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Standards Secretariat
Acoustical Society of America
335 East 45th Street
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AMERICAN NATIONAL STANDARD
Procedures for Calibration of Underwater Electroacoustic Transducers

ABSTRACT

This standard establishes measurement procedures for calibrating electroacoustic transducers and describes forms for presenting the resultant data. It is a revision of American National Standard S1.20-1972 (R1977). Both primary and secondary calibration procedures are specified for the frequency range from a few hertz to a few megahertz. Procedures are specified for determining the measurable characteristics of free-field sensitivity, transmitting response, directional response, impedance, dynamic range, equivalent noise pressure level, and overload pressure level. Equations are given for obtaining the derived characteristics directivity factor, directivity index, efficiency, theoretical equivalent noise pressure level, and quality factor (*Q*). A coordinate system and forms of data presentation are specified so that results may be readily compared and easily understood.

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FOREWORD

[This Foreword is not a part of American National Standard Procedures for Calibration of Underwater Electroacoustics Transducers, ANSI S1.20-1988 (Revision of ANSI S1.20-1972) (ASA Catalog No. 75-1988).]

This standard establishes measurement procedures for calibrating electroacoustic transducers and describes forms for presenting the resultant data. Both primary and secondary calibration procedures are specified for the frequency range from a few hertz to a few megahertz. A coordinate system and forms of data presentation are specified so that results may be readily compared and easily understood.

This standard was developed under the jurisdiction of Accredited Standards Committee S1, Acoustics, using the American National Standards Institute (ANSI) Accredited Standards Committee Procedures. The Acoustical Society of American holds the Secretariat for Accredited Standards Committee S1, Acoustics.

Accredited Standards Committee S1, Acoustics, under whose jurisdiction this standard was developed, has the following scope:

> Standards, specifications, methods of measurement and test, and terminology in the fields of physical acoustics, including architectural acoustics, electroacoustics, sonics and ultrasonics, and underwater sound, but excluding those aspects that pertain to safety, tolerance, and comfort.

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Working Group S1-9, Calibration of Underwater Electroacoustic Transducers, which assisted Accredited Standards Committee S1, Acoustics, in the development of this standard, has the following membership:

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J. E. Blue	W. P. Flaherty
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Suggestions for improvements in this standard will be welcomed. They should be sent to the Standards Manager, Standards Secretariat, Acoustical Society of America, 335 East 45th Street, New York, NY 10017-3483.

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American National Standard Procedures for Calibration of Underwater Electroacoustic Transducers

1 SCOPE

This standard establishes measurement procedures for calibrating underwater electroacoustic transducers and describes forms for presenting the resultant data. It is a revision of American National Standard S1.20-1972 (R1977).

2 PURPOSE

To establish procedures for the calibration of underwater electroacoustic transducers.

3 APPLICATIONS

3.1 Primary and secondary calibration procedures are specified for the frequency range from a few hertz to a few megahertz.

3.2 A coordinate system and forms of data presentation are specified so that results may be readily compared and easily understood.

3.3 Procedures are specified for determining the measurable characteristics of free-field sensitivity, transmitting response, directional response, impedance, dynamic range, equivalent noise pressure level, and overload pressure level. Equations are given for obtaining the derived characteristics directivity factor, directivity index, efficiency, theoretical equivalent noise pressure level, and quality factor (Q).

3.4 Underwater electroacoustic transducers can be divided into the following groups to show the reasons for these measurements:

Group 1—Sonar echo-ranging, active acoustic tracking, transponder, depth-sounding, communication, and object-locating transducers.
Group 2—Hydrophones, including hydrophone arrays and listening sonar used for noise measurements, propagation studies, and signal analysis.
Group 3—Standard transducers.
Group 4—Auxiliary projectors for measurement purposes.

3.4.1 Group 1 transducers operate at a single frequency or within a narrow to moderate range of frequencies, when efficiency is important. A single transducer or array is often used for both projecting and receiving. Some transducers are trainable relative to their mounting bracket and enclosure, but most are instead equipped with an electronic scanning device. Large transducers belonging to this group are usually enclosed in a dome.

Commonly measured characteristics of these transducers are transmitting response, free-field sensitivity, impedance, and directional response. Efficiency, directivity index, mechanical Q, and acoustic power output are computed. Equivalent noise pressure level, overload pressure level for the normal operating duty cycle, and impedance under pulsing conditions sometimes are required. A description of the performance of auxiliary equipment such as scanning switches and domes may require special types of directional response patterns as defined in 4.4.

Operating conditions may require that measurements be made over a range of temperature and pressure. Hysteretic effects caused by any varying ambient conditions also should be measured.

3.4.2 Group 2 transducers are usually broadband and usually are designed for minimum self-noise. They may be omnidirectional or directional for measurement of ambient noise. They may be highly directional when used for passive or listening sonar. To minimize self-noise, they may contain a premplifier or transformer for reducing impedance and noise in the electrical circuit.

Commonly measured characteristics of transducers in this group are free-field voltage sensitivity, directional response patterns, and equivalent noise pressure level. Operating conditions may require measurements over a range of temperature and hydrostatic pressure. The hydrophone voltage coupling loss [see 7.18 of American National Standard Acoustical Terminology (Including Mechanical Shock and Vibration), S1.1-1960 (R1976)] may be required. Both magnitude and phase of the sensitivity as a function of frequency may be required of elements of an array or for signal analysis.

3.4.3 Group 3 transducers are standard hydrophones and reciprocal transducers. Projectors are not often used as standards because a standard hydrophone usually will compensate better for any lack of free-field conditions, or, as expressed another way, projector output sound pressure level for a given voltage or current input is very dependent on boundary conditions.

Commonly measured characteristics of these transducers are free-field sensitivity, transmitting response, directional response patterns, impedance, and equivalent noise pressure level. The ranges of sound pressure and frequency within which the transducer is reciprocal must be determined. This sound pressure range is narrower than the dynamic range [see 7.19 of American National Standard S1.1-1960 (R1976)]. If the standard transducer is to be used under varying temperatures and hydrostatic pressures, then the effects of these variations on impedance, free-field sensitivity, transmitting response, and directional response, together with hysteretic effects, should be determined. If a standard hydrophone contains a preamplifier, a coupling loss measurement may be requested.

3.4.4 Transducers in Group 4 consist of projectors [see 6.65 of American National Standard S1.1-1960 (R1976)] that are used in comparison calibrations of hydrophones, directional response measurements, and measurements of the acoustic properties of media. These transducers should be stable at least throughout the period of measurement or the instabilities measured and compensated. Although the transmitting response, impedance, and directional response pattern over the operating range should be measured, a precise determination may not be required.

4 DEFINITIONS

4.1 Letter Symbols

Letter symbols used in this standard comply with those given in American National Standard Letter Symbols for Acoustics, Y10.11-1953 (R1959), American National Standard Acoustical Terminology, S1.1-1960 (R1976), and American National Standard Preferred Reference Quantities for Acoustical Levels, S1.8-1969 (R1974).

4.2 Terminology

Terminology used in this standard is based on definitions given in American National Standard S1.1-1960 (R1976).

4.3 Sonar Dome

An acoustically transparent, streamlined enclosure to minimize noise by reducing turbulence and cavitation that would otherwise occur about the transducer because of its passage through the water.

4.4 Terminology for Special Types of Directional Response Patterns

[See 7.4 of American National Standard S1.1-1960 (R1976).]

4.4.1 Conical Pattern

A description of the response of a transducer as a function of direction on a specified conical surface; the apex of the cone is at the effective acoustic center of the transducer.

NOTE: Although the line joining the measured transducer and the measuring transducer sweeps out a cone during the measurement, the pattern is plotted on a plane. A conical pattern becomes a conventional pattern when the apex angle of the cone is 180 deg.

4.4.2 Preformed Pattern

A description of the response as a function of direction for elements of a transducer or an array in fixed combination with a beam-forming electrical network that determines the phase and amplitude relationship between inputs or outputs of each of the elements of the transducer or the transducers in the array.

4.4.3 Scanning Pattern

The pattern obtained from a transducer and scanning device used for sound reception when the transducer is fixed with respect to a plane-progressive sound wave and the scanning device is operated.

NOTES:

(1) A scanning device is an electrical network that varies the relative phase and magnitude of the output of each of the elements of the transducer or array; it usually is connected to the array through a commutative device.

(2) A transducer with its scanning device may be used for transmitting sound.

4.4.4 Difference Pattern

The directional response of a split transducer [see 6.66 of American National Standard S1.1-1960 (R1976)] when the electrical outputs of the two halves are combined by phasor subtraction.

NOTE: A difference pattern usually will have two equal lobes with a null between them in the direction of the principal axis. The terminal connections to the transducer must be specified.

4.4.5 Sum Pattern

The directional response of a split transducer [see 6.66 of American National Standard S1.1-1960

(R1976)] when the electrical outputs of the two halves are combined by phasor addition.

NOTE: A sum pattern usually will have one major lobe in the direction of the principal axis (that is, the pattern of a nonsplit transducer). The terminal connections must be specified.

4.5 Open-Circuit Effective Bandwidth of a Specified Receiving System

The bandwidth of an ideal system that has (1) a constant free-field voltage sensitivity equal to the maximum sensitivity of the specified system, and (2) the same root-mean-square open-circuit voltage appearing at its terminals as does the specified system, when the two systems are receiving equal input signals having a uniform distribution of power at all frequencies.

5 PROCEDURES FOR MEASURING PERFORMANCE CHARACTERISTICS

5.1 Methods and Measurement Conditions

The choice of technique for primary calibration depends upon the frequency range to be covered. The free-field reciprocity method, using either continuous sinusoidal or pulsed sound waves, is adequate for most of the ultrasonic and audio-frequency range. A coupler reciprocity method is used to cover the infrasonic and lower audio-frequency range in which the longer wavelengths make it difficult to obtain a free field.

The secondary calibration methods require the use of a calibrated standard hydrophone to measure the sound pressure level. The hydrophone to be calibrated then is subjected to the same sound pressure level by substituting it for the standard hydrophone. An underwater sound projector is calibrated by means of the standard hydrophone and measurements of separation distance and relevant input voltage, current, or power.

When several characteristics of one transducer are measured, care should be taken that temperature, pressure, electrical grounding, acoustic load, etc., remain constant. Those conditions that affect the measurements must be specified.

All measured characteristics are assumed to be for the steady-state condition, unless specifically stated otherwise. When pulsed-sound techniques are used, the pulse duration and shape must be such that steady-state, free-field conditions are essentially realized.

5.2 Preparation of Transducers for Measurement

Transducers must be properly prepared for measurement to ensure an accurate calibration. It is especially important that all surfaces be clean and free of air bubbles.

5.2.1 Use of Wetting Agents

To ensure proper acoustic coupling of the transducer to the water, a wetting agent[1] should be applied to the active face of the transducer after it has been thoroughly cleaned and before it is immersed for acoustic stabilization (see 5.2.2). The efficacy of the cleaning operation can be determined by observing the meniscus while the transducer is being lowered into the water. Breaks in the meniscus are indicative of inadequantly cleaned areas. When a sonar dome is included, its inside and outside surfaces must also be thoroughly cleaned and treated with a wetting agent.

5.2.2 Acoustic Stabilization

Before any calibration measurements are made, the transducer should be placed in the water at the proper depth for a period of time sufficient for the transducer to attain temperature equilibrium with the medium. This procedure and that recommended in 5.2.1 should ensure a bubble-free active face.

The characteristics of some transducer materials are dependent on temperature. It is thus essential that temperature equilibrium be established and that the temperature be measured. The stability of the transducer response is one factor in determining temperature equilibrium.

5.3 Measurement of Sensitivity and Response-Audio and Ultrasonic Frequency Range

[See 1.12 and 1.13 of American National Standard S1.1-1960 (R1976).]

5.3.1 Test for Free Field

[See 4.6 of American National Standard S1.1-1960 (R1976).]

In a free field, the acoustic pressure produced by a projector at points sufficiently distant from the projector for spherical divergence (see 5.3.2.6.5) will vary inversely as the distance from the effective acoustic center [see 7.11 of American National Standard S1.1-1960 (R1976)] of the projector, provided correction is made for the attenuation due to absorption and scattering. This attenuation will not be significant at the usual separation distances of a few meters in fresh water up to 600 kHz and in saltwater up to 300 kHz. This "inverse-distance" law provides a test for free-field conditions. If this test and a calibration are to be valid, the magnitude of the signal-plus-noise must exceed the noise by a factor appropriate for the accuracy desired (at least 20 dB for about $\pm$ 1-dB error).

For transducer calibrations in the presence of reflecting boundaries, selection and orientation of the measuring and measured transducers can be such that their angular deviation loss [see 7.8 of American National Standard S1.1-1960 (R1976)] will minimize the effect of reflections. In some instances, such as measurements in a tank, the pulsed-sound technique may be required to produce an effective free field. In this method, a pulse of sound long enough to simulate steady state at the measured transducer is used with a gated receiving system for reception of the direct signal and suppression of all signals due to reflections (see Appendix A).

5.3.2 Procedures for Primary Calibrations of Free-Field Sensitivity and Transmitting Response

(See Appendix F, Reciprocity Theory.)

5.3.2.1 Requirements for a Reciprocal Transducer as a Basis of Reciprocity Calibrations

[See 6.6 and 7.30 of American National Standard S1.1-1960 (R1976).]

A reciprocal transducer must be linear, passive, and reversible. If two reciprocal transducers are coupled acoustically, the ratio of the driving current in the first transducer to the open-circuit voltage across the terminals of the second or receiving transducer, called the open-circuit transfer admittance, is equal to the ratio that would be observed if the functions of transmission and reception were reversed. If the transducers are identical in construction, they can be nonlinear to the same extent and yet seem reciprocal in this test, if one uses the same drive levels in the two cases. Before the first transducer can be presumed to be reciprocal, therefore, the test should be performed several times, using a different type for the second transducer each time.

5.3.2.2 Free-Field Voltage Sensitivity

[See 7.13 of American National Standard S1.1-1960 (R1976).]

