NRL Report 7260

High-Pressure Piezoelectric Ceramic Hydrophone for Infrasonic and Audio Frequencies

USRD Type H48

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Abstract

A pressure-sensitive reference hydrophone for the frequency range 0.3 Hz to 20 kHz at hydrostatic pressure to 68.9 megapascals (10,000 psi) and temperature from 0 to 30°C has been developed by the Naval Research Laboratory, Underwater Sound Reference Division. The nominal open-circuit crystal sensitivity of the hydrophone is −199 ± 1 dB re 1 V/μPa from 1 Hz to 20 kHz; the output of the lead zirconate-titanate spherical element is increased by a transistorized, 10-dB-gain preamplifier. A novel cable gland improves the high-pressure reliability of the hydrophone.

Problem Status

This is an interim report on the problem.

Problem Authorization

NRL Problem S02-31

Project RF 05-111-401-4472

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HIGH-PRESSURE PIEZOELECTRIC CERAMIC HYDROPHONE FOR INFRASONIC AND AUDIO FREQUENCIES

USRD TYPE H48

Introduction

Until the type H48 hydrophone was developed, a calibration standard had not been available for the low-frequency USRD System J [1] for use at pressure above 17 megapascals (17 MPa, approximately 2500 psi). Development of the H48 has produced a comparison standard that can be used in System J to its maximum hydrostatic pressure 68.9 MPa (approximately 10,000 psi) and in the similar System K to 6.89 MPa. It is useful in other systems in the frequency range 0.3 Hz to 20 kHz. The hydrophone can be calibrated by reciprocity to 68.9 MPa in the USRD high-pressure coupler [2] by using a simple adapter.

Design Considerations

Construction

The hydrophone is shown assembled in Fig. 1 and in section in Fig. 2; it is an omnidirectional, pressure-sensitive standard consisting of the

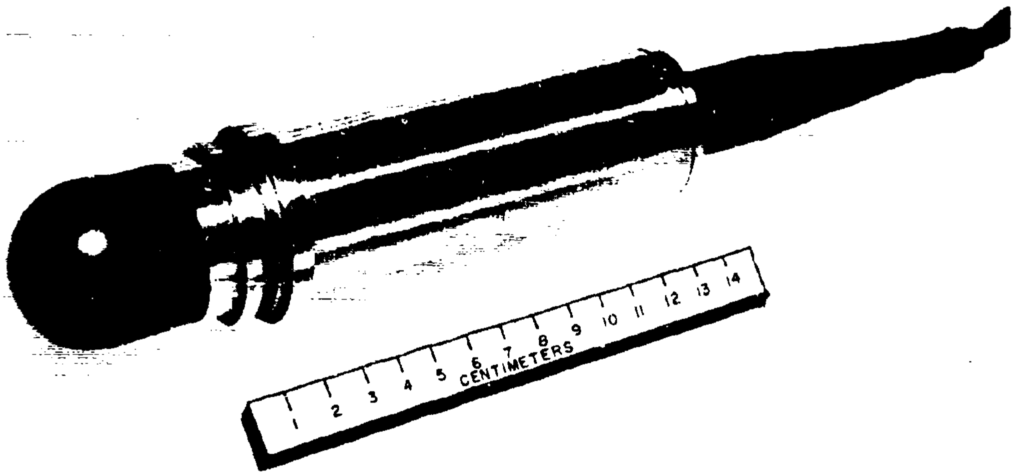

Fig. 1. USRD type H48 high-pressure hydrophone for infrasonic and audio frequencies.

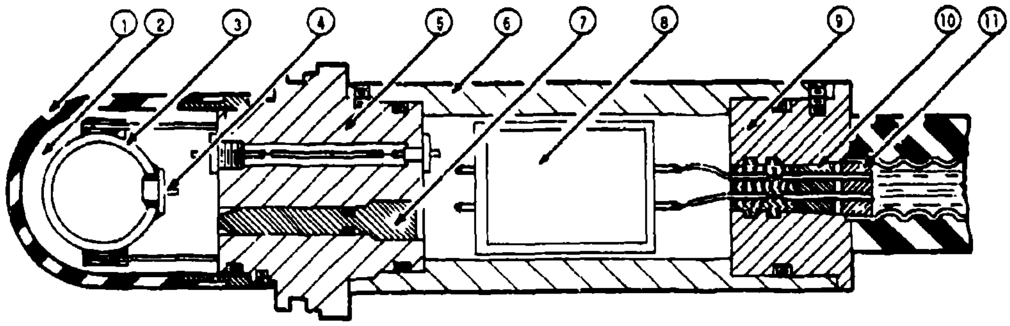

Fig. 2. Sectional view, type H48 hydrophone: (1) butyl window; (2) castor oil; (3) sensitive element; (4) glass-to-metal seal; (5) mounting plug; (6) housing; (7) oil plug; (8) transistorized preamplifier; (9) cable plug; (10) cable terminal; (11) cable spacer.

