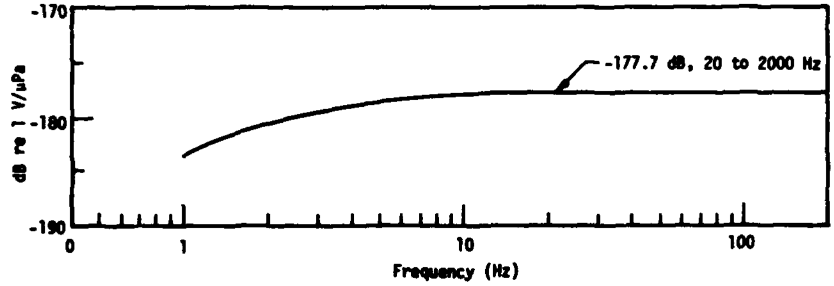


Fig. 18. Free-field voltage sensitivity of H62 hydrophones with 1-Hz cutoff at 3°C under the pressures 21 kPa and 6.89 MPa.

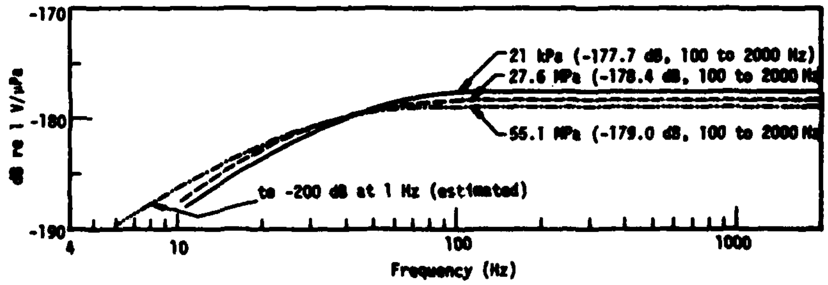


Fig. 19. Free-field voltage sensitivity of H62 hydrophone with 30-Hz cutoff at 20°C (average of serials 1Y through 8Y).

Field Evaluation

Postrecovery visual inspection of two H62 hydrophones that had been operated continuously while submerged in the ocean for several months showed them to be in nearly new condition, and postcalibration measurements were in good agreement with those made a year earlier. Other units have been deployed to depths of 5 km with equally good results. The expanded aluminum used for the sensor support frame appeared to be the weakest mechanical component of this model of hydrophone; in future models, the sensor support frame will be made of a heavier gage aluminum or stainless steel. Some corrosion observed on the aluminum pad eyes at the top of the hydrophones is believed to be the result of galvanic currents. Because corrosion was not found on all the hydrophones, it may have occurred only where metals other than aluminum passed through the pad eyes. Corrosion was found in the aluminum end plug of hydrophones that were exposed to strong ocean currents. The severity of galvanic corrosion of most metals, particularly aluminum, when not adequately protected clearly indicates that any metal hydrophone parts and supporting equipment should be made of the same materials wherever possible and should be further protected with a plastic or elastomer coating.

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References

[1] G. W. McMahon, "Sensitivity of Liquid-Filled, End-Capped, Cylindrical Ceramic Hydrophones," J. Acoust. Soc. Amer. 36, 695-696 (1964).

[2] I. D. Groves, Jr., "Thermal Shock Test of Capped Piezoelectric Ceramic Tubes," NRL Memorandum Report 2379, 24 Jan 1972 [AD-736 920].

[3] E. T. O'Neill, "Pressure-Balanced High-Pressure Hydrophone," J. Acoust. Soc. Amer. 34, 1661-1662 (1962).

[4] L. L. Beranek, *Acoustics* (McGraw-Hill, New York, 1954), p. 135.

[5] E. T. O'Neill, "Hydrophone Development at Hudson Laboratories," Columbia Univ., Hudson Labs. Technical Report No. 108, 24 Sep 1963.

[6] G. M. Wenz, "Acoustic Ambient Noise in the Ocean: Spectra and Sources," J. Acoust. Soc. Amer. 34, 1936-1956 (1962).

[7] H. J. Hebert, Jr., "Calibration of USRD Type H62 Hydrophones Serials 1Y through 42Y," USRD Calibration Report No. 3420, 3 Jul 1972.

Appendix A

Computation of Orifice Sizes for Stainless Steel End Caps of H62 Sensor Elements

1-Hz Cutoff Frequency at 0°C and 34.5 MPa

The required orifice size is readily determined from the expression derived in the Design Section of this report:

$$a = 2(f\eta \ell_0 V/\beta)^{\frac{1}{4}} \quad (3)$$

where η is the viscosity of castor oil (9.525 $N \cdot s/m^2$ at 0°C and 34.5 MPa), ℓ_0 is the length of the orifice (6.35×10^{-3} m), V is the internal volume $\pi r^2 \ell$ of the ceramic cylinder (inside radius r is 0.0222 m and length ℓ is 0.0508 m; $V = 7.865 \times 10^{-5}$ m^3), and β is the bulk modulus of castor oil (2.82×10^9 N/m^2 at 0°C). Then

$$a = \left[(1)(9.525)(6.35\times10^{-3})(7.865\times10^{-5})/(2.82\times10^9)\right]^{\frac{1}{4}}$$

$$= 4.05\times10^{-4} \text{ m}$$

$$= 0.0159 \text{ in.,}$$

and the diameter of 0.0318 in. is approximated by that of a No. 67 orifice drill (0.032 in.).

10-Hz Cutoff Frequency at 0°C and 0 Pa

Determination of the orifice size required for a 10-Hz cutoff frequency is identical to the preceding calculation except for substitution of the new frequency and the changed values of the physical properties of castor oil at 0°C and 0 Pa, $\eta = 5.73$ $N \cdot s/m^2$ and $\beta = 2.34 \times 10^9$ N/m^2. Then

$$a = \left[(10)(5.73)(6.35\times10^{-3})(7.865\times10^{-5})/(2.34\times10^9)\right]^{\frac{1}{4}}$$

$$= 0.6656\ 10^{-3} \text{ m}$$

$$= 0.0262 \text{ in.,}$$

and the diameter 0.0524 in. is approximated by that of a No. 55 orifice drill (0.052 in.).