The magnitude and phase of the free-field voltage sensitivity of an electroacoustic transducer can be determined by a three-transducer reciprocity calibration. Use of this procedure requires three transducers (a projector P, the hydrophone H to be calibrated, and a reciprocal transducer T that can be used as both a hydrophone and a projector). A series of three projector–hydrophone measurements is made using either P or T as a projector and H or T as a hydrophone. The measurements are made under free-field conditions with the hydrophone located in the farfield of the projector. The three experimental arrangements are indicated in Fig. 1. The input current and output voltage values are complex; i.e., they include both amplitude and phase. The input currents in arrangements 1 and 2 are chosen to be identical. In this case, i_P does not appear in the final expression for the sensitivity of the hydrophone and need not be measured.

For each arrangement the distance is that measured between acoustic centers. For arrangement 1, the farfield pressure p_{PH} produced at H, which is located d_1 meters from P, is

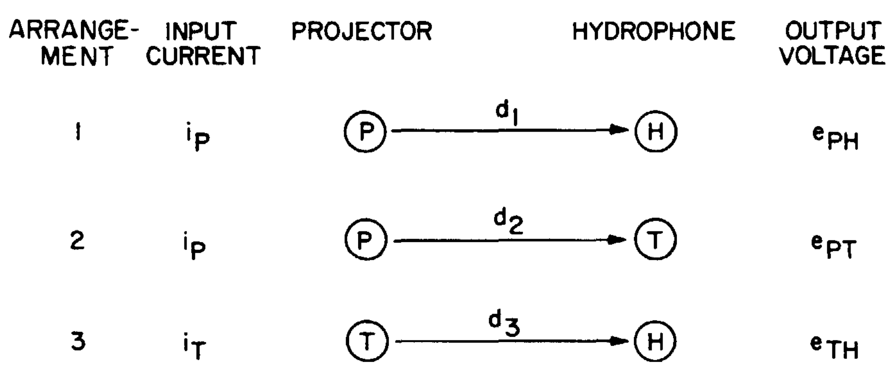

FIG. 1. Transducer arrangements for reciprocity calibration.

$$p_{PH} = [i_P(S_i)_P d_0/d_1]\exp[jk(d_0 - d_1)], \quad (1)$$

where $(S_i)_P$ is the transmitting current response of P, and d_0 is the reference distance, normally equal to 1 m, at which the transmitting pressure is specified in the definition of $(S_i)_P$. The wavenumber $k = \omega/c$, where ω is the angular frequency in radians per second and c is the sound speed of the surrounding medium in meters per second. The assumed time dependence $\exp(j\omega t)$ has been suppressed for convenience. The open-circuit voltage produced by H is given by

$$e_{PH} = (M_e)_H p_{PH} = [(M_e)_H i_P (S_i)_P d_0/d_1] \times\exp[jk(d_0 - d_1)], \quad (2)$$

where $(M_e)_H$ is the receiving voltage sensitivity of H.

Similarly, we obtain for arrangement 2

$$e_{PT} = (M_e)_T p_{PT} = [(M_e)_T i_P (S_i)_P d_0/d_2] \times\exp[jk(d_0 - d_2)], \quad (3)$$

where $(M_e)_T$ is the receiving voltage sensitivity of T. Combining Eqs. (2) and (3) yields

$$e_{PH}/e_{PT} = [(M_e)_H d_2/(M_e)_T d_1] \times\exp[jk(d_2 - d_1)]. \quad (4)$$

Since T is a reciprocal transducer, we have $(M_e)_T = J(S_i)_T$, where J is the complex spherical wave reciprocity parameter

$$J = (4\pi d_0/j\omega\rho)\exp(jkd_0) \quad (5)$$

and ρ is the density of the surrounding medium. From arrangement 3, we obtain

$$e_{TH} = (M_e)_H p_{TH} = [(M_e)_H i_T (S_i)_T d_0/d_3] \times\exp[jk(d_0 - d_3)]. \quad (6)$$

Combining Eqs. (4) and (6), with the use of Eq. (5), produces the following expression for the receiving voltage sensitivity of the hydrophone H:

$$(M_e)_H = \{[(4\pi e_{PH} e_{TH} d_1 d_3)/(j\omega\rho e_{PT} i_T d_2)] \times\exp[j(\omega/c)(d_1 + d_3 - d_2)]\}^{1/2}. \quad (7)$$

The SI derived pressure unit is the pascal (Pa) (1 Pa $=$ N/m^2). The derived unit of free-field voltage sensitivity $(M_e)_H$ is the volt per pascal. The free-field voltage sensitivity is expressed in decibels referenced to 1 V per micropascal. [See Sec. 4 of American National Standard Preferred Reference Quantities for Acoustical Levels S1.8-1969 (R1974).]

5.3.2.2.1 Magnitude of Free-Field Voltage Sensitivity. For many applications, one only needs to know the magnitude of the free-field voltage sensitivity of an electroacoustic transducer. This is a much easier measurement to make than one involving phase since positioning of the transducers is not as critical as for phase. For a magnitude only calibration, one can let $d_1 = d_2 = d_3 = d$ and ignore the phase of the complex spherical reciprocity parameter of Eq. (5). The magnitude of the free-field voltage sensitivity is then given by

$$|(M_e)_H| = \left|\frac{e_{PH}e_{TH}}{e_{PT}i_T} J\right|^{1/2} \quad (8)$$

5.3.2.2.2 Phase of Free-Field Voltage Sensitivity. The difficulty in determining the phase of $(M_e)_H$ by the reciprocity method lies in accurately determining both the sound speed and the measurement distances d_1, d_2, and d_3. For example, at 100 kHz in water, an error of only 1 mm in any one of the distances gives a phase error of about 12°. However, we can avoid this difficulty by positioning all three transducers P, H, and T in a straight line with H located between P and T.[2] This assures that $d_2 = d_1 + d_3$. Then Eq. (7) simplifies to

$$(M_e)_H = [(4\pi e_{PH} e_{TH} d_1 d_3)/(j\omega\rho e_{PT} i_T d_2)]^{1/2}. \quad (9)$$

Since the distances and sound speed no longer appear explicitly in a phase term in Eq. (9), the accuracy of the phase of $(M_e)_H$ calculated using Eq. (9) is limited only by the accuracy of the phase measurements of the voltages and current and by positioning. A special measurement framework that can minimize positioning errors is illustrated by Fig. 2. With this straight-line arrangement, a hydrophone which is omnidirectional in the horizontal plane can be calibrated with little phase error from positioning errors. The logistics for making the measurements are as follows:

(1) The transducers are mounted as shown in Fig. 2 with H facing toward P. The output voltage of H is measured with P being driven (e_{PH}).

(2) The hydrophone H and its hanger are removed from the framework. The output voltage of T is measured with P being driven (e_{PT}).

(3) The hydrophone and its hanger are replaced in the framework and positioned so that H faces toward T. The output voltage of H is measured with T being driven (e_{TH}).

(4) The input current to T (i_T) is measured.

After determining the four complex quantities e_{PH}, e_{PT}, e_{TH}, and i_T, Eq. (9) gives the desired amplitude and phase angle of the hydrophone sensitivity. This procedure yields the phase angle relative to the axis of rotation of the hydrophone hanger. Because of this and the presence of interference from unavoidable reflections from the hydrophone hanger, the hydrophone should be calibrated in the same hanger that will support it later when it is being used for measurements. The calibration is representative of both the hydrophone and the hanger.

5.3.2.3 Free-Field Current Sensitivity

[See 7.14 of American National Standard S1.1-1960 (R1976).]

In the arrangements shown in Fig. 1, measurements of projector current and open-circuit hydrophone voltage are replaced by measurements of the input voltage across the projector terminals and the output short-circuit current from the hydrophone and receiving transducer. The magnitude of the free-field current sensitivity is given by

$$|(M_i)_H| = \left| \frac{i_{PH} i_{TH}}{i_{PT} e_T} J \right|^{1/2}, \tag{10}$$

while the complex (amplitude and phase) free-field current sensitivity is given by

$$(M_i)_H = \{[(4\pi i_{PH} i_{TH} d_1 d_3)/(j\omega\rho i_{PT} e_T d^2)] \times \exp[j(\omega/c)(d_1 + d_3 - d_2)]\}^{1/2}. \tag{11}$$

The SI derived unit of free-field current sensitivity $(M_i)_H$ is the ampere per pascal (A/Pa). The free-field current sensitivity level is expressed in decibels, *re*: one ampere per micropascal ($1\ \text{A}/\mu\text{Pa} = 10^5\ \text{A}/\mu\text{bar}$). [See Sec. 4 of American National Standard S1.8-1969 (R1974).]

5.3.2.4 Transmitting Current Response

[See 7.16 of American National Standard S1.1-1960 (R1976).]

The magnitude of the transmitting current response of a projector P at frequency f and at the distance 1 m in a specified direction is given by

$$|(S_i)_P| = \left| \frac{e_{PT} e_{PH} i_T}{e_{TH} J} \right|^{1/2} \frac{d}{|i_P|}. \tag{12}$$

The SI derived unit of transmitting current response $(S_i)_P$ is the pascal meter per ampere (Pa·m/A). The transmitting current response level is expressed in decibels, *re*: one micropascal meter per ampere ($1\ \mu$Pa·m/A). [See Sec. 4 of American National Standard S1.8-1969 (R1974).]

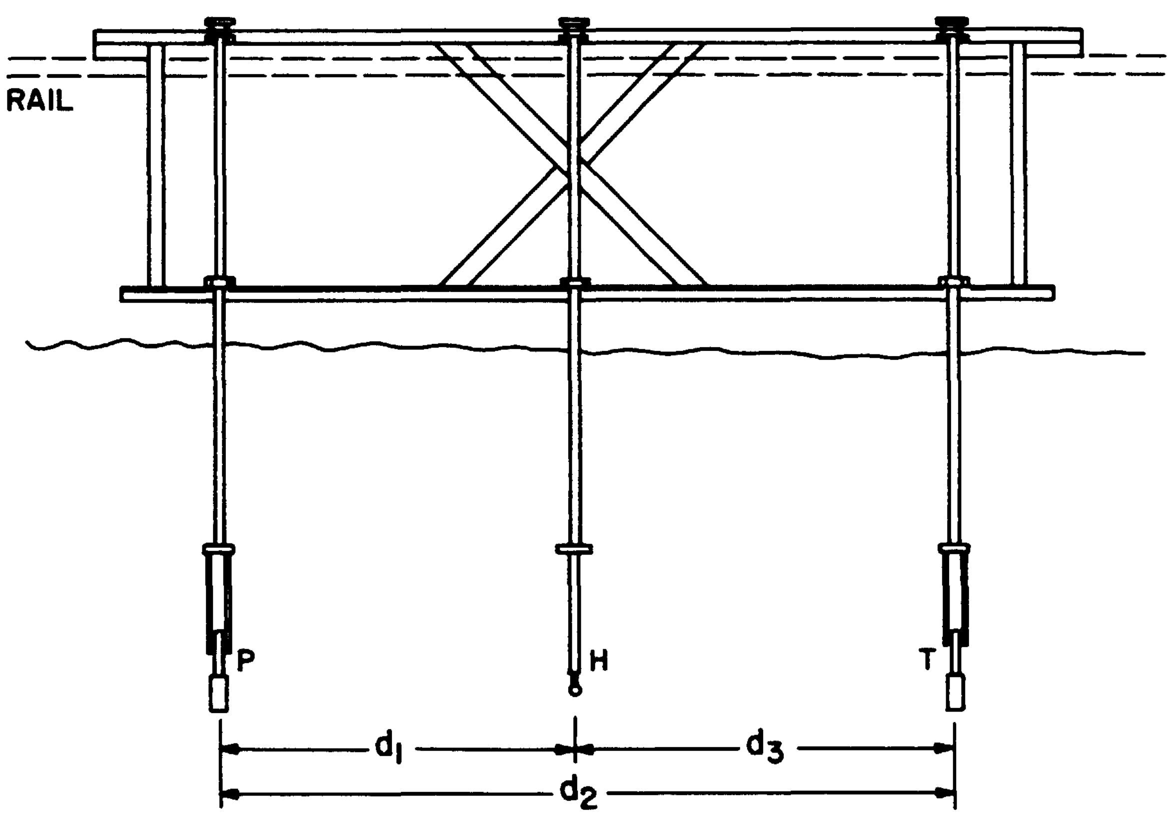

FIG. 2. Measurement framework for supporting the three transducers in-line.

5.3.2.5 Transmitting Voltage Response

[See 7.15 of American National Standard S1.1-1960 (R1976).]

With the arrangements shown in Fig. 1 and the voltage and current measurements of 5.3.2.3, the transmitting voltage response $(S_e)_p$ of projector P at frequency f and at the distance 1 m in a specified direction is given by

$$|(S_e)_P| = \left|\frac{i_{PT} i_{PH} e_T}{i_{TH} J}\right|^{1/2} \frac{d}{|e_P|}. \qquad (13)$$

The SI derived unit of transmitting voltage response $(S_e)_P$ is the pascal meter per volt (Pa·m/V). The transmitting voltage response level is expressed in decibels, *re*: one micropascal meter per volt (1 μPa·m/V). [See Sec. 4 of American National Standard S1.8-1969 (R1974).]

5.3.2.6 Sources of Error in Reciprocity Calibrations

There are several possible sources of error besides those that can be identified by the tests for free field (5.3.1) and for a reciprocal transducer (5.3.2.1), and these must be examined. In a reciprocity calibration, three currents and three voltages must be measured, as seen in the foregoing sections. Generally, the current is measured by the voltage generated in the secondary of a current transformer or it is measured as the voltage drop across a standard resistance placed in series with the transducer whose current is to be measured (5.3.2.6.1). Thus a voltmeter can be used for all electrical measurements. Because the equations for sensitivity and response then show an equal number of voltages in the numerator and the denominator, the voltmeter need not be a standard. It must, however, be linear, stable, and should have an impedance that is very large with respect to that of all measured voltage sources. All electrical measurements must be made at the same terminals of the transducer. Because three experimental arrangements are required for a calibration, stability of the measuring equipment is essential.