sensitive element, a transistorized preamplifier, and a high-pressure cable gland, all assembled as a unit within a stainless-steel housing that resists corrosion and withstands high pressure. The element is attached to a mounting plug by butyl rubber mounts and is enclosed in a butyl rubber boot filled with castor oil. This method of mounting reduces the acoustical coupling between the element and the housing; the castor oil serves as the coupling medium between the element and the boot. Diffraction caused by proximity of the element and the housing does not limit the usefulness of the hydrophone except at frequencies higher than 20 kHz.

Sensitive Element

The element, shown in Fig. 3, consists of a 2.54-cm-diam sphere with 0.317-cm-thick wall. A lead zirconate-titanate sphere was chosen for the sensitive element because of (1) its stability at high pressure, (2) its high capacitance, which minimizes coupling loss at low frequency, and (3) the high sensitivity that can be attained. The electrical connection to the electroded inside surface of the sphere passes through a glass-to-metal seal secured by a high-strength epoxy adhesive. Glass-to-metal seals also connect the high- and low-signal leads from the sphere to the preamplifier unit in the adjacent section.

Preamplifier

The transistorized preamplifier provides a nominal 10-dB gain (Fig. 4) to the output of the element. The input impedance of the preamplifier is 1000 MΩ shunted by 15 pF capacitance; the output impedance is 35 Ω in series with 100 pF. The power required is 4.5 mA at 12 V d-c.

Cable Gland Assembly and Case

The stainless-steel (type 316) housing and the novel cable gland design provide adequate strength for hydrostatic pressure to 68.9 MPa.

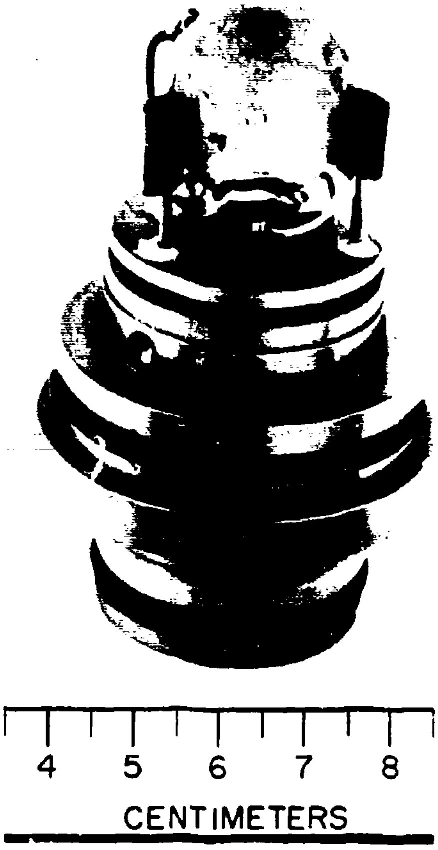

Fig. 3. Spherical lead zirconate-titanate element on type H48 mounting plug.

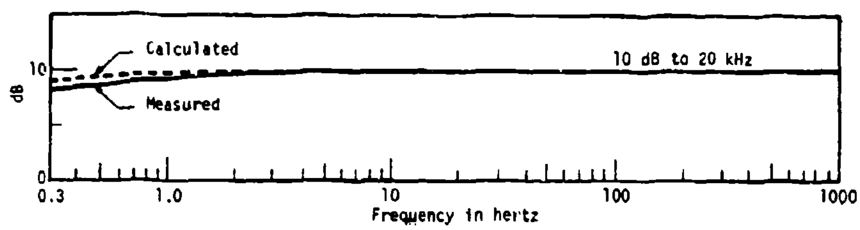

Fig. 4. Type H48 hydrophone voltage coupling gain (ratio in decibels of voltage at preamplifier output to open-circuit crystal voltage).

