2

Measurement and Generation of Underwater Sounds

2.1 Electroacoustic Transducers

Acoustic signals are detected and generated with devices called electroacoustic transducers. These devices convert electrical energy into acoustic energy or acoustic energy into electrical energy. Transducer that converts acoustic energy into electrical energy has traditionally been called hydrophones or receiving transducers. Likewise, devices that convert electrical energy into acoustic energy are referred to as projectors or transmitting transducers. Many electroacoustic devices are used for both receiving and transmitting acoustic signals and are referred to as transducers.

In many instances, a bioacoustician has to construct his/her own transducer because of a special application requiring an unusual design or size, or because of budgetary constraints. The goal of this chapter is to provide sufficient information so you could, if necessary, construct transducers with a reasonable certainty of being successful, but without the need to become a transducer "expert." It is not our goal to provide an in-depth analysis of transducer material and design, which would be beyond the scope of this book. Those interested in a deeper discussion of underwater acoustic transducer material and design should refer to books by Wilson (1988), Bobber (1970), Huerter and Bolt (1955) and Cady (1964).

Most transducers convert energy from one form into another by using (a) materials with *electrostriction* on *piezoelectric* properties, (b) materials with *magnetostriction* properties, and (c) electrodynamics principles. Piezoelectric properties are found in some crystalline substances such as quartz, ammonium dihydrogen phosphate (ADP), and Rocelle salt. These crystals acquire an electrical charge between certain crystal surfaces when placed under pressure, or they acquire a stress when a voltage is placed across them. Electrostrictive materials exhibit the same effect as piezoelectric crystals, but are polycrystalline ceramics that have to be properly polarized by subjecting them to a high electrostatic field while in a melted form under high temperature and cured into a solid with the electrostatic field still being impressed. Popular electrostrictive materials are barium titanate and lead zirconate titanate, and they are commonly referred to as piezoelectric

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ceramics. Magnetostrictive materials change dimensions, producing stresses when placed in a magnetic field; and conversely, elastic strain changes the flux density and induces an electromotive force in a conductor that surrounds the material. Electrodynamic transducers operate like in-air speakers, but are adapters for operation under water. They are particularly effective for the generation of relatively low-frequency sounds.

Although many different materials have been the subject of research and development for use in underwater transducers, most of the modern devices are constructed out of piezoelectric ceramics, either barium titanate (BaTi) or lead zirconate titanate (PZT). Over the past two decades, the use of lead zirconate titanate has far outstripped that of barium titanate. One distinct advantage of piezoelectric ceramics over piezoelectric crystals and magnetostrictive materials is the relative ease at which they can be molded into desirable shapes such as hemispheres, cylinders, and plates. Still easier to shape are the piezoelectric plastics and rubbers, which will be discussed later in this section. These materials are becoming increasingly popular as individuals become accustomed to making and using them for the reception of acoustic signals.

2.2 Sensitivity and Frequency Response of Piezoelectric Elements

Underwater acoustics can be used for many different purposes such as navigation, communication, target location, intruder detection, and even the monitoring of marine life, requiring the availability of many different types of acoustic sensors and sound generator devices. The major differences between a general measurement transducer and other special purpose transducers are the sensitivity and frequency-response characteristics. High sensitivity over a very wide band of frequency is desired in general purpose measurement transducers, whereas special purpose transducers often operate over a very narrow band of frequency. Some general purpose hydrophones have good sensitivity over a four-decade range of frequency.

Although most piezoelectric ceramic are isotropic and not piezoelectric prior to poling (polarization), after poling they become anisotropic; their electromechanical properties differ for electrical or mechanical excitation along different axes of a crystallographic coordinate system. There are also coupling or interaction between properties along the different axes so that a system of nine linear partial differential equations is necessary to describe the piezoelectric action in the presence of a sound field. We will instead take a simplified approach to the discussion of piezoelectric ceramics, but still attempt to include the most important issues involved in the design, construction, and use of piezoelectric transducers.