5.3.2.6.1 Current Measure. Two methods for measuring transducer currents are in general use. In the better method, the current is measured by the voltage generated in the secondary of a current transformer when the primary is placed in series with the transducer and often in the high side of the circuit. A shielded transformer of toroidal configuration having a primary of low impedance and low capacitance to the secondary and to the ground is recommended. In the other method, the current is measured as the voltage drop across a standard resistance in series with the transducer and generally in the ground side of the circuit. This resistor must be located at the transducer terminal, its value must be less than 1% of the value of the resistive component of the complex impedance, and it must never be more than a few ohms in order to avoid noticeable errors resulting from additional currents through distributed capacitance to ground. A third method has been used to measure the current in small, low-frequency, coupler projectors. A large standard capacitor is placed in series with the projector, and the current is computed from the measured voltage across the capacitor and its reactance. The method can be used to 1 Hz or less provided the capacitor is of sufficiently low dissipation.

5.3.2.6.2 Hydrophone Output Voltage. The impedance of the voltmeter should be greater than approximately 1000 times the impedance of the hydrophone for measurements involving phase and greater than approximately 100 times the impedance of the hydrophone if only magnitude is desired; if it is not, a correction to open-circuit voltage must be made (see 5.8). The measured voltages may range from a few microvolts to volts. Acoustic and electrical interference should be eliminated, if possible, by modifying the measuring conditions. The undesired, interfering signals are those transmitted electromagnetically and acoustically by indirect paths. The pulse technique can be used to separate the desired, direct-path acoustical signal from the undesired, interfering signals. A gated receiving system measures the direct-path acoustical signal and blocks out the interference. The measured signal can be detected by means of an oscilloscope. In sweep-frequency, continuous-wave measurements, the interference that results from two signals from a common source (acoustic reflections or electromagnetic transmission and the desired signal) can be resolved by computation (see 5.11.2).

5.3.2.6.3 Effective Acoustic Center. American National Standard S1.1-1960 (R1976) defines the effective acoustic center of a projector as "the point from which spherically divergent sound waves, observable at remote points, appear to diverge." In practice, the acoustic center is the point used for positioning the projector and measuring distances, and through which any axis of rotation must pass. Except for spherical projectors, the acoustic center must be determined experimentally. Some logical point is selected and then tested by a distance-loss experiment; that is, the sound pressure from the projector must be inversely proportional to the distance from the acoustic center to the point of measurement, or the 6-dB-per-double-distance rule must apply, for all orientations.

Most projectors are symmetrical in an up–down and right–left sense; therefore, errors in selecting the acoustic center usually are in the axial direction (x axis in 5.7.2.1). Such position errors usually are only a few percent or less of the projector-to-hydrophone distance, and, therefore, cause measurement errors of only a few tenths of a decibel. For this reason, the selection of the acoustic center can be quite arbitrary, if long distances between transducers are feasible.

The concept of an acoustic center applies by definition only to a projector. A hydrophone is presumed to be in a sound field of plane progressive waves where the sound pressure amplitude is independent of position. In practice, of course, this is not true, and the hydrophone position is that of its acoustic center when viewed as a projector. The test of a hydrophone's acoustic center is the same as that for a projector; that is, when the hydrophone is placed at two or more distances from a source of spherical waves, its output should be inversely proportional to the distance.

5.3.2.6.4 Transducer Alignment. In a reciprocity calibration with highly directional transducers, a slight misalignment may be a significant source of error. It is essential that the direction of the measured sensitivity or response of a transducer relative to its principal axis be the same for each arrangement, whether the transducer is used as a projector or as a hydrophone. If this alignment is accomplished acoustically, it must be performed each time at the same frequency, since the orientation of the maximum may be a function of frequency.

5.3.2.6.5 Source Proximity. Spherical wave divergence, as would be obtained from a true point source, is approximated by real transducers only beyond a minimum source distance such that

$$d > \pi a^2/\lambda \text{ and } d > a, \tag{14}$$

where a is the largest radius of a piston source or half the length of a line source, d is the source distance from the field point, and λ is the wavelength of the sound.

Beyond this minimum distance from a circular piston or line source, the sound pressure at a point receiver will be within 4% of that calculated by assuming spherical divergence. This minimum distance also exists for a finite receiver and a point source. Physically, the requirement that the transducer look like a point source means that the variation in distance from the measuring position to any place on the surface of the transducer must be small in comparison with a wavelength or the distance. The expressions are equally valid for a transducer shaded to reduce minor lobes, because the effective radius or half-length then is less than a (see Ref. 3).

5.3.3 Procedures for Secondary Sensitivity and Response Calibrations

In a secondary calibration, the unknown sensitivity or response is determined by reference to a standard hydrophone. The method requires less time and equipment because only two electrical measurements are made. Careful selection of the measuring transducers for optimum directivity can compensate for lack of ideal free-field conditions. Accuracy and reliability can be increased by averaging the results of measurements made with two or more standard hydrophones.

5.3.3.1 Free-Field Voltage Sensitivity

The secondary calibration of a hydrophone requires a projector that need not be reversible nor linear, but linearity is desirable. The sensitivity of the standard hydrophone should be stable and free from hysteretic effects resulting from the expected variations of ambient temperature and pressure. If boundaries disturb the free-field conditions, then an error is introduced. The pulsed-sound technique can be used (see Appendix A) in the kilohertz and megahertz frequency ranges. At lower frequencies, the error can be reduced by using a standard hydrophone whose angular deviation loss [see 7.8 of American National standard S1.1-1960 (R1976)] is equal to that of the measured hydrophone.

A comparison is made by placing the standard and the unknown hydrophones successively in the same position in the sound field of the projector. The magnitude of the free-field voltage sensitivity $(M_e)_H$ of the measured hydrophone is given by

$$|(M_e)_H| = |(M_e)_{\text{ref}}| \cdot \left| \frac{e_H}{e_{\text{ref}}} \right| , \tag{15}$$

where

$(M_e)_{\text{ref}}$ = free-field voltage sensitivity of the reference or standard hydrophone,
e_H = open-circuit voltage output of the measured hydrophone,
e_{ref} = open-circuit voltage output of the standard hydrophone.

NOTE: If the standard and unknown hydrophones are so different in size and directivity that the measurements cannot be made with the two of them successively at the same position, a correction for distance loss must be applied to one of the open-circuit voltages.

5.3.3.2 Free-Field Current Sensitivity

The procedure is similar to that outlined in 5.3.3.1:

$$|(M_i)_H| = |(M_e)_{\text{ref}}| \cdot \left| \frac{i_H}{e_{\text{ref}}} \right| , \tag{16}$$

where

$(M_i)_H$ = free-field current sensitivity of the measured hydrophone,
$(M_e)_{\text{ref}}$ = free-field voltage sensitivity of the standard hydrophone,
i_H = short-circuit current output of the measured hydrophone, and
e_{ref} = open-circuit voltage output of the standard hydrophone. [See statement after Eq. (11) *re*: $(M_i)_H$ and statement after Eq. (7), *re*: $(M_e)_{\text{ref}}$.]

5.3.3.3 Transmitting Current Response

A secondary calibration of a projector can be obtained by using a standard hydrophone to measure the generated sound field. The hydrophone must be located at sufficient distance, in the specified direction, for a spherically divergent sound field to exist at that spot. The apparent sound pressure at 1 meter then is determined by multiplying the measured sound pressure at the remote point by the ratio of the distance d in meters at that point from the acoustic center of the projector to the reference distance (1 meter). The transmitting current response is given by

$$|S_i| = \left| \frac{e_{\text{ref}}}{i_P (M_e)_{\text{ref}}} \right| d, \tag{17}$$

where

S_i = transmitting current response of the projector,
e_{ref} = open-circuit voltage output of the standard hydrophone,
d = distance between the acoustic center of the projector and the hydrophone,
i_P = current flowing at the projector electric input terminals,
$(M_e)_{\text{ref}}$ = free-field voltage sensitivity of the standard hydrophone.

NOTE: If the projector obeys the electroacoustical reciprocity theorem, then its free-field voltage sensitivity can be determined by the procedure outlined in 5.3.3.1 and the transmitting current response can be computed from the expression

$$|S_i| = 1/2|M_e|\,\rho f. \tag{18}$$

The SI derived unit of transmitting current response (S_i) is the pascal meter per ampere (Pa·m/A). Transmitting current response level is expressed in decibels, *re*: one micropascal meter per ampere (1 μPa·m/A). [See Sec. 4 of American National Standard S1.8-1969 (R1974).]

5.3.3.4 Transmitting Voltage Response

The procedure is similar to that described in 5.3.3.3. The transmitting voltage response is given by

$$|S_e| = \left| \frac{e_{\text{ref}}}{e_P (M_e)_{\text{ref}}} \right| d, \tag{19}$$

where

S_e = transmitting voltage response of the projector,
e_{ref} = open-circuit voltage output of the standard hydrophone,
d = distance between the acoustic center of the projector and the hydrophone,
e_P = signal voltage applied to the projector electric input terminals,
$(M_e)_{\text{ref}}$ = free-field voltage sensitivity of the standard hydrophone.

5.3.3.5 Sources of Error in Secondary Calibrations

The sources of error in reciprocity calibrations (see 5.3.2.6) exist in a secondary calibration; however, fewer data are required in a secondary calibration. For example, in the measurement of sensitivity, the projector current and the separation distance need not be measured but must be the same when the standard and measured hydrophones are successively placed in the sound field. Accuracy and reliability can be increased by averaging the results of measurements with two or more standard hydrophones.

5.4 Measurement of Sensitivity and Response—Infrasonic and Low Audio-Frequency Range

5.4.1 Coupler Reciprocity Calibration of a Hydrophone

The absolute calibration of a hydrophone at low audio and infrasonic frequencies can be determined in a very small chamber called a coupler. This technique was originally developed and used for air acoustics[4,5] where the chamber medium was air or another gas. A gas coupler can be used to calibrate hydrophones, but a liquid-filled coupler is preferred because it operates to higher frequencies and is particularly useful to calibrate a hydrophone as a function of hydrostatic pressure.

5.4.1.1 Procedures

A coupler consists of a chamber whose boundaries are rigid and whose longest dimension is smaller than 0.1 wavelength in the medium. Thus the sound pressure produced in the chamber is approximately uniform in magnitude and phase throughout the chamber. A projector P, a reciprocal transducer T, and a hydrophone H are wholly or partially inserted into the chamber. Often, all three transducers are designed especially for calibration in a coupler and only the active piezoelectric elements protrude into the chamber. Other parts of the transducer form part of the coupler walls or chamber boundary, as shown in Fig. 3.

Partial insertion keeps the maximum dimension of the acoustic medium small, and couplers have been used to calibrate small probe hydrophones to frequencies as high as 10 kHz in this way. If the hydrophone has not been designed for coupler calibration and must be completely inserted into the chamber, the chamber must be large and the high-frequency limit is of the order of a few hundred hertz.

The same electrical measurements are made as in spherical-wave reciprocity [see Eqs. (1) and (2) and Fig. 1], but here the reciprocity parameter J is the acoustic susceptance of the medium and its boundaries; that is,

$$J = j\omega C, \tag{20}$$

where

ω = angular frequency,

C = acoustic compliance of the medium and its boundaries.

Implicit in the use of Eq. (20) is the assumption that the system is compliance controlled. All resonances, therefore, should be at frequencies higher than the intended calibration frequency range. The principal measurement problem and source of error is the determination of C. The liquid must be deaerated and thoroughly purged of gas bubbles. Soft gaskets must be isolated from the medium. No pressure release material can be used. Then, if the walls are thick and rigid, the compliance C will be proportional to the compressibility of the liquid medium:

$$J = j\omega C = j\omega\beta V, \tag{21}$$

where

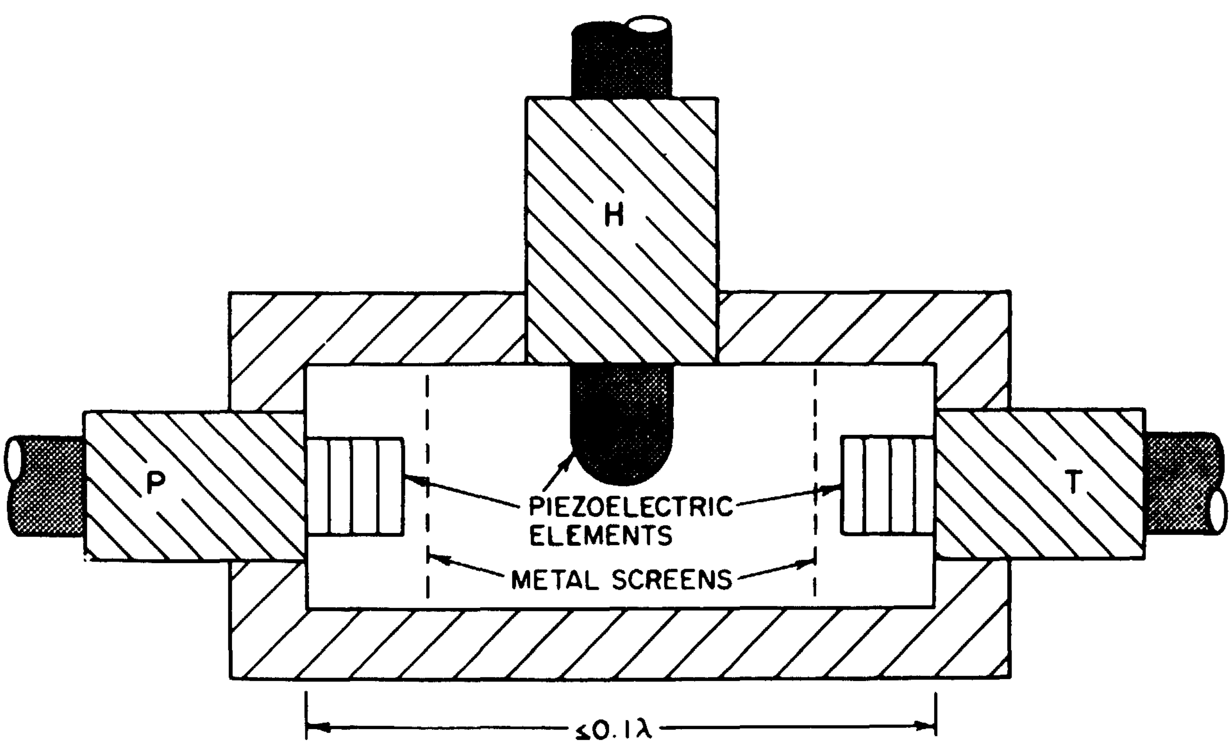

FIG. 3. Simplified schematic diagram of a liquid coupler.