A section of the housing and gland is shown in Fig. 5. The cable gland consists of a swaged ferrule with a high-pressure protective tapered cable terminal that joins the 4-conductor shielded cable to the preamplifier assembly. This design is very effective, because the seal becomes tighter as the hydrostatic pressure increases.

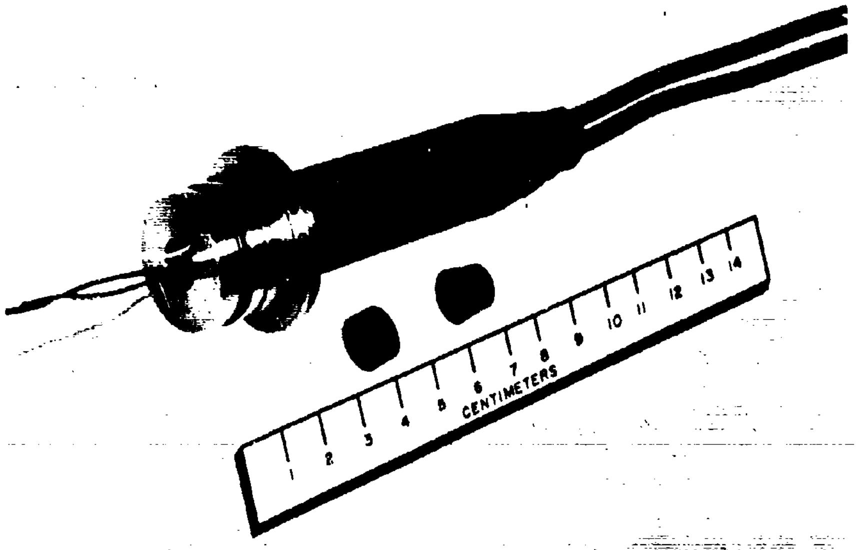

Fig. 5. Cable plug with (shown externally) cable spacer and tapered cable terminal.

Acoustic Window Material

The acoustic window of the H48 is made of H862A butyl rubber developed by the Naval Applied Science Laboratory especially for long-life hydrophones. The high-pressure coupler in which the H48 is calibrated cannot accommodate a large element, so both the size of the window and its hemispherical shape are important.

Theory

Sensitivity

The open-circuit sensitivity of the ceramic sensor element in the flat region of the characteristic curve is [3]

$$M_0 = \frac{b}{\eta^2 + \eta + 1}\left(\frac{\eta^2 + \eta - 2}{2} g_{33} - \frac{\eta^2 + \eta + 4}{2} g_{31}\right) \quad (1)$$

where b is the outside radius, a is the inside radius, $\eta = a/b$, and g_{31} and g_{33} are the piezoelectric voltage constants--the ratio between the field strength induced and the stress applied--of the ceramic material.

The appropriate values for Eq. 1 are: $g_{33} = 23\times10^{-3}$ V·m/N, $g_{31} = -11\times10^{-3}$ V·m/N, $a = 0.9525\times10^{-2}$ m, $b = 1.27\times10^{-2}$ m, and $a/b = 0.75$. When the substitution is made and the result is expressed in decibels, we obtain M_0 = -198.6 dB re 1 V/μPa, which is in excellent agreement with the measured value -198.2 dB re 1 V/μPa.

Low-Frequency Cutoff

An important specification in hydrophone design is the low-frequency cutoff--the frequency at which the end-of-cable sensitivity drops by 3 dB from its nominal value and thereafter continues to drop at the rate 6 dB/oct. The low-frequency cutoff is determined by the time constant of the RC circuit consisting of the parallel combination of the blocked capacitance C_b and the input resistance R_b of the sensitive element, and the input resistance R_a and shunt capacitance C_a of the preamplifier. Other leakage resistances and stray capacitances are lumped into one of these parameters.

The low-frequency cutoff is given by

$$f_{-3dB} = \frac{R_a + R_b}{2\pi (C_a + C_b)(R_a R_b)} . \quad (2)$$

Substituting in Eq. 2 the specification values for the element and for the particular preamplifier (R_a = 1 GΩ, R_b = 100 GΩ, C_b = 4600 pF, and C_a = 15 pF), we get f_{-3dB} = 0.035 Hz. Extrapolation of the measured data from 0.3 Hz yields the 3-dB-down point at approximately 0.08 Hz, indicating that the input resistance of the preamplifier probably is less than that specified.