The sound pressure level (SPL) measured by a hydrophone can be determined from a knowledge of the hydrophone free field sensitivity, the gain in the measurement system and the amount of voltage measured. Let M_h be the free field voltage sensitivity of a hydrophone in dB re 1 V/μPa, and assume that the hydrophone is connected to an amplifier of gain G in dB, then the SPL in dB re 1 μPa is given by the equation

$$\mathrm{SPL} = |M_h| - \mathrm{G} + 20 \log V, \tag{2.1}$$

where V is the voltage read off an oscilloscope or voltmeter. It is conventional to measure the rms voltage so that SPL will be the rms SPL. However, there are times when it is considerably more convenient to measure either peak or peak-to-peak voltages. In these cases, SPL will be either the peak or peak-to-peak SPL in dB re 1 μPa. The input impedance of an amplifier should be much higher than the impedance of the hydrophone so that "loading" effects will not affect the measurements. In most broadband hydrophones, the impedance decreases with frequency. If acoustic measurement of a sound source was conducted with a hydrophone located at a range of R from the source and the source level (SL), defined as the SPL at a reference range of 1 m, is desired, the transmission loss must be taken into account. If the hydrophone is not very far from the source (less than several tens of meters at most), we can assume spherical spreading loss so that using Eq. (1.51) the source level can be written as

$$\mathrm{SL} = \mathrm{SPL} + 20 \;\log R + \alpha R, \tag{2.2}$$

where α is the sound absorption coefficient in dB/m, and will be discussed later in Chapter 3.

Sounds can be produced in water by driving a transducer with a signal generator and a power amplifier. The transmit sensitivity of a transducer is generally given in terms of its source level per volt or per ampere of drive. Let S_v be the voltage transmit sensitivity in dB re 1 μPa/volt and S_i be the current transmit sensitivity in dB re 1 μPa/amp; the source level in dB re 1 μPa will be

$$\mathrm{SL} = S_v + 20 \log V_{in}, \tag{2.3a}$$

$$\mathrm{SL} = S_i + 20 \log I_{in}, \tag{2.3b}$$

where V_{in} is the voltage and I_{in} is the current at the input of the transducer cable. The SPL at any distance from the transducer can be calculated by subtracting the transmission loss from Eq. (2.3). The use of the nomenclature M for the hydrophone (receive) sensitivity and S for the projector sensitivity is a holdover from airborne acoustics where M stands for microphone and S for speaker. Throughout this chapter for convenience sake, M and S will be used interchangeably on a dB and linear scale.

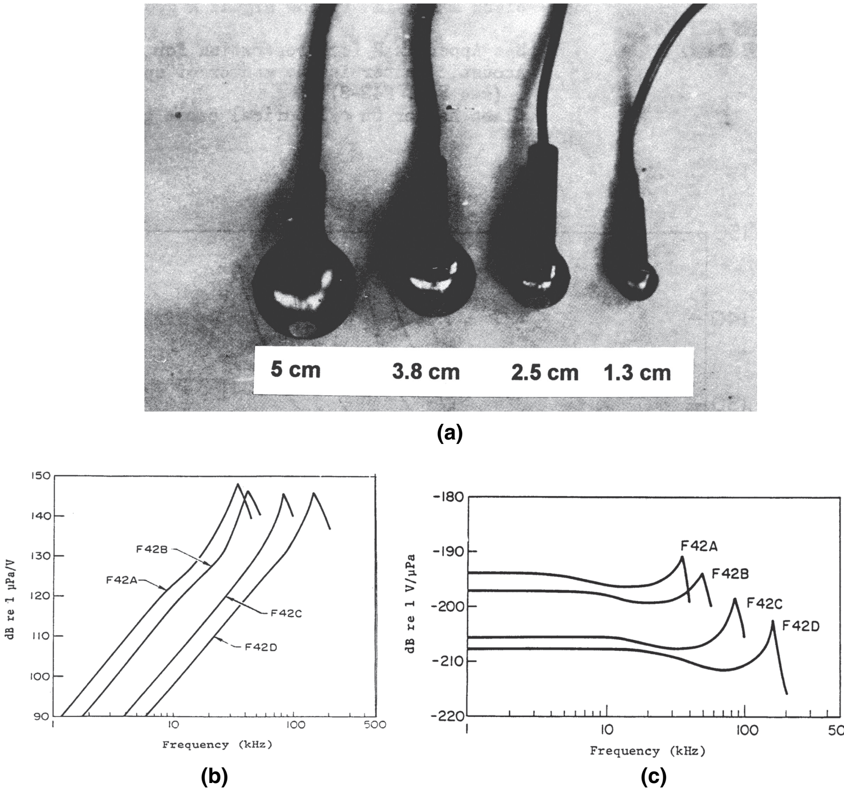

FIGURE 2.1. **(a)** Photograph of the USRD family of F42 spherical hydrophones; **(b)** the transmit response curves; **(c)** the receive response curves.