V = liquid volume,

β = adiabatic compressibility.

The compressibility can be calculated from the density ρ and the speed of sound c:

$$\beta = 1/\rho c^2. \quad (22)$$

Both ρ and c are functions of pressure and temperature. Data on β, ρ, and c can be found in appropriate references[6–14] or measured. Figure 4 shows some typical values of β.

The volume V is measured by filling or emptying the coupler with a carefully metered amount of liquid.

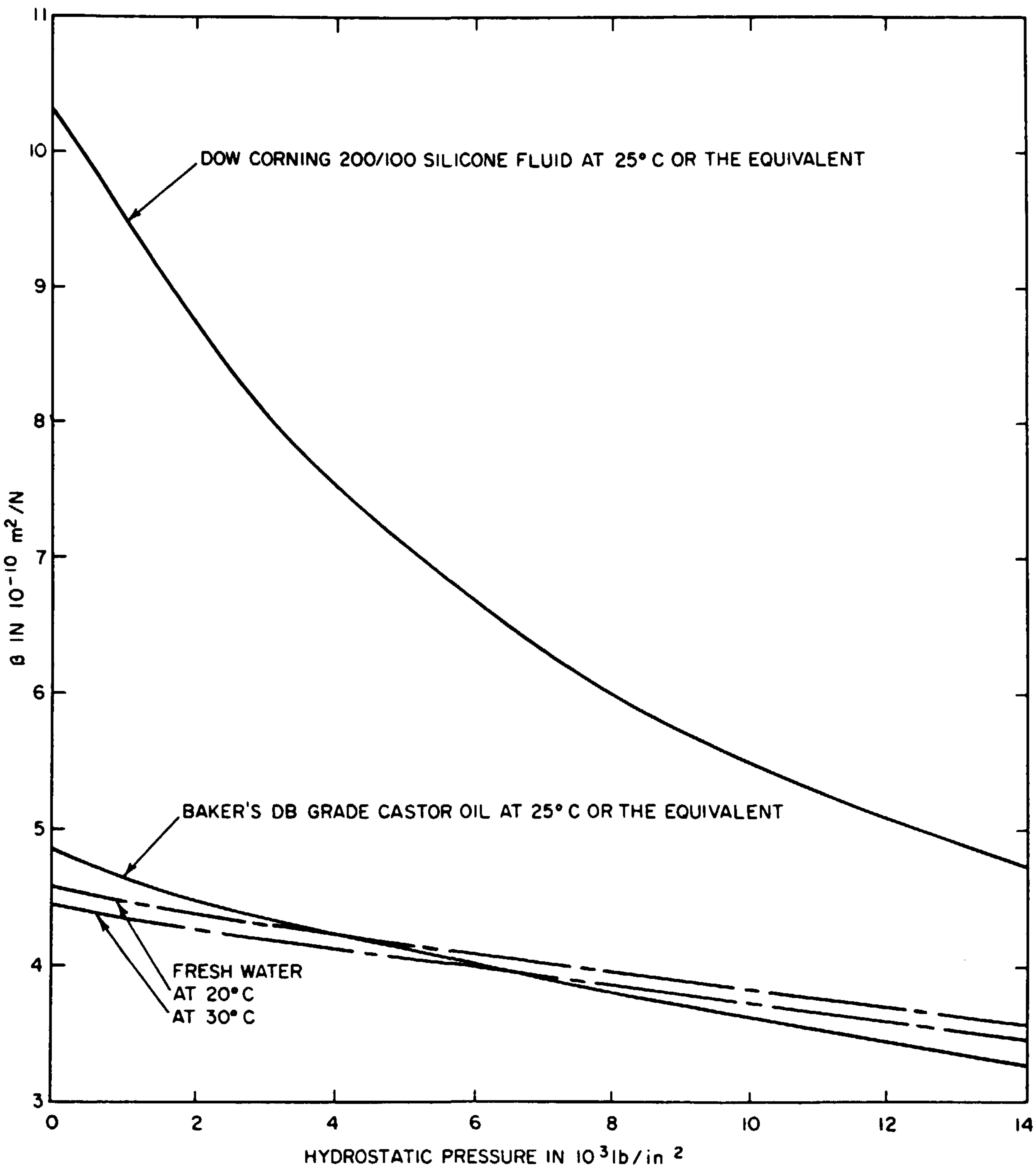

FIG. 4. Adiabatic compressibility of coupler fluids. NOTE: Silicone and castor oil data from Ref. 12; water data calculated from Ref. 13.

If it cannot be assumed that all boundaries are much less compliant than the medium, the compliance must be measured. This can be done statically[15] by measuring the additional volume ΔV of liquid necessary to produce a change Δp in the static pressure:

$$J = j\omega C = j\omega \frac{\Delta V}{\Delta p}. \tag{23}$$

The static measurement has the disadvantage of being an isothermal measurement. Reference data show the isothermal compressibility of water to be 1% to 3% higher than the adiabatic.[13] Ordinarily, errors of less than 3% are negligible, unless high accuracy is desired.

The compressibility also can be determined dynamically by combining C with a known mass to form a Helmholtz resonator.[16]

All three transducers should contain volume expander piezoelectric elements. Lithium sulfate crystals, lead metaniobate ceramic disks, and lead zirconate titanate spheres or capped cylinders are typical elements.

5.4.1.2 Practical Limitations and Measurement Accuracy

The high-frequency limit is set by the criterion that the maximum dimension of the liquid should not be greater than 0.1 wavelength. There is no theoretical low-frequency limit. In practice, the electrical problems in driving a small piezoelectric projector with very high electrical impedance set a practical lower limit of about 5 Hz. Electrical crosstalk between projector and hydrophone must be avoided. Metal screens inside the chamber and between the transducers are used to suppress crosstalk.

The useful frequency range can be tested by measuring the ratio of hydrophone output voltage to projector or reciprocal transducer input voltage. The ratio is constant through the frequency range in which the system is compliance controlled.

If a dielectric oil is used as the liquid medium rather than water, the usual rubber boot for protecting the piezoelectric elements of P and T can be dispensed with.

The plumbing used for filling, circulating, or pressurizing the liquid should be kept as simple as possible to facilitate removal of gas bubbles and to avoid including pipes or tubing as part of the chamber.

Measurement accuracy depends largely on the accuracy in measuring C in Eq. (23). Calibration accuracy typically is estimated as in the range ± 0.3 to ± 0.5 dB.

5.4.2 Secondary Sensitivity Calibration

In a secondary calibration, the unknown free-field sensitivity is determined by reference to a standard hydrophone. A closed chamber, a source of sinusoidal pressure variation, a voltmeter, and the standard hydrophone are required. Only the sensor portion of the hydrophone need be within the closed chamber; however, the standard and the measured hydrophones must displace the same volume in the coupler when one is substituted for the other. With the voltage input to the source maintained constant,

$$(M_e)_H = (M_e)_{\text{std}}(e_H/e_{\text{std}}), \tag{24}$$

where

$(M_e)_H$ = sensitivity of the measured hydrophone,
$(M_e)_{\text{std}}$ = sensitivity of the standard hydrophone,
e_H = open-circuit output voltage of the measured hydrophone,
e_{std} = open-circuit output voltage of the standard hydrophone.

Measurements can be made in an air-filled coupler driven by a source such as a telephone earpiece.[17] Measurements can be made over a wider frequency range and a wider dynamic range in a liquid-filled coupler. In this case, a radially poled piezoceramic cylinder can be the source and the wall of the coupler. The inner surface of the wall of the source is at ground potential, thus eliminating the problem of electrostatic coupling between the source and the hydrophone.[18] Although a simple rubber gasket seal is sufficient to close an air-filled coupler, the liquid-filled coupler requires a low-compliance seal commensurate with the low compliance of the coupler chamber. A split conical metal ring in a conical seat, backed up by a retained rubber gasket, is used to seal around the metal housing containing the preamplifier—a common type of hydrophone construction. Deaeration of the liquid is not required, if a reservoir of liquid above the closure allows one to seal the hydrophone in place under the liquid.[18] The liquid generally is water containing a small amount of wetting agent. It should be allowed to stand for an hour or two before the calibrator is used. Sensitivity can be measured from 1 Hz to 5 kHz in a coupler chamber 5 cm in diameter by 12 cm long. A variation of this technique consists of using a chamber large enough to accommodate a source, a standard hydrophone, and the measured hydrophone simultaneously. A large chamber will have a lower high-frequency limit.

5.5 Sensitivity and Response Data Presentation

Sensitivity and response data generally are tabulated or plotted on semilogarithmic coordinate paper where a linear scale of 10 dB per inch is often used as the ordinate and a logarithmic frequency scale is used for the abscissa. In certain situations, such as in determining a quality factor for the transducer, a linear frequency scale might be used for the abscissa. The coordinate system for specifying orientation, as described in 5.7.2.1, shall be assigned to the measured transducer. The direction of the radius vector from the field point to the position of the measuring transducer shall be specified by θ and ϕ. The reference sound pressure generally is 1 micropascal (1 micronewton/meter^2) and the reference distance is 1 meter. Each calibration must be identified as to the type of sensitivity or response, reference electrical terminals with the means of connection and grounding conditions, acoustic signal range or level if the device is nonlinear, accuracy of measurement, ambient pressure and temperature range. Most calibration facilities measure voltages and currents in an unbalanced circuit. This is preferred, inasmuch as few electroacoustic devices can be truly balanced electrically because of unbalanced stray capacitances to the water. If sensitivity or response at resonance is presented, the type of resonance should be specified [see 6.6 in this standard and 3.5 of American National Standard S1.1-1960 (R1976)].

5.6 Precision and Accuracy of Sensitivity and Response Measurements

The distinction between precision requirements and accuracy requirements should be well understood and should be appropriate to the purpose for which the measurement is intended. When a standardizing institution such as the National Bureau of Standards issues a certificate for a standard, it attributes to that standard a numerical value together with a statement about the uncertainty of this value. An uncertainty statement is necessary because, from a philosophical viewpoint, one cannot be absolutely certain of the true value. The standardizing laboratory can never be absolutely certain that the certified value falls within the limits stated in the certificate; however, from a practical viewpoint, it is quite justified in having confidence in a calibration value based on its knowledge of the calibration process and the physical nature of the device calibrated. This confidence is generally transmitted in the form of an uncertainty statement.

If one makes repeated calibration measurements on an electroacoustic transducer, one will obtain a spread in the data if the measurements are conducted by a sufficiently fine measurement scale. The spread of the data is a measure of the precision of the measurement rather than the accuracy of it, and the standard deviation is the usual numerical measure of precision. Accuracy is defined as the difference between the mean value of a very large number of measured values and the true value which is somewhat of a nebulous value. When a calibrating activity makes a single measurement on a transducer that it is familiar with using a calibration technique and system that it is thoroughly familiar with, then it is justified in claiming that the measured value falls with an interval of $\pm X$ dB with a certainty of $YZ\%$.

Trott,[19] reporting on an international round-robin calibration of several hydrophones, found the average deviation of all data from all hydrophones was ± 0.6 dB. Blue[20] found that an interval of ± 0.5 dB about the true values for two small hydrophones calibrated well below resonance would contain 90% of the measured values of sensitivity. These results were obtained in four different facilities using four different measurement systems. One must be extremely careful about giving precision, accuracy, or confidence interval statements based on one calibration of an unknown transducer.

5.7 Directional Response of Sensitivity and Response Measurement

[See 7.4 of American National Standard S1.1-1960 (R1976).]

5.7.1 Procedure

Directional response patterns normally describe the sensitivity or response of a transducer as a function of the direction of the sound waves, as if a distant field point of observation were moved through a spherical coordinate system. In practice, the field point of observation is held fixed in the water and the transducer is rotated in space. Patterns, on a sampling basis, should be made at two or more distances to the field point to ensure validity. The measured or rotated transducer may be receiving or projecting sound.

A complete determination of the characteristics of a dome and a transducer combination is an experimental task of considerable magnitude. Important cases, however, are characterized by a transducer fixed relative to a dome and, in many of these cases, there is a single plane (or, at most, only a few planes) of practical significance, so that the number of variables is conveniently limited. Examples of such cases are (1) a cylindrical (omnidirectional-in-azimuth), scanning transducer used for sound projection fixed relative to a dome and (2) an omnidirectional hydrophone fixed relative to a dome. In these simple cases, the characteristics of the dome are readily derived from one set of directional response patterns in the significant plane at the specified frequency of the transducer without the dome, and another set of patterns of the dome-enclosed transducer, the two sets of patterns being taken with careful regard to maintenance of (1) the reference axes for direction and (2) the reference excitation (constant electric input power, if the patterns are transmitting patterns, and constant free-field sound pressure, if the patterns are receiving patterns).

Characteristic of a nonsimple case is a trainable, and perhaps tiltable, unidirectional (searchlight) transducer in a fixed dome. Here, the location of the transducer is fixed (on its train-tilt shaft or mount), but its orientation is adjustable at will. For this case, directional response patterns of the transducer itself and sets of directional response patterns for the transducer and dome combination, in significant planes and for various representative orientations of the transducer in the dome, are made and presented together. From these, the important distortions of the transducer's directional characteristics by the dome are made apparent, but the dome insertion loss is not specifically derived therefrom for independent presentation. As a supplement to this set of patterns, however, the dome insertion loss for a direction of sound transmission to or from the effective acoustic center of the transducer along the axis of its sound beam is measured as the transducer is systematically trained (with tilt angle fixed) or tilted (with its train angle fixed) through the full angular range with reference to the dome axes. The dome insertion loss, so measured, usually is presented graphically by a plot of dome insertion loss versus direction in a specified plane (or conical surface of specified apex angle and cone axis orientation); the pattern produced by this plot is commonly called a dome loss pattern [see 9.11 of American National Standard S1.1-1960 (R1976)].

5.7.2 Data Presentation

5.7.2.1 Specification of Orientation

A system of left-handed polar coordinates in r, θ, and ϕ shall be assigned to each transducer. The assignment of coordinates as shown in Fig. 5 shall be clearly indicated, preferably by means of a sketch or photograph. The transducer shall be considered fixed with respect to the assigned coordinates.