Operating Characteristics

When the hydrophone is oriented in the left-handed coordinate system defined in "American Standard Procedures for Calibration of Electroacoustic Transducers, Particularly Those for Use in Water, Z24.24-1957," the geometrical center of the sphere is at the origin of coordinates and the longitudinal axis of the housing coincides with the Z axis. In Systems J or K, sensitivity is measured along this axis; in open-water calibration, sensitivity is measured along the X axis, and the serial number scribed on the housing serves as the reference mark in the direction of the +X axis.

Free-Field Voltage Sensitivity

Figure 6 provides a typical end-of-cable calibration of the type H48 hydrophone at 0 (atmospheric) pressure. The sensitivity is -188.0 ± 1.0 dB re 1 V/μPa from 1 Hz to 20 kHz. The nominal open-circuit element voltage is -198 ± 1.0 dB throughout the range. Change in sensitivity caused by temperature in the range 0 to 30°C is negligible. Variation with pressure

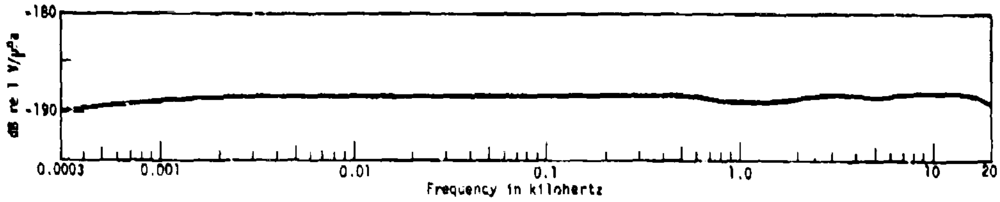

Fig. 6. Typical free-field voltage sensitivity, type H48 hydrophone; open-circuit voltage at end of 9-m cable.

to 34.5 MPa is within ±0.1 dB. The sensitivity at 68.9 MPa is approximately 1 dB lower than that at 34.5 MPa.

Noise Voltage and Equivalent Noise Pressure

The noise voltage shown in Fig. 7 was measured with General Radio wave analyzer model 1554A through an 80-dB-gain low-noise amplifier. The equivalent noise pressure of Fig. 8 follows from the relation

$$p_{en} = e_{en}/M_0, \tag{3}$$

where, at a given frequency, p_{en} is the equivalent noise pressure in micropascals, e_{en} is the rms noise voltage in a band 1 Hz wide, and M_0 is the free-field voltage sensitivity in volts per micropascal. For example, at 1000 Hz,

$$20 \log p_{en} = -245.0 - (-189.0) = -156.0 \text{ dB re } 1\ \mu\text{Pa}.$$

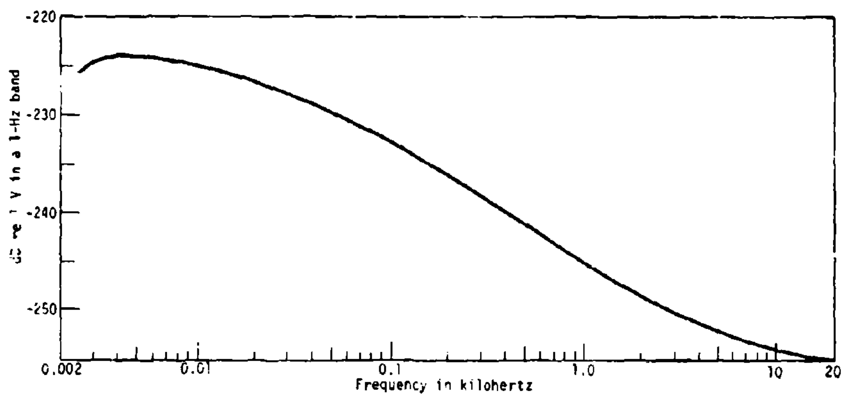

Fig. 7. Noise voltage, type H48 hydrophone; 9-m cable.