A family of F-42 spherical hydrophones of different diameters (standard hydrophones from the U. S. Navy's Underwater Sound Reference Detachment [USRD]) is shown in Fig. 2.1a, with the transmit and receive sensitivity curves as a function of frequency shown in Fig. 2.1b,c, respectively. The diameter of the elements are 5.00, 3.81, 2.54, and 1.27 cm for the model A, B, C, and D, respectively. The sensitivity curves indicate that the larger the diameter the more sensitive the response, but with a smaller frequency range. The positive peak in each response curve occurs at the resonance frequency of the different elements. Resonance has to do with the vibrational characteristic of a structure. Any structure will have certain frequencies at which larger vibrations can be induced with a small driving function having minimal energy. These characteristic frequencies are called resonance frequencies, and their exact values will depend on the shape, size, and material composition of the structure. Resonance in transducer elements will be treated in more detail in a later section of this chapter. The receiving response of a spherical hydrophone is relatively flat for frequencies below the resonance frequency, peaks at the resonance frequency and then drops off rapidly for frequencies above the resonance frequency.

2.2.1 Equivalent Circuit and Resonance

The shape of the receiving sensitivity curves shown in Fig. 2.1 can be explained by considering a simple equivalent circuit for a piezoelectric transducer. In Section 1.2.4, we used an analogy between an electrical circuit and a plane acoustic wave propagating in a fluid. Acoustic pressure was said to be analogous to voltage, and the velocity of a particle under the influence of an acoustic pressure wave was analogous to current, and in this manner derived the specific acoustic impedance expressed by Eq. (1.40). The impedance of an electrical circuit is the ratio of voltage and current and can be characterize by its resistance, inductance, and capacitance. In an analogous manner, we can also characterize a piezoelectric element by its mechanical impedance, defining this impedance as the ratio of the force on and the velocity of the element. We can define a mechanical impedance for the piezoelectric element as

$$Z_{\mathrm{m}} = R_{\mathrm{m}} + j\left[\omega L_{\mathrm{m}} - \frac{1}{\omega C_{\mathrm{m}}}\right] = R_{\mathrm{m}} + j\left[\omega m - \frac{s}{\omega}\right], \tag{2.4}$$

where R_{m} is the mechanical resistance associated with mechanical losses in the element, $L_{\mathrm{m}} = m$ is the effective mass of the vibrating element and is analogous to electrical inductance, $C_{\mathrm{m}} = 1/s$ is the mechanical compliance or stiffness of the material and is analogous to the electrical capacitance, and ω is the radian frequency defined as $\omega = 2\pi f$. The mechanical impedance is a complex quantity with a real and imaginary part, and is referred to as the mechanical resistance and reactance, respectively. Its unit is not ohms, since the quantity is a ratio between force and velocity rather than voltage and current. If a sinusoidal force (either electrical or acoustics) is applied to the element, the element will vibrate at a velocity of

$$u = \frac{F\mathrm{e}^{j\omega t}}{R_{\mathrm{m}} + j\left[\omega L_{\mathrm{m}} - \frac{1}{\omega C_{\mathrm{m}}}\right]} = \frac{F\mathrm{e}^{j\omega t}}{R_{\mathrm{m}} + j\left[\omega m - \frac{s}{\omega}\right]}, \tag{2.5}$$

where F is the magnitude of the sinusoidal force. There will be a frequency, called the resonance frequency, at which $\omega L_{\mathrm{m}} = 1/\omega C_{\mathrm{m}}$ ($\omega m = s/\omega$). At this frequency, the impedance is real and has its minimum value so that the velocity (Eq. (2.5)) is at its maximum. The relative velocity amplitude as a function of frequency is shown in Fig. 2.2, where f_0 is the resonance frequency and Δf is the 3-dB bandwidth. Another important parameter used to describe resonance is the Q of the element, which is defined as

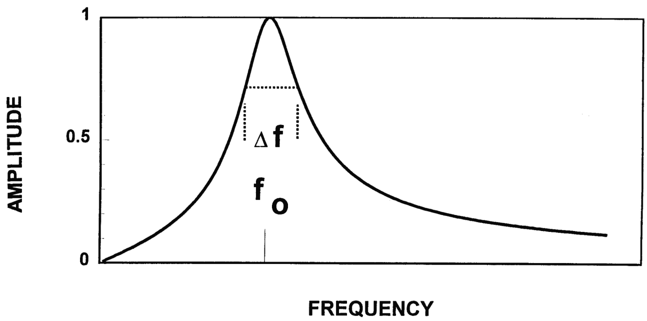

FIGURE 2.2. An example of a resonance response curve.