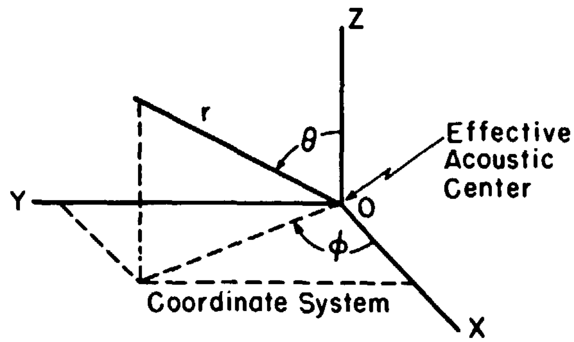

FIG. 5. Coordinate system.

Such terms as left, right, up, down, and azimuth angle are as viewed from the transducer in its normal operating position. The positive y axis is directed outward from the designated right-hand side and ϕ is the azimuth angle. For consistency, the orientation of the transducer in the coordinate system shall conform to the following system whenever possible:

(1) The origin of the coordinate system shall be at the effective acoustic center (see 5.3.2.6.3). In most measurements, this is taken as an arbitrary point from which all measurements of distance are made and about which the transducer is rotated in making directivity measurements.

(2) When an arbitrary choice is indicated, account should be taken of prominent features of the transducer in making the assignment of coordinates.

(3) The positive z axis ($\theta = 0°$) shall be directed up for the intended operating position of the transducer.

(4) The positive x axis ($\theta = 90°$, $\phi = 0°$) shall be the direction of zero azimuth and coincide with any existing horizontal acoustic axis; ϕ is equivalent to the azimuth angle.

(5) The positive y axis ($\theta = 90°$, $\phi = 90°$) shall be the direction of 90° azimuth and will be outward from the designated right-hand side of the transducer as viewed from the transducer.

(6) Point or spherical transducers (omnidirectional) shall be oriented in the coordinate system by an arbitrary choice with the axes specified in relation to a reference mark [see 6.50 of American National Standard S1.1-1960 (R1976)].

(7) Cylindrical or line transducers (omnidirectional in one plane for which the cylinder axis or line is the normal) shall be oriented with the axis of the cylinder or line coinciding with the y or z axis, depending upon the normal operating position. For end-fire line arrays, the x axis shall be the axis of the line in the direction of the end-fire beam.

(8) Plane or piston transducers shall be oriented with the normal to the plane or piston coinciding with the x or z coordinate axis, depending upon the normal operating position, and the other two axes in the plane of the active face.

This orientation scheme is adequate for most directional response calibrations; however, odd configurations or more complex transducer systems, such as a trainable transducer within a dome, will require a more complex method of specifying its orientation.

5.7.2.2 Graphic Representation

A directional response pattern usually is presented in the form of a two-dimensional polar graph. The response or angular deviation loss in decibels is plotted as the radial coordinate and the direction of the field point with respect to the measured transducer as the angular coordinate.

NOTE: The decibel scale may be in terms of angular deviation loss [see 7.8 of American National Standard S1.1-1960 (R1976)] if several directional response patterns of one transducer are to be compared.

The scale for a polar plot of the relative response is often selected to be 10 dB per inch with an available range of at least 40 dB below the maximum response. The scale for the angle is one degree per degree of rotation of the measured transducer.

NOTE: Humid conditions will cause graph paper to expand a greater amount in one direction than it does normal to that direction. This differential expansion may produce an error of $\pm 1/4$ dB when the pattern is recorded on a polar recorder.

The pattern of a highly directional transducer (narrow beam or suppressed minor lobes) sometimes is plotted on linear coordinate paper for better angular resolution of the data, with a linear scale of 10 dB per inch (range 40 dB or more) as the ordinate and a linear angular scale for the abscissa.

5.7.2.3 Conditions of Measurement

Each directional response pattern must be identified as to the type of pattern, frequency or frequency band, pattern orientation within the specified coordinate system, and the ambient conditions upon which the pattern depends such as temperature, pressure or immersion depth, speed of sound, and distance. If more than two terminals exist, the electrical connections should be specified.

5.7.3 Sources of Error and Accuracy in Measurement

The accuracy of directional response pattern measurements is affected by the same quantities that limit the accuracy of sensitivity and response measurements, together with some additional requirements. A larger separation distance generally is required, because correction for spherical divergence is not practicable. The signal level attributable to reflections and noise generally must be lower than for measurement of sensitivity or response on the principal axis, because of the low-level signals encountered at some angles to be measured (see Sec. 3.11 of Ref. 21). If the acoustic center is not on the axis of rotation, there may be phase and magnitude errors in the measured directional response caused by varying separation distance and parallax. The transducer must be rotated slowly enough for the recording system to respond accurately to the maximum rate of change in the signal level that will occur in the pattern nulls. Resolution and hysteresis of the recording system may be additional sources of error.

In general, errors in patterns in the region of maximum response can be expected to be about 0.5 dB. In addition, an error of 1 dB for each 10 dB of angular deviation loss to 30 dB can be expected. When the error is substantially different from these values, the magnitude and source of the error should be stated. The accuracy and method of positioning the transducer within the coordinate system also must be stated (see 5.3.2.6.4).

5.8 Hydrophone Voltage Coupling Loss

[See 7.18 of American National Standard S1.1-1960 (R1976).]

To facilitate the use of an electroacoustic element having a high electrical impedance, the element may be combined with an electric network such as a preamplifier or a transformer. A piezoelectric hydrophone often will consist of an element and preamplifier. The free-field voltage sensitivity may be specified in terms of the open-circuit element voltage. A voltage coupling loss measurement will be required to determine the ratio of the open-circuit output voltage of the element to the open-circuit output voltage of the electrical network. A coupling loss measurement may be useful when the characteristics of the preamplifier are in doubt. The hydrophone may be connected to a complete noise or signal measuring system in addition to its own electric network. A means for measuring the hydrophone voltage coupling loss then can be used to calibrate the complete measuring system.

With modern solid-state circuitry, preamplifiers are stable enough to allow the use of end-of-cable calibrations; in such cases, coupling loss measurements at the element terminals are not necessary.

5.9 Electrical Impedance and Admittance Measurements

5.9.1 Method of Measurement

Impedance or admittance of a transducer shall be measured as the complex electrical impedance or admittance across the same terminals at which the associated sensitivities and responses are measured and with normal acoustic loading. The type of bridge or measurement technique used shall be compatible with the operational conditions of the transducer (balanced or unbalanced).

5.9.2 Presentation of Data

Normally, the data will be plotted as series values of resistance *R* and reactance *X* as a function of frequency, as in Fig. 6, or parallel values of conductance *G* and susceptance *B* as a function of frequency, as in Fig. 7, on linear or log–log graph paper. Equal scales shall be used for *R* and *X* or *G* and *B*, the choice of paper depending upon the accuracy and range of data to be plotted. When high accuracy is required, the impedance should be tabulated as frequency, resistance, and reactance or frequency, conductance, and susceptance. It may be presented as an equal-scale plot of *X* vs *R*, as in Figs. 8 and 9, or *B* vs *G*, as in Figs. 10 and 11, with frequency as the parameter.

The type of impedance, loaded [see 5.35 of American National Standard S1.1-1960 (R1976)], motional [see 5.37 of American National Standard S1.1-1960 (R1976)], balanced or unbalanced, and the conditions of the medium that affect the measurements (specific acoustic impedance, temperature, pressure, or depth of submergence, etc.) must be stated. [See Sec. 5 of American National Standard S1.1-1960 (R1976) for definitions of types of impedance and admittance.]

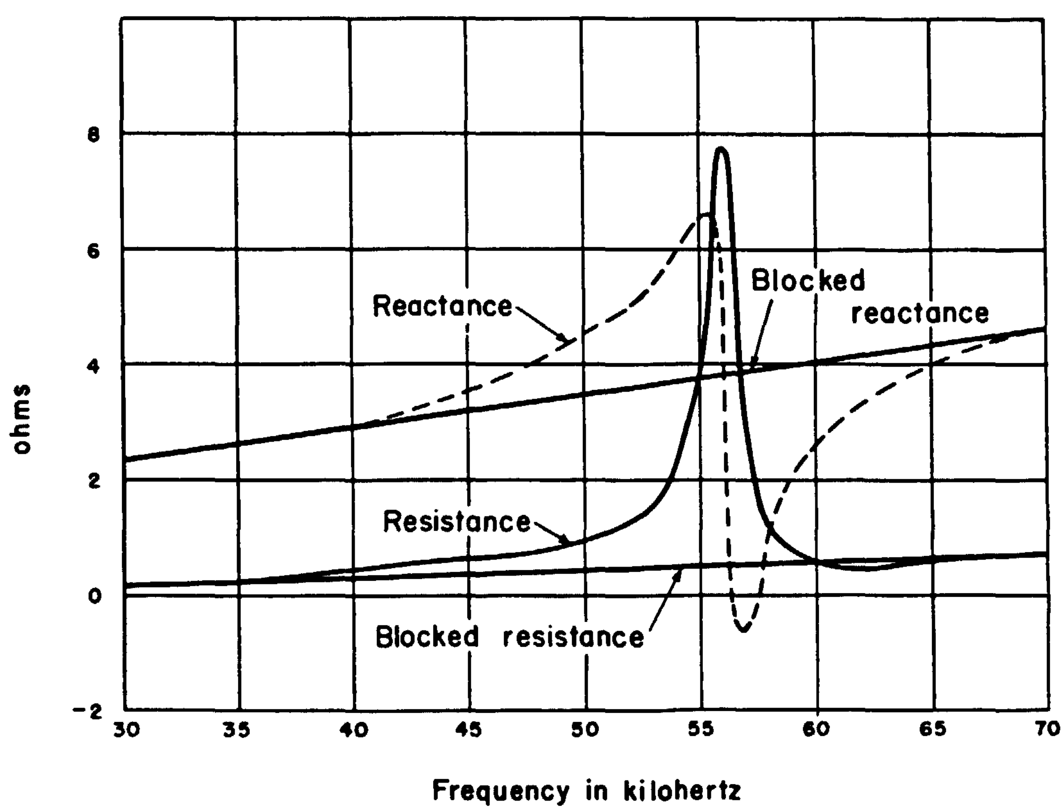

FIG. 6. Equivalent series impedance with extrapolated blocked resistance and reactance.

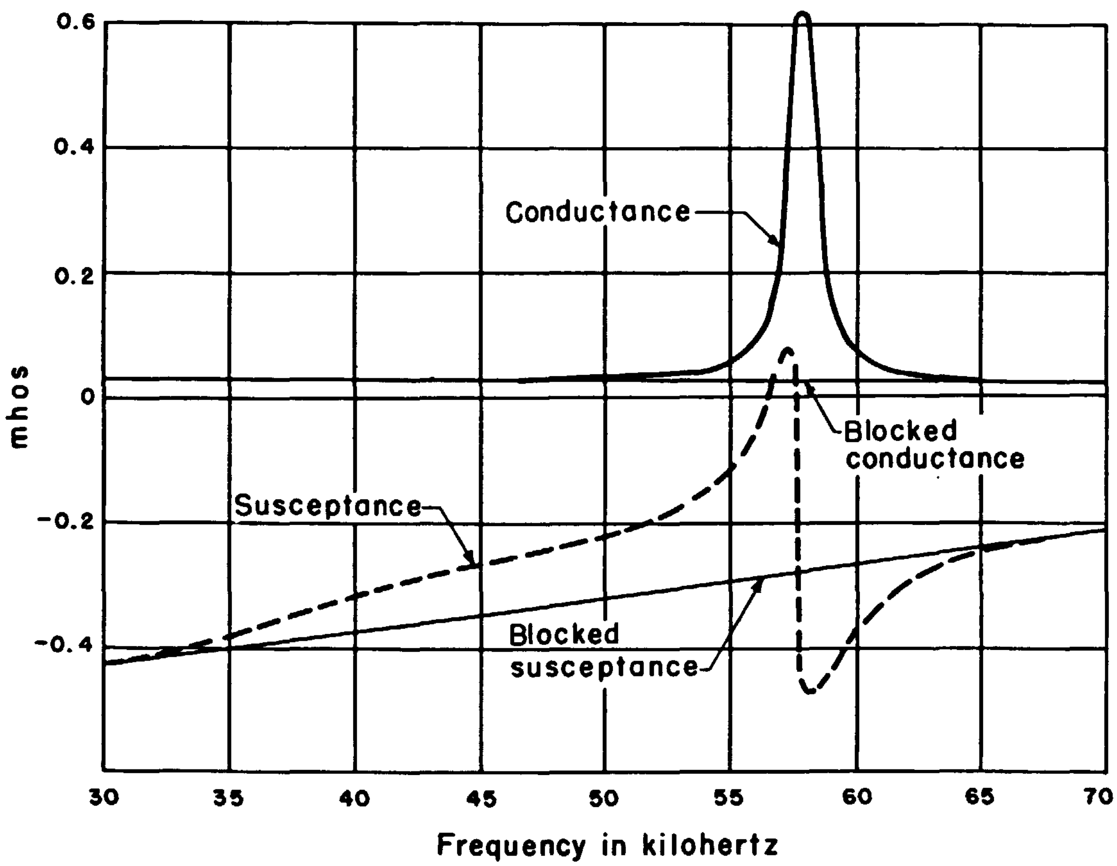

FIG. 7. Equivalent parallel admittance with extrapolated blocked conductance and susceptance.

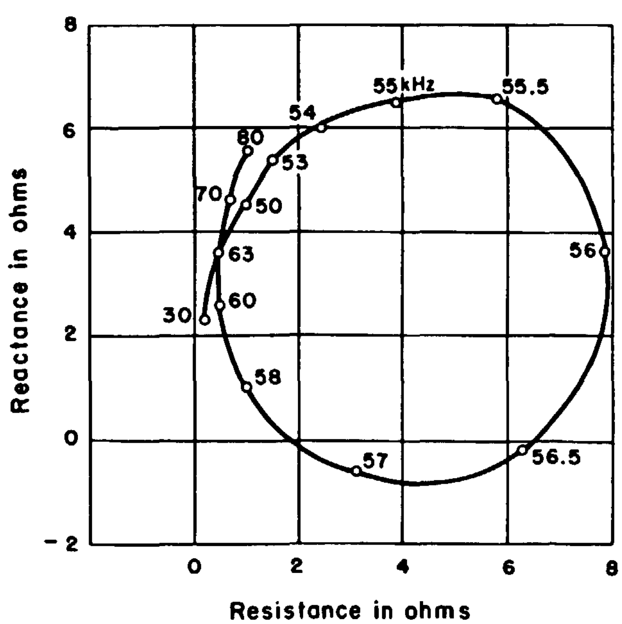

FIG. 8. Equivalent series impedance—Reactance versus resistance.