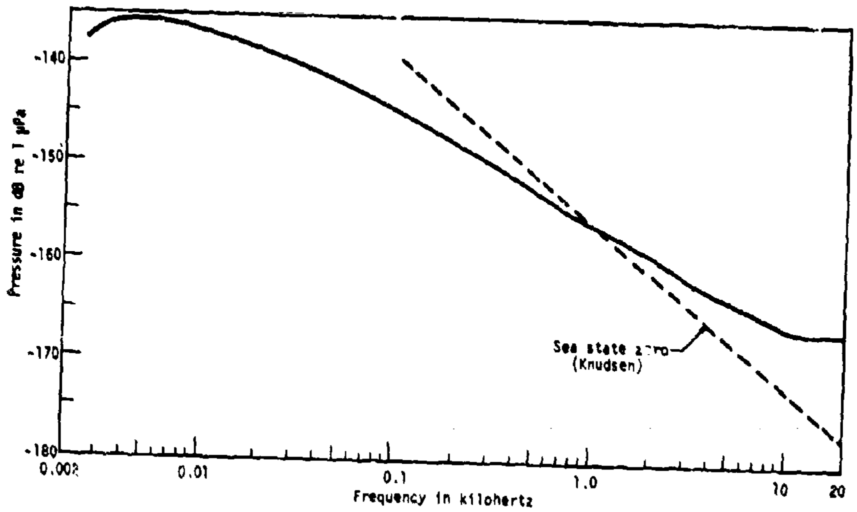

Fig. 8. Equivalent noise pressure, type H48 hydrophone.

Directional Characteristics

Directivity patterns in the XZ plane are shown in Fig. 9. The breakup in the patterns starting at 10 kHz is caused by diffraction from the hydrophone housing; however, it does not limit the usefulness of the hydrophone in the low-frequency measurement system.

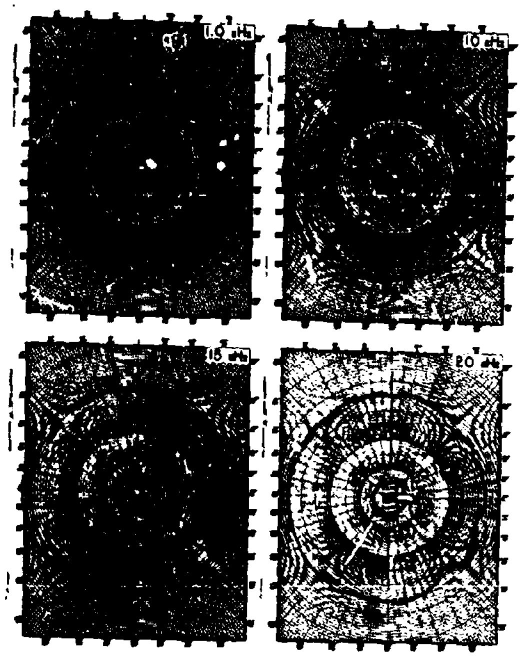

Fig. 9. Directivity patterns in the XZ plane, type H48 hydrophone; center to top of grid, each pattern, equals 50 dB.

Conclusion

The USRD type H48 hydrophone is a stable laboratory standard for infrasonic and audio-frequency measurements. The end-of-cable sensitivity provides extremely high signal-to-noise ratio in closed-tank facilities with very-low-frequency sources. The H48 is particularly useful at USRD because its design permits it to be calibrated by reciprocity in the USRD high-pressure coupler [2] for use in the low-frequency, high-pressure systems J and K.

Acknowledgment

The author acknowledges the invaluable suggestions contributed by R. J. Kieser, Head, Development and Design Section, and T. A. Henriquez, Research Physicist, Standards Branch, toward the design of the hydrophone.

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2. C. C. Sims and T. A. Henriquez, "Reciprocity Calibration of a Standard Hydrophone at 16 000 psi," J. Acoust. Soc. Amer. 36, 1704-1707 (1964).

3. A. A. Anan'eva, *Ceramic Acoustic Detectors* (Consultants Bureau, New York, 1965), p. 46.

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13. ABSTRACT

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Page 6, equation immediately above Fig. 7 should read:

$$20 \log p_{en} = -145.0 - (-189.0) = +44.0 \text{ dB re } 1\ \mu\text{Pa}.$$

Page 6, Fig. 7, change the ordinate scale to read, beginning at the top: -120, -130, -140, -150.

Page 7, Fig. 8, change the ordinate scale to read, beginning at the top: +60, +50, +40, +30, +20.