$$Q = \frac{f_0}{\Delta f}. \tag{2.6}$$

The parameter Q is also used to describe the relative bandwidth of resonance in electrical circuits. The bandwidth of the resonance curve is inversely proportional to the mechanical resistance of the element. If R_m is small, the curve falls off very rapidly and the resonance is sharp. If R_m is large, the curve falls off more slowly and the resonance is broad.

A piezoelectric transducer in an acoustic field can be thought of as having an *electrical component* and a *mechanical component*. An acoustic wave will apply a stress on the piezoelectric element, which in turn will cause the element to be strained. The strain on the element will cause an electrical voltage to appear across the electrodes of the transducer. If we let ϕ be the electromechanical voltage to force conversion ratio (a given force on the hydrophone element will generate an electrical voltage across the electrodes), we can depict a piezoelectric transducer by the simple equivalent circuit shown in Fig. 2.3a, where C_e is the capacitance across the terminal of the transducer. The sensitivity of a receiving transducer (M_h) is merely the ratio of the acoustic pressure and the open-circuit voltage generated across the electrodes ($M_h = V_{0c}/p$). For the equivalent circuit of Fig. 2.3, the receiving sensitivity can be expressed as

$$M_h = \frac{V_{0c}}{p} = \frac{\varphi A}{j\omega C_e \varphi^2 \left(R_m + j\left[\omega m - \frac{s}{\omega}\right]\right) + 1}. \tag{2.7}$$

At all frequencies except perhaps near resonance, $j\omega C_e \phi^2 Z_m >> 1$ (Bobber, 1970), so that the receiving sensitivity is nearly inversely proportional to ωZ_m. At very low frequencies, $s/j\omega >> [R_m + j\omega m]$ so that

$$M_h \approx \frac{A}{\phi C_e s} = \frac{A}{\phi C_e / C_m}. \tag{2.8a}$$

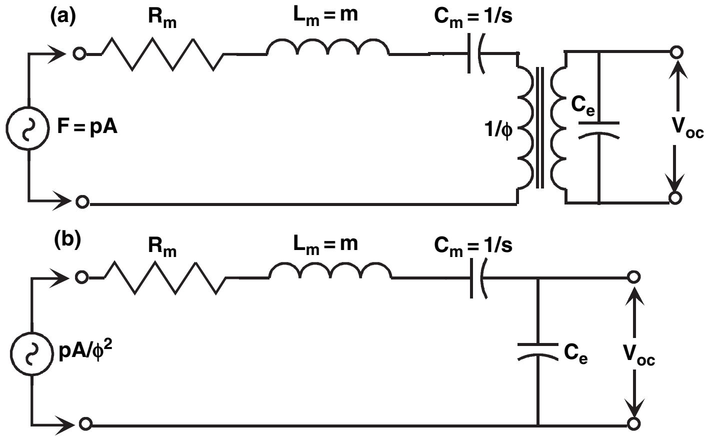

FIGURE 2.3. (**a**) A simple equivalent circuit for a piezoelectric element used as a hydrophone; (**b**) same equivalent circuit with the transformation constant reflected back to the source.

A generalized receiving response piezoelectric element as a function of frequency is shown in Fig. 2.4, relating the various areas of the response curve to the relative values of the components making up the mechanical impedance. Above the resonance frequency, $j\omega m >> (R_m + 1/j\omega C_m)$ (Bobber, 1970), so that the sensitivity falls off rapidly with frequency with a slope that is inversely proportional to the square of the frequency as can be seen in Eq. (2.8b). The generalized

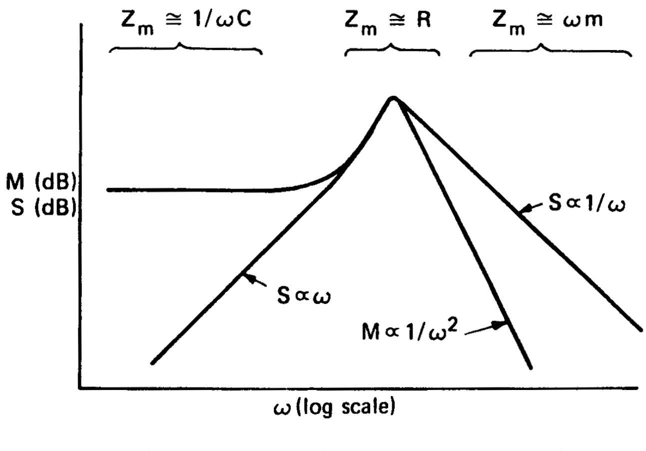

FIGURE 2.4. Generalized response curves for a piezoelectric transducer (adapted from Bobber, 1970).