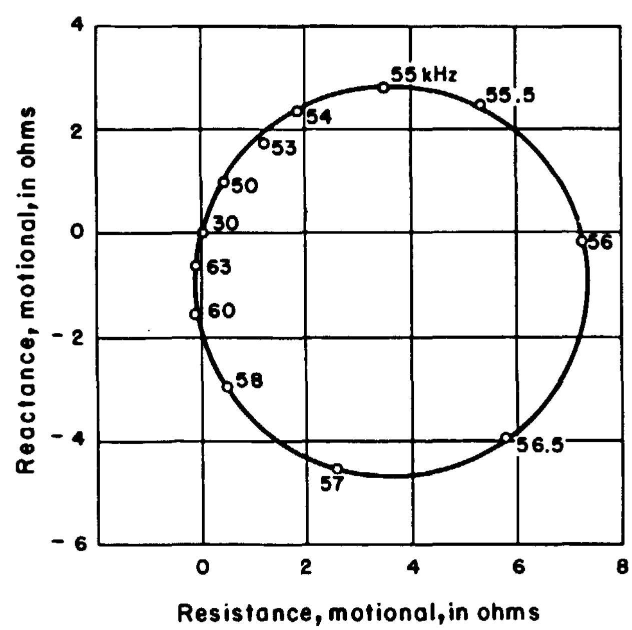

FIG. 9. Motional impedance circle diagram.

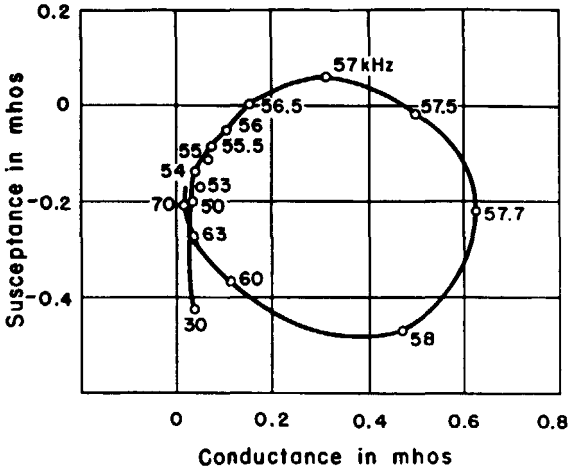

FIG. 10. Equivalent parallel admittance—Susceptance versus conductance.

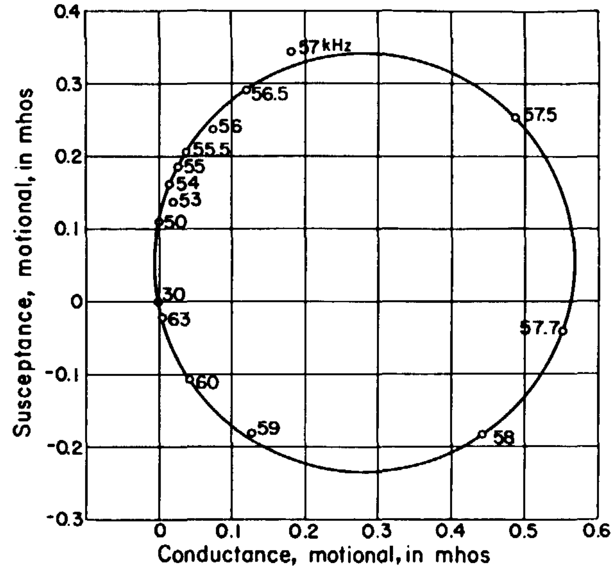

FIG. 11. Motional admittance circle.

5.10 Dynamic Range

[See 7.19 of American National Standard S1.1-1960 (R1976).]

The dynamic range of a transducer generally is expressed as a range of sound pressure level, that is, the range of sound pressure level at 1 meter for a projector, and the range of sound pressure level in a plane-progressive wave for a hydrophone.

The two measurements required for determining the dynamic range of a hydrophone are the equivalent noise pressure level [see 7.26 of American National Standard S1.1-1960 (R1976)] and the overload (pressure) level [see 2.11 of American National Standard S1.1-1960 (R1976)]. The equivalent noise pressure level shall be determined by the procedure outlined in 5.10.1. The method of measuring the overload pressure level shall be determined by the procedure outlined in 5.10.2 and the intended use of the hydrophone. The method selected for determining the overload level and its criteria must be specified when giving the value of the dynamic range, and the cause of overload should be stated, if known. Extreme care must be taken in establishing a sound field of the desired waveform when measuring the receiving overload pressure level.

No method of measurement is given in this standard for the dynamic range of a projector, inasmuch as the lower limit of sound level output is extremely difficult to determine and has very little practical value. The measurement of the overload level is specified.

NOTE: The range of sound pressure for which a transducer is reciprocal is not equivalent to the dynamic range because the dynamic range extends beyond the linear range of the transducer.

5.10.1 Equivalent Noise Pressure Level

[See 7.26 of American National Standard S1.1-1960 (R1976).]

5.10.1.1 Measured Value

When the noise level of the transducer and associated network used for sound reception is sufficiently high, it is possible to determine the noise voltage through use of a wave analyzer with a narrow-band filter. Generally, the ambient water noise is too great to permit measurement of the equivalent noise pressure level. If the electrical impedance of the hydrophone is not appreciably affected by its acoustical load, this measurement can be made with the hydrophone suspended in air or vacuum in a soundproof chamber. For some hydrophones, the noise is due to the associated network, and the acoustic sensing unit can be replaced, for this measurement, by a simple equivalent electrical network.

From the measured noise voltage e_n and the filter characteristic, the inherent root-mean-square open-circuit voltage e_{en} of the transducer, due to noise in a band 1 Hz wide, is calculated from the expression

$$e_{en} = e_n (\delta_0 f)^{1/2} / (\delta f)^{1/2}, \qquad (25)$$

where

δf = the effective bandwidth [see 7.27 of American National Standard S1.1-1960 (R1976)] of the filter,

$\delta_0 f$ = the reference bandwidth (1 Hz).

This noise voltage e_{en} and the free-field voltage sensitivity give the equivalent noise pressure of the hydrophone:

$$p_{en} = e_{en}/M_e, \tag{26}$$

where

p_{en} = transducer equivalent noise pressure in micropascals at the frequency f (hertz),

M_e = free-field voltage sensitivity in volts per micropascal at the frequency f (hertz).

NOTES:

(1) The free-field voltage sensitivity M_e and the voltage e_n must refer to (or be measured at) the same electrical terminals. The equivalent noise pressure level can be expressed in decibels *re*: 1 micropascal.

(2) If the equivalent noise pressure level of the transducer is a function of secondary variables, such as ambient temperature or pressure, the applicable value of these quantities should be stated.

5.10.1.2 Theoretical Value

When it is not possible to measure accurately the noise voltage of a passive hydrophone, but it is possible to obtain its loaded impedance, it is permissible to calculate the noise voltage by using the equation for thermal noise and the measured value of the equivalent series resistance. The theoretical root-mean-square open-circuit voltage e_{en} that is due to thermal noise in a band $\delta_0 f$ wide is

$$e_{en} = (4kTR\delta_0 f)^{1/2} \tag{27}$$

and

$$p_{en} = e_{en}/M_e$$

as before, or

$$\begin{aligned} 20\log_{10}(p_{en}/p_0) = {} & 10\log_{10}(R/1\ \text{ohm}) \\ & - 20\log_{10} M_e/(1\ \text{V}/\mu\text{Pa}) \\ & - 198\ \text{dB},\ re\text{: } 1\ \mu\text{Pa} \end{aligned} \tag{28}$$

at 15 °C for $\delta_0 f = 1$ Hz, where

k = Boltzmann gas constant (1.38×10^{-23} joule per kelvin),

p_0 = 1 micropascal,

T = absolute temperature in kelvin,

R = equivalent series resistance of the electrical impedance of the transducer in ohms (in general, this is a function of frequency),

$-198 = 10\log_{10} 4\,kT$.

NOTE: An attempt should be made to measure the noise voltage before resorting to the theoretical computation.

5.10.2 Overload (Pressure) Level

[See 2.11 of American National Standard S1.1-1960 (R1976).]

The overload level is, by definition, the pressure level above which reliable and normal operation ceases to exist. It may be the result of overheating, overstressing of mechanical parts, depolarization, electrical breakdown, cavitation of the medium, or nonlinearity due to one of the above or other causes. In electrodynamic transducers, overheating of the coil or overstressing of the diaphragm or spring supports may be the cause of overload. Overheating under continuous excitation or high-duty cycle pulsing often will be the cause of overload for some piezoelectric transducers. Nonlinear distortion may be the indication of overload under pulsing, low-duty cycle, conditions.

5.10.2.1 Hydrophone Overload Level

The overload pressure level for a hydrophone generally is specified in terms of the sound pressure level in a plane-progressive sinusoidal sound wave of frequency f propagated parallel to the acoustic axis of the hydrophone. The method of measuring, the type of indication, and the cause of overload, if known, should be specified.

5.10.2.2 Projector Overload Level

The overload pressure level for a projector is specified in terms of the level measured at or corrected to a distance of 1 m from the effective acoustic center of the transducer. The method of measuring, the type of indication, and the cause of overload, if known, should be specified. If the maximum obtainable sound pressure level is limited by distortion, then the criteria for determining this upper limit shall be completely described when giving the value. Those test conditions such as frequency, temperature, hydrostatic pressure, and pulse duration and rate, that affect the overload level measurement, must be specified.

Some pitfalls in making this measurement are: (1) overload of the receiving hydrophone system; (2) overload of power source driving the transducer (because the impedance of some transducers changes at high power levels, it is possible that a mismatch exists between the source and the transducer, even though they were matched at low power levels); (3) cavitation of the medium that occurs without being recognized.

NOTE: For methods of measuring distortion and definitions of terms, see Refs. 4 and 22.

5.10.2.3 Cavitation Limit

[See 10.10 of American National Standard S1.1-1960 (R1976).]

Cavitation is defined as the formation of cavities in the medium. As applied to underwater sound transducers, cavitation is regarded as the formation of cavities during the part of the cycle in which the sum of the static and instantaneous sound pressures is a minimum. The onset of cavitation is a function of the signal frequency and pulse length and of the condition of the medium more than it is of the transducer itself. It is not accurately reproducible. Such quantities as the hydrostatic pressure, temperature, and gas content of the water are among the most important parameters. Cavitation can be differentiated from the overload limit, resulting from other causes, by a change in one or more of these ambient conditions. Cavitation is of practical importance because it often is the cause of overload.

Determining the level at which cavitation commences by observing the formation of cavities usually is not practical for a large, high-power transducer operating under pulsed-sound conditions in its normal medium. The onset of cavitation is determined more reliably by watching for certain characteristics of the received pulse. Some of these characteristics are: (1) at the beginning of the pulse, a deviation from a linear relationship between acoustic power output and electrical power input; (2) sound pulse decay before the end of the electrical pulse; (3) asymmetry between positive and negative pressure excursions of the pulse; (4) appearance of the second harmonic of the exciting frequency (generally, this is the best indication of the onset of cavitation); (5) a ragged appearance of the pulse; and (6) the development of higher-order harmonics, subharmonics, and an increase in high-frequency content of the wave, nonharmonic to the exciting frequency. Item (6) will occur at higher sound pressure levels than those needed to generate the second harmonic, Item (4). An audible change in the perceived signal may also signal the outset of cavitation. These manifestations are dependent on frequency, pulse length, pulse repetition rate, and the water conditions (moving or quiet) surrounding the transducer. Cavitation may occur at shallow depths at acoustic powers as low as 0.1 W/cm^2.

The cavitation limit generally is specified in terms of the sound pressure level at 1 meter from the effective acoustic center of the transducer in the direction of the acoustic axis. Cavitation may occur at the active surface of the transducer or within the nearfield, if a transducer is highly directional.

5.11 Correction Factors

Correction factors for source proximity may be required because of the limited separation distances sometimes needed to reduce the relative level of reflected sound to direct sound, to maintain a signal level above noise, or because of the size of a calibration tank. Elimination of the effects of unwanted electrical transmission or reflected sound from the response data may also be required. In specifying a response, any use of these corrections must be acknowledged.

5.11.1 Source Proximity

The existence of boundaries or a limit on the available signal level sometimes requires that a compromise be made in the separation distance. The receiving sensitivity of a hydrophone then may be reduced because the phase and magnitude of the spherical wave across its active element differ from those that would exist if the measurements were made in a plane wave. Similarly, the pressure in the nearfield of a finite projector is less than would exist for an equivalent point source.

5.11.1.1 Sound Pressure Reduction

Equations have been derived for such ideal sources as a uniform line and uniform piston in an infinite plane baffle.[23,24] From these equations, the reduction in pressure, expressed in decibels, has been plotted for various ratios of the length or diameter to wavelength versus distance. This same reduction in sensitivity applies to a hydrophone under similar conditions of size, wavelength, and distance. A 5-dB correction is allowable in transducer measurements. This correction is not practical in the measurement of directivity (see 5.7.3).

5.11.1.2 Particle Velocity Augmentation

When directivity in the audio range is desirable, a hydrophone sensitive to the particle velocity or pressure gradient may be used. The hydrophone may be calibrated in terms of the equivalent plane-wave sound pressure. To calibrate this hydrophone or to apply this calibration to a measurement within the spherically divergent sound field of an equivalent point source requires that the apparent sound pressure be corrected for the particle velocity augmentation in the nearfield. The correction factor is given by the expression

$$\left(\frac{|dp/dr|}{|p|}\right)_{\substack{\text{spherical}\\ \text{wave}}} \div \left(\frac{|dp/dr|}{|p|}\right)_{\substack{\text{plane}\\ \text{wave}}} = \left[1 + \left(\frac{\lambda}{2\pi r}\right)^2\right]^{1/2}, \tag{29}$$

where

dp/dr = sound pressure gradient,
p = sound pressure,
λ = sound wavelength,
r = distance from the point source to the hydrophone.

The receiving sensitivity must be reduced accordingly. The correction [Eq. (29)] expressed in decibels as a function of frequency is presented graphically in Fig. 12 for several separation distances.[21,25]

NOTE: Sometimes a hydrophone is sensitive to the pressure gradient over a narrow frequency band. This condition will cause a hydrophone to be directional in a frequency range where a hydrophone of the same size sensitive only to the sound pressure would be omnidirectional, particularly where $\lambda/2\pi r > 1$. Abnormal pressure reduction as a function of distance will occur also for $\lambda/2\pi r > 1$, since the particle velocity is not a simple function of distance; therefore, a greater distance is required to provide free-field, plane-wave conditions.

5.11.2 Interference

In a sweep-frequency, continuous-wave measurement of sensitivity or response, any violation of free-field conditions caused by secondary transmission paths will appear as a sinusoidal variation on the oth-

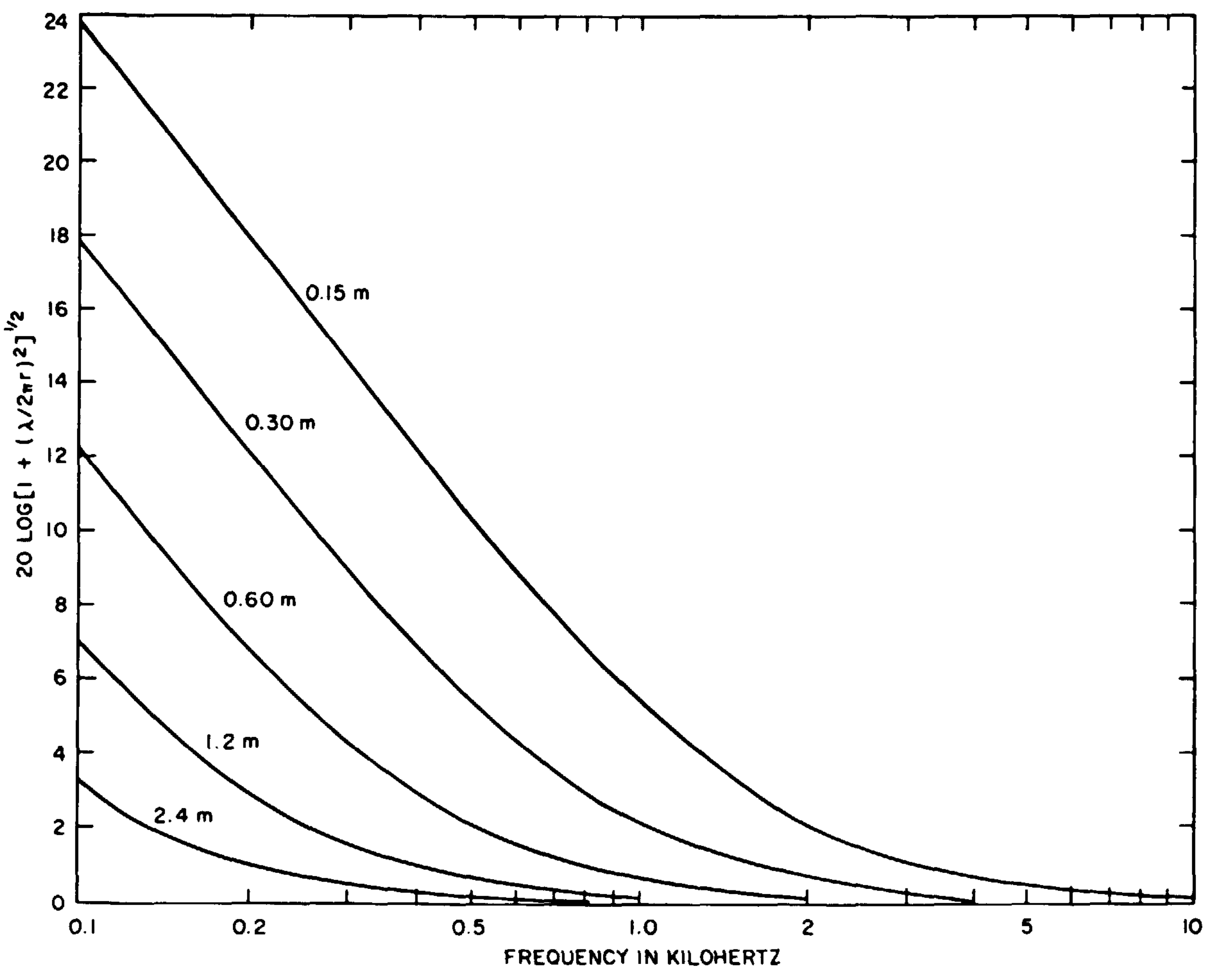

FIG. 12. Particle velocity augmentation in a spherically divergent sound field at various distances from a point source.

erwise irregular plot of hydrophone output as a function of frequency. These secondary transmission paths can be either acoustic or electrical. The frequency interval δf between peaks is related to the acoustic path difference δr between the primary and the secondary transmission paths by the expression

$$\delta f = c/\delta r, \tag{30}$$

where

c = speed of sound in the water.

The magnitude of the interfering signal can be determined from the amplitude of the sine-wave pattern. The source of the signal can be determined by comparing the computed δr with the geometry of the physical arrangement. At low frequencies, the fractional change in frequency may be too small to obtain a value for δf; then, the correction must be estimated and can be checked by varying the distance, or depth, or both.

Because the output-versus-frequency plot for a hydrophone–projector combination usually is irregular, the correction should be limited to about 6 dB and a ratio of $\delta f/f$ less than 0.1.

If interference is apparent, directivity patterns can be measured under the existing conditions only by the pulse technique (see Appendix A).

6 COMPUTATION OF DERIVED CHARACTERISTICS

6.1 Directivity Factor and Directivity Index

The directivity factor or the directivity index provides a quantitative description of the farfield directional characteristics of a transducer.

6.1.1 Directivity Factor (R_θ)

[See 7.6 of American National Standard S1.1-1960 (R1976).]

The directivity factor can be expressed as

$$R_\theta = \frac{4\pi r^2 p_a^2}{\int_{\text{sphere}} p^2(\theta,\phi)\,dS} = 4\pi\left[\int_0^{2\pi}\int_0^{\pi}\left(\frac{p(\theta,\phi)}{p_a}\right)^2 \sin\theta\, d\theta\, d\phi\right]^{-1}, \tag{31}$$

where

$p(\theta,\phi)$ = sound pressure as a function of direction at some fixed distance,
p_a = sound pressure in the reference direction at the same distance,
r = radius of a sphere whose center is the effective acoustic center of the source,
dS = differential element of area on the surface of the sphere.

For sound reception, $p(\theta,\phi)$ and p_a are replaced by the open-circuit voltage of the hydrophone as a function of the direction of the impinging sound wave, and the center of the sphere is the effective center of the hydrophone.

NOTES:

(1) If the maximum response is neither an axis of symmetry nor the reference direction for angular coordinates, the direction of p_a must be carefully indicated.

(2) In the calculation of efficiency (see 6.4), the specified direction must be the direction used in determining the transmitting response.

Equation (31) can be evaluated from directivity patterns by the use of special plots and a planimeter, special charts, or by incremental summation. See Refs. 21 and 26. The exact value of this integral is obtainable mathematically only for certain ideal cases (see Directivity, Directivity Index section of References). The directivity factor of a circular piston source in an infinite rigid baffle is given by

$$R_\theta = (ka)^2\left(1 - \frac{J_1(2ka)}{ka}\right)^{-1}, \tag{32}$$

which approaches

$$\frac{4\pi(\text{area of source})}{\lambda^2}, \quad \text{for } ka > 2\pi, \tag{33}$$

where

$k = 2\pi/\lambda$,
λ = wavelength of sound in the water,
a = radius of the piston source,
J_1 = Bessel function of the first kind and order 1.

The directivity factor of a uniform line source is given by

$$R_\theta = 2\left(\int_{-\pi/2}^{\pi/2} \frac{\sin^2[(l\pi/\lambda)\sin\theta]}{(l\pi/\lambda)^2\sin^2\theta}\cos\theta\, d\theta\right)^{-1}, \tag{34}$$

where

l = length of the line source.

Equation (34) can be written also in the form

$$R_\theta = 2x[\pi - 1/x - (\sin 2x)/x + (\cos 2x)/2x^3 - \cdots]^{-1}, \tag{35}$$

where

$$x = \pi l / \lambda.$$

From this, it is seen that

$$R_\theta \to 2l/\lambda, \quad \text{for } l > \lambda. \tag{36}$$

(See Refs. 23 and 27.)

6.1.2 Directivity Index (D_i)

[See 7.7 of American National Standard S1.1-1960 (R1976).]

$$D_i = 10 \log_{10}(R_\theta). \tag{37}$$

(See Refs. 21 and 27 for charts and graphs of D_i for some types of radiators.)

6.2 Acoustic Power Output (P_a) and Acoustic Power Level (L_p)

The total radiated power is obtained by integrating the acoustic intensity over a sphere of radius r surrounding the source. If the integration for the directivity factor (see 6.1.1) is used, then the equation for the acoustic power output is

$$P_a = \frac{4\pi r^2}{R_\theta} \cdot \frac{p_a^2}{\rho c} \text{ watts} \tag{38}$$

if all quantities are expressed in SI units.

The acoustic power level L_p in water [see American National Standard S1.8-1969 (R1974)] is

$$L_p = 10 \log_{10}(P_a/P_0) \text{dB } re\text{:1 pW} = 20 \log_{10}(r/r_0) + 20 \log_{10}(p_a/p_0) - D_i - 50.9 \text{ dB } re\text{:1 pW} \tag{39}$$

for standard seawater at 15 °C, salinity 35 (‰), where

- r = radius of the sphere in meters,
- p_a = sound pressure in pascals (Pa) on the principal axis of the source at distance r,
- p_0 = reference pressure (1 micropascal),
- r_0 = reference distance (1 meter),
- P_a = acoustic power output in watts,
- P_0 = reference power (1 picowatt),
- ρ = density of the water in kilograms per cubic meter,
- c = speed of sound in the water in meters per second.

6.3 Electrical Power Input (P_e)

This is computed from measurements of current, voltage, and power factor at the transducer terminals. For low-level measurements, where the transducer impedance is not a function of power input, it is permissible to use e^2G or i^2R, where G and R are the parallel conductance and series resistance in ohms as measured with an ac bridge at the transducer terminals with normal acoustic loading and normal electrical grounding conditions.

6.4 Transmitting Efficiency (η)

[See 1.60 of American National Standard S1.1-1960 (R1976).]

The transmitting efficiency is expressed as the ratio of P_a/P_e or

$$\eta = \frac{4\pi r^2}{R_\theta} \cdot \frac{{p_a}^2}{\rho c} \cdot \frac{1}{i^2 R}, \tag{40}$$

where all quantities are expressed in SI units. The symbols are defined in 6.1.1, 6.2, and 6.3.

If the radius of the sphere is 1 meter, then Eq. (40) can be expressed as

$$\eta = \frac{4\pi S_i^2}{\rho c R_\theta R}, \tag{41}$$

with all quantities in SI units. Expressed in decibels for standard seawater at 15 °C, salinity 35 (‰) [see 9.1 of American National Standard S1.1-1960 (R1976)], it is

$$10 \log_{10} \eta = 20 \log_{10}|S_i| - D_i - 10 \log_{10} R/1 \text{ ohm} - 170.9 \text{ dB}, \tag{42}$$

where, as before, $20 \log_{10}|S_i|$ is in decibels, re: 1 micropascal meter per ampere (1 μPa·m/A).

NOTES:

(1) In Eq. (40), e^2G can be substituted for i^2R. The transmitting voltage response S_v can be substituted for S_i and G for R in Eqs. (41) and (42).

(2) Efficiency at resonance can be computed from the measurement of motional impedance in water and in air.[28-31,21]

6.5 Open-Circuit Effective Bandwidth [$(\text{Ebw})_0$]

(See 4.5.)

The open-circuit effective bandwidth of an electroacoustic transducer used for sound reception is expressed as

$$(\mathrm{Ebw})_0 = (|(M_e)_{\max}|)^{-2} \int_0^\infty (|M_e(f)|)^2\, df, \quad (43)$$

where

$M_e(f)$ = free-field voltage sensitivity of the transducer,

$(M_e)_{\max}$ = maximum value of the free-field voltage sensitivity.

The expression can be evaluated with practical accuracy by integrating over a finite band of frequencies. If the transducer is combined with a bandpass filter, then the limits of the integration are the limits of the passband.

6.6 Quality Factor (Q)

[See 3.6 of American National Standard S1.1-1960 (R1976).]

Quality factor is a measure of the sharpness of resonance. For a simple resonant circuit or its mechanical equivalent,

$$Q = \omega_0/(\omega_2 - \omega_1) = f_0/(f_2 - f_1), \quad (44)$$

$$Q = 1 \Big/ 2f_0 \left[\frac{d\theta}{df}\right]_{f=f_0},$$

where

$\omega_0 = 2\pi f_0$,

f_0 = resonance frequency in hertz [see 3.4 and 3.5 of American National Standard S1.1-1960 (R1976)] of a series resonant circuit,

$\omega_2 = 2\pi f_2$,

$\omega_1 = 2\pi f_1$,

f_2, f_1 = quadrantal or half-power frequencies,

θ = phase angle of the system's impedance (or admittance).

For clarity of discussion, the equations are expressed for a series mechanical circuit and applied to an electrical circuit and a parallel resonant circuit in Notes (1) and (2).

The first of these relations gives Q as the reciprocal of the fractional bandwidth of a singly resonant system, that is, as the ratio of the system's resonance frequency to the frequency interval between its quadrantal or half-power frequencies (the frequencies at which the power dissipated is one-half that dissipated at resonance), if the force (or voltage) across the impedance is maintained constant. The second of these relations gives Q as one-half the rate of change at resonance of the phase angle of the system's impedance (or admittance) with incremental change in the ratio of the frequency to the resonance frequency.