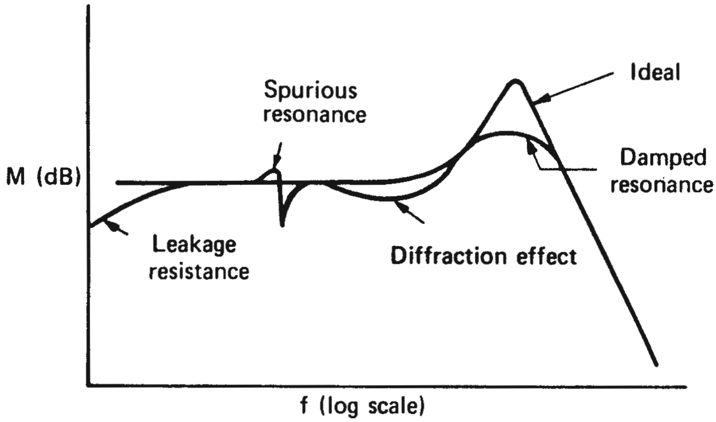

FIGURE 2.5. Typical effects of resonant damping, diffraction, spurious resonances and leakage.

$$M_{\mathrm{h}} \approx \frac{-\mathrm{A}}{\omega^2 C_{\mathrm{e}} \varphi m} = \frac{-\mathrm{A}}{\omega^2 C_{\mathrm{e}} \varphi L_{\mathrm{m}}} \tag{2.8b}$$

transducer response curves of Fig. 2.4 pertain to an ideal situation. Real calibration curves seldom look like the idealized curves, as can be seen by comparing the curves of Figs. 2.1 and 2.4. The resonant peak is damped and spurious resonances may appear as shown in Fig. 2.5. At very low frequency, the capacitive reactance of the element will become larger than the resistivity of, or the leakage resistance around, the element causing the response to roll off at a 6-dB per octave rate as the frequency decreases. The diffraction effect has to do with the presence of the transducer disturbing the acoustic field, causing perturbation of the field as the wave propagates around the transducer.

Piezoelectric elements are reciprocal devices, which mean that they can be used for both receiving and transmitting acoustic signals. Sounds are produced by driving the element with a signal generator connected across the electrodes of the element. The electrical voltage will cause the element to vibrate and couple acoustic energy into the water.

We will now consider the transmit sensitivity response of a piezoelectric element. The transmit sensitivity curves shown for the F-42 family of transducers in Fig. 2.1b are typical of the piezoelectric elements. There is a parameter called the reciprocity parameter and is usually designated as J, which relates the receive sensitivity to the current transmit sensitivity (S_{i}) of a piezoelectric element, and is defined as

$$J = \frac{M_{\mathrm{h}}}{S_{\mathrm{i}}}. \tag{2.9}$$

For this discussion, J can be expressed as (Bobber, 1970)

$$J = \frac{b}{f}, \tag{2.10}$$

where f is the frequency and b is a constant. Inserting Eqs. (2.9) and (2.10) into Eq. (2.7), we get

$$S_{\mathrm{i}} = \frac{\varphi \mathrm{A}\omega / b'}{j\omega C_{\mathrm{e}}\varphi^2 (R_{\mathrm{m}} + j[\omega m - s/\omega]) + 1}, \tag{2.11}$$

where $b' = 2\pi b$. At all frequencies expect perhaps near resonance, $j\omega C_{\mathrm{e}}\phi^2 Z_{\mathrm{m}} >> 1$ (Bobber, 1970), and at very low frequencies, $s/j\omega >> [R_{\mathrm{m}} + j\omega m]$. Therefore, the mechanical impedance is dominated by the stiffness of the material so that the Eq. (2.11) can be reduced to

$$S_{\mathrm{i}} \approx \frac{\mathrm{A}\omega}{b' C_{\mathrm{e}}\varphi\, s}. \tag{2.12}$$

The generalized transmission response curve for a piezoelectric transducer is depicted by the curve denoted as S in Fig. 2.4. At all frequencies except perhaps near resonance, $j\omega C_{\mathrm{e}}\phi^2 Z_{\mathrm{m}} >> 1$ (Bobber, 1970), and at very low frequencies, $1/j\omega C_{\mathrm{m}} >> [R_{\mathrm{m}} + j\omega m]$. Therefore, below resonance, the current transmit sensitivity varies linearly with frequency until the resonance frequency is approached. Above the resonance frequency, $j\omega m >> (R_{\mathrm{m}} + 1/j\omega C_{\mathrm{m}})$ (Bobber, 1970), so that the sensitivity falls off rapidly with frequency with a slope that is inversely proportional to the frequency. From Eqs. (2.3a,b), the voltage transmit sensitivity, $S_{\mathrm{v}} = I_{\mathrm{in}}/V_{\mathrm{in}}\ S_{\mathrm{i}} = S_{\mathrm{i}}/Z_{\mathrm{in}}$. At low frequencies below resonance, Z_{in} decreases linearly with frequency so that S_{v} will be a function of ω^2 or f^2, as can be seen in the voltage transmit sensitivity curves of the spherical transducers of Fig. 2.1.

2.2.2 Resonance of Different Shaped Elements

It is important to have some understanding of the resonance of transducer elements because of the large role resonance plays in the response characteristics of transducer elements. The specific resonant frequency of a transducer element will depend on its shape, size, and material composition. If we are interested in projecting high-amplitude signals into the water, it would be best to operate close to the resonance frequency of the element. Conversely, if we are interested in receiving signals over a wide frequency band with the response of the hydrophone being relatively flat over the frequency band, then we would want to operate as far below the resonant frequency of the element.

A free-standing element of a given shape will vibrate in many different modes, and a resonant frequency will be reached whenever the wavelength of the signal in the element is a integer number of half a wavelength. Therefore, the size and shape of the element along with the speed of sound of the material associated with different modes are important in determining its resonant frequencies. Figure 2.6 shows the modes of some simple element shapes along with the fundamental resonant frequency for the specific mode of vibration. The parameter N_n is related to the sound velocity of the material and is referred to as the frequency constant. This parameter is usually provided by the piezoelectric ceramic manufacturer and different for different material compositions and modes of vibration. Some typical values for the barium titanate and lead titanate zirconate compositions are given in Table 2.1. Some coupling is always present between the various modes of vibration depicted in Fig. 2.6, and the upper frequency limit of the relatively flat response portion of a receiving hydrophone

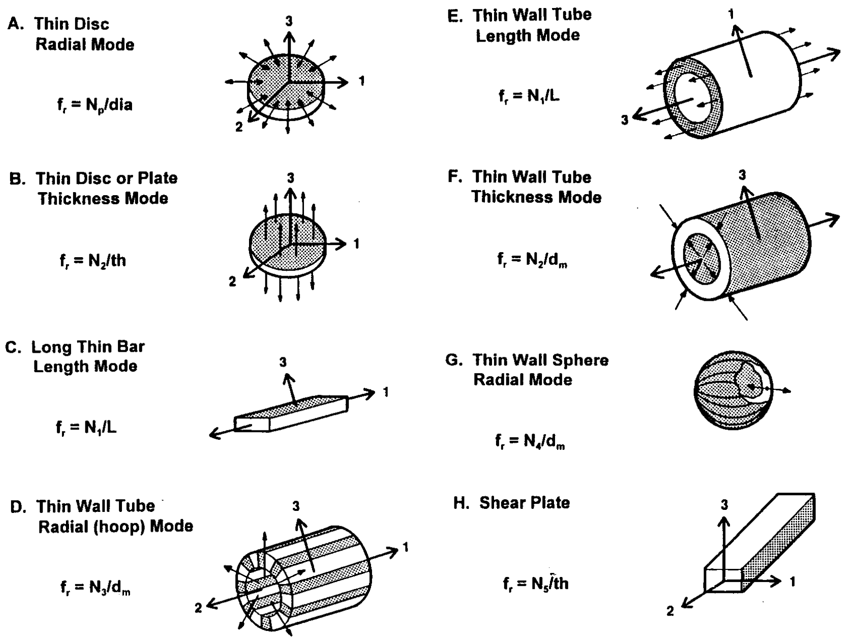

FIGURE 2.6. Vibration modes of piezoelectric elements. The direction of polarization is along the **3**-axis usually coinciding with the z-axis and the **1** and **2**-axes coincide with the x and y-axes of a Cartesian coordinate system, respectively (with permission of Edo-Western Corp.).

TABLE 2.1. Typical Values of Frequency Constant for Barium Titanate and Lead Zirconate Titanate

Parameter	Vibrational mode	Freq. const. (Hz/m) barium titanate	Freq, const. (Hz/m) lead zirconate titanate
N_1	Length mode	1321–2324	1359–2337
N_2	Thickness mode	1727–2845	1765–2858
N_3	Circumferential mode	851–1461	876–1473
N_4	Radial mode	1435–2438	1473–2464
N_5	Shear mode	1067–1575	1092–1600
N_p	Planar mode	1943–3150	1961–3188

sensitivity curve is somewhat below the frequency of the lowest natural mode of vibration of the element.

2.2.3 Measurement of Resonant Frequency

The lowest resonant mode of a piezoelectric element can be easily measured using the circuit shown in Fig. 2.7 and performing the measurement in air. The oscillator should generate a constant voltage, and in the ideal case, $R << Z_{res}$, where Z_{res} is the impedance of the element at resonant. The variation of impedance as a function of frequency showing the effects of resonance and anti-resonance is shown in Fig. 2.7b. The piezoelectric material behaves capacitively below f_r and above f_a, and between the two frequencies it behaves inductively. The phase angle of the element also undergoes a sign change at both the resonance frequencies, and can be used to measure resonant frequencies. While the ideal case is easy to realize in measuring either resonant or anti-resonant conditions, it is more difficult to accurately measure both with a single R. The high Q of the element in air makes it difficult to find a value of R that results in good signal-to-noise ratio anti-resonance and yet meet the condition $R << Z_{res}$ at resonance.

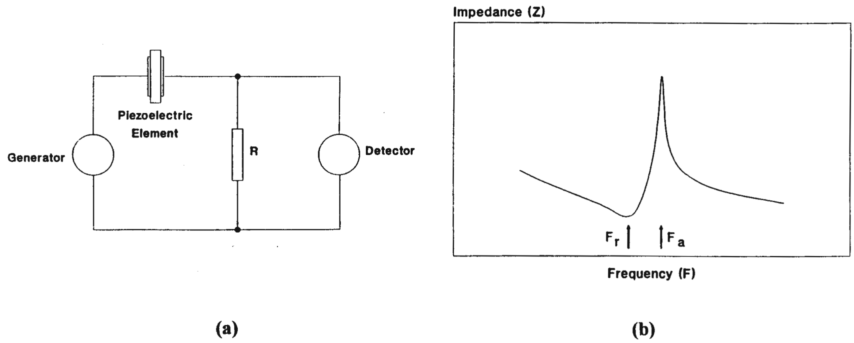

FIGURE 2.7. **(a)** Constant voltage generator circuit for measuring resonant frequency; **(b)** variation of impedance with frequency.

2.3 Hydrophone Sensitivity Using Piezoelectric Parameters

A piezoelectric ceramic is a complex electromechanical device that requires many parameters, such as the dielectric constant, loss tangent, piezoelectric charge coefficients, piezoelectric coupling coefficients, elastic constants to adequately describe its electromechanical properties. Since a piezoelectric ceramic is anisotropic, some of the parameters will have different values along the different axes of the crystallographic coordinate system. It would be far beyond the scope of this book to attempt an in-depth examination of the properties of piezoelectric material. Fortunately, the receiving sensitivity of some simple hydrophone geometries can be calculated from the piezoelectric voltage coefficient usually supplied by ceramic manufacturers. This coefficient is normally denoted as $\mathbf{g_{ij}}$, where the **i** subscript refers to the direction in which the electrode is perpendicular to and **j** is the direction of the applied stress caused by the acoustic wave. The **i** and **j** subscripts can have values of 1, 2 or 3 corresponding to the x, y, and z-axis, respectively (see Fig. 2.6).

We will consider some simple cases, assuming that the piezoelectric element has dimensions that are much smaller than the wavelength of the sound in a fluid, so that the acoustic pressure is essentially uniform over the dimension of the element. Usually, the frequency of operation of a hydrophone receiver is well below the frequency of