The term Q is significant also in describing the transient behavior of a singly resonant system that is less than critically damped ($Q > 0.5$), either mechanical or electrical. If the frequency of the force or voltage coincides with the resonance frequency of the system ($f_0 = 1/T_0$), it takes Q cycles, or a total time QT_0, for the velocity or current to build up to 96% of its final (steady-state) value. Similarly, if the force or voltage is removed, it takes Q cycles for the velocity or current to decay to 4% of its value at the time of removal. Thus Q is a measure of the duration of the transient and is used in specifying the buildup or decay time of the system under pulsed excitation. This use rests on interrelations between $Q(= m\omega_0/r)$ and the transient characteristic constants of the vibratory system, namely, the damping factor $a = r/2m$ and the logarithmic decrement $\delta = \alpha T_0$. Specifically, $Q = \pi/\alpha T_0 = \pi/\delta$. The vibratory system consists of a mass m, compliance C_m, and resistance r.

NOTES:

(1) The same equations apply to an electrical system of inductance, capacitance, and resistance.

(2) For the elements in parallel at parallel resonance, Q is the ratio of the magnitude of susceptance to conductance at the resonance frequency and the two expressions for Q, in terms of frequencies and rate of change of phase, are the same as before. Here, the quadrantal frequencies are the frequencies at which the power dissipated is one-half that dissipated at resonance if the total velocity (or current) through the paralleled elements is maintained constant.

The typical resonant transducer, when used in an electrical circuit, appears as a complex electrical impedance or admittance. As such, it has a Q, in the quality factor sense, which is not at all the Q that specifies the sharpness of the mechanical resonance. Differentiation between the two Q's ordinarily is made by using subscripts or by qualifying terms. Thus the Q that specifies the sharpness of mechanical resonance is the mechanical Q or Q_m, and the Q that specifies the magnitude of the ratio of the electrical reactance to electrical resistance, or the magnitude of the ratio of the electrial susceptance to electrical conductance, is the electrical Q or Q_e. The resonance frequency f_0, the sharpness of the mechanical resonance Q_m, and the time constant $Q_m T_0$ of the resonant mechanical system are quantities to be measured, or derived from measurements, in the course of a transducer's calibration. Controlling performance specifications applicable to the transducer may set forth required values or limiting values for these quantities.

The various response-frequency curves of a resonant transducer exhibit peaks at or near the mechanical resonance. The maximum motional impedance and admittance also will occur at or near the mechanical resonance. The appropriate response-frequency curve for the selection of the resonance frequency is that one in which the excitation, electrical or acoustical, varies with frequency in such a way that the driving force exerted on the mechanical system is constant and the observed quantity is one that is proportional to the velocity in the mechanical system. Under these conditions, the response-frequency curve will have its maximum at f_0 and will be symmetrical about f_0 if the frequency scale used is logarithmic. This provides a test, which is performed by plotting M_e or S_i/f (magnetostrictive coupling) and M_i or S_e/f (piezoelectric coupling) against frequency on a logarithmic frequency scale. The frequency at the maximum in the symmetrical curve is $f_0 \cdot Q_m = f_0^2/(f_2 - f_1)$, where f_2 and f_1 are the frequencies (one above and the other below f_0) at which the quantity plotted for the symmetric curve has fallen to 1/2 (or -3 dB) relative to its maximum at f_0.

(3) Only if the mechanical system of a resonant transducer, including the normal acoustic load, is truly singly resonant will the appropriate response-frequency curve exhibit the required symmetry and the appropriate motional circle be clean and undistorted.

The electrical Q (or Q_e of a transducer) of principal interest is the value at the mechanical resonance f_0; the acoustic loading must be specified. In specifying a mechanical Q, the nature of the electrical termination must be stated as well as the acoustic load; that is, the electrical termination must be an open circuit or a short circuit, depending upon the nature of the electromechanical coupling as stated above.

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APPENDIX A: FREE-FIELD CALIBRATION IN A LABORATORY TANK

[This Appendix is not a part of American National Standard Procedures for Calibration of Underwater Electroacoustic Transducers, ANSI S1.20-1988, but is included for information purposes only.]

Spherical wave divergence, as would be obtained from a true point source, is approximated only beyond a minimum source distance such that

$$d > \pi a^2/\lambda \text{ and } d > a, \tag{A1}$$

where

d = distance,

a = largest radius or half-length of the source,

λ = wavelength of the sound.

Beyond this minimum distance from a piston or line source, the sound pressure at a point receiver will be within 4% of that calculated for spherical divergence. This minimum distance also exists for a finite receiver and a point or spherical source. For the measurement of directivity, the distance should be at least twice this minimum value. Sensitivity and response can be measured at less than this minimum distance and the data corrected to farfield conditions (Refs. A1, A2, and A3).

In the pulse technique, the source emits a pulse of sound at, for example, the rate 20 pulses per second. The output of the hydrophone is measured while the acoustic pulse arriving by the straight-line path is impinging on the hydrophone. The undesired signals in a free-field calibration are those transmitted electromagnetically and acoustically by indirect reflection paths. The pulse technique permits the desired signal to be separated from these undesired signals in the time domain. The electromagnetic transmission is practically instantaneous; the desired signal is delayed by the test distance divided by the speed of sound (d/c); the undesired acoustically reflected signals are delayed by $(d + \Delta d)/c$. The additional path Δd must be sufficient to allow measurement of the desired signal at the steady-state acoustic condition and the steady-state condition within the electrical circuit. The dimensions of the laboratory tank can be stated in terms of the separation distance d and this additional path Δd required for measurement of the desired signal under steady-state conditions:

$$\text{Tank length, } L > d + \Delta d \tag{A2}$$

$$\text{Tank width and depth, } W > (L^2 - d^2)^{1/2}. \tag{A3}$$

With these dimensions, the first reflections from the surface, bottom, and sides are delayed sufficiently for measurement of the steady-state portion of the desired signal when the source and receiver are symmetrically positioned in the tank at half the water depth. Under these conditions, an absorbent lining is not required, but it may be useful in reducing reverberation and thus facilitating a higher pulse repetition frequency for more rapid data acquisition.

The chief disadvantage of the pulsing technique is that a pulse consists of a spectrum of frequencies, whereas a continuous sinusoidal signal contains only one frequency. Undistorted transmission of a pulse through the transmitting amplifier, sound projector, hydrophone, and receiving system requires a broadband, constant overall system response above and below the measuring signal frequency. Some variation from the ideal conditions will always exist. Mathematical treatments of pulse transmission are given in Refs. A4, A5, and A6.

The transmitted pulse generally is a rectangular pulse, modulating the carrier frequency, which is the measurement frequency. For measurement purposes, the bandwidth of the overall system should be 2 to 20 times the reciprocal of the pulse duration. A bandwidth that is approximately twice the reciprocal of the pulse duration will yield a maximum signal-to-noise ratio; however, the amplitude of the pulse envelope in this case will be 2 dB above the amplitude of the corresponding pulse transmitted when the bandwidth is 20 times the reciprocal of the pulse duration. A bandwidth that is twice the reciprocal of the pulse duration sometimes is referred to as the essential bandwidth.

The pulse repetition rate in the calibration of underwater sound transducers generally is of the order of 1 to 100 pulses per second. The pulse duration will vary from 0.1 to 10 milliseconds, depending upon the frequency and the path delay of the undesired reflected signals. Thus the spectrum resulting from pulse modulation will have an essential bandwidth that varies from 0.2 to 20 kHz. It will contain within this band a line spectrum with the number of lines varying from 2 to 20 000. Generally, the receiving system is gated to receive only the steady-state portion of the transmitted pulse. A broadband receiving system that produces no distortion of this gated portion is essential for valid measurements. This gated pulse duration determines the required bandwidth of the receiving system.

In a reciprocity calibration, the measurements consist of determining three transfer impedance magnitudes, the ratio of the open-circuit received voltage to the driving current into the projector. The driving current can be observed on the oscilloscope as the voltage drop across a calibrated resistor in series with the projector. This voltage drop can be adjusted in amplitude by means of a calibrated variable attenuator until it is equal to the amplitude of the received voltage. The time delay through the water path makes it possible to view these two pulses simultaneously and compare the current pulse with the steady portion of the received voltage. Both signals pass through the adjustable bandpass filter for improvement of the signal-to-noise ratio. In a comparison calibration by the substitution method, the voltage across the projector or the voltage drop representing the current can be the reference signal to be matched with the steady-state received voltage signal from the standard hydrophone and then from the unknown or measured hydrophone. The gated receiving system is not required when an oscilloscope is used as the detector.

The measured portion of the acoustic pulse must represent the free-field, steady-state condition for receiving; the pulse must be free of any effects due to the tank boundaries; the pulse must be of sufficient duration to allow steady-state response to be measured. Steady-state response relates the pulse duration to the sharpness of the resonance and the acoustic path length of the pulse to the dimensions of the hydrophone. The number of cycles in the pulse must be equal to or greater than the Q of the measured transducer to allow steady-state response to be measured at resonance. The acoustic path length of the pulse must be greater than twice the length of the measured transducer in the direction of propagation, so that reflections within the transducer are included in the measured portion of the pulse. Obviously, the response of a line or array transducer to sound along its length will not be the same for a continuous wave and for a pulse shorter than or equal to the length of the line. Thus the minimum pulse length generally is a function of orientation in directivity measurements.

Most pulse detectors are peak detectors and are calibrated in peak or rms values. The time constant of the detector must be short enough to respond to a very few cycles and long enough to average any slight distortion in the measured position of the pulse. Wave form and pulse shape must be continuously monitored by means of an oscilloscope for any required readjustment of the circuitry.

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APPENDIX B: EFFECT OF AMBIENT HISTORY ON THE MEASURED RESPONSE

[This Appendix is not a part of American National Standard Procedures for Calibration of Underwater Electroacoustic Transducers, ANSI S1.20-1988, but is included for information purposes only.]

A hydrostatic pressure greater than a few pounds per square inch may change the characteristics of a transducer permanently or temporarily in several ways.[B1] For example: (1) It may compress some of the pressure-release materials used in the transducer's construction, which, in turn, may alter the radiation loading on the transducer. Furthermore, the transducer may require a period of time to recover after hydrostatic pressure has been removed, or it may fail to recover completely. (2) It may effectively alter the magnetic or electric polarization when hydrostatic pressure is transmitted to the active elements of magnetostrictive or piezoelectric transducers.

Variation in ambient temperature likewise will cause hysteresis in response or sensitivity of some piezoelectric transducers. Excessive driving current may raise the element temperature sufficiently to depolarize ceramic or magnetostrictive elements, and thus permanently alter the transducer response and directivity.

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APPENDIX C: RELIABLE RANGE OF HYDROPHONES

[This Appendix is not a part of American National Standard Procedures for Calibration of Underwater Electroacoustic Transducers, ANSI S1.20-1988, but is included for information purposes only.]

Omnidirectional standard hydrophones usually are reliable in the flat-response region below resonance. Orientation is not critical. Complex waveforms, such as are present in noise or pulses, can be reproduced faithfully if all significant harmonics lie in the flat-response region. In the region of resonance, response and directivity generally show large variations with changes in frequency and direction, thus making the frequency determination and orientation in the sound field more critical. Changes in temperature and static pressure may affect the hydrophone-case resonance and thus may cause wide variations in both response and directivity.[C1]

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[C1] R. J. Bobber, *Underwater Electroacoustic Measurements* (Naval Research Laboratory, U.S. Government Printing Office, Washington, DC, 1970). [Available from the Defense Technical Information Center (DTIC), Cameron Station, Alexandria, VA 22314.]

APPENDIX D: RELIABLE RANGE OF PROJECTORS

[This Appendix is not a part of American National Standard Procedures for Calibration of Underwater Electroacoustic Transducers, ANSI S1.20-1988, but is included for information purposes only.]

Projectors generally are limited to a frequency range of less than 5 octaves. The low-frequency limit depends on the loss in efficiency caused by the rapid drop in radiation resistance. The high-frequency limit is set by the breakup of the radiating surface that occurs at resonance and causes rapid fluctuations in the transmitting response versus frequency, or by the frequency at which the directivity becomes critically sharp.[D1]

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APPENDIX E: MEASUREMENT OF ATTENUATION COEFFICIENT AND CORRECTION OF RESPONSE

[This Appendix is not a part of American National Standard Procedures for Calibration of Underwater Electroacoustic Transducers, ANSI S1.20, 1988, but is included for information purposes only.]

In addition to the loss from normal spherical-wave divergence, the intensity or pressure may be further reduced by viscosity, scattering, and intramolecular processes. This reduction is an exponential decrease with an attenuation coefficient a. It can be neglected in the sonic and ultrasonic range up to approximately 1 megahertz for calibrations in fresh water, and below a few kilohertz in saltwater. A correction must be made for absorption in a reciprocity calibration and in a secondary calibration of transmitting response; however, no correction is required in a comparison calibration of receiving sensitivity.

The absorption coefficient can be determined in a free field by means of the relative level measurements, as a function of distance, when the projector-to-hydrophone distance is known to be sufficient for spherical divergence. Then, the attenuation coefficient is

$$a = \frac{1}{r_2 - r_1} \cdot \left(20 \log_{10} \frac{|e_1|}{|e_2|} - 20 \log_{10} \frac{|r_2|}{|r_1|}\right), \quad \text{(E1)}$$

where

a = absorption coefficient in decibels per meter,
r_1 = minimum separation distance in meters,
r_2 = second separation distance in meters,
e_1, e_2 = voltage outputs of the hydrophone at r_1 and r_2 for constant projector input.

Because the coefficient is temperature dependent, it should be measured at the same water temperature that exists at the time of calibration.

In the reciprocity calibration (see 5.3.2), the attenuation coefficient enters into the J factor as a distance loss correction. Thus, in the J, where r is in meters,

$$|J| = (2r/\rho f) \cdot 10^{ar/20}. \quad \text{(E2)}$$

In the transmitting response calibration (5.3.2.4 and 5.3.2.5), the attenuation reduces the sound pressure output at the distance r by the factor $10^{\alpha r/20}$ and, therefore, the value of the response S_i must be increased above the measured value by $10^{\alpha r/20}$. If the projector is used for sound generation, the attenuation α' under the existing conditions must be determined, and the output pressure computed from its transmitting response must be corrected by $10^{\alpha' r/20}$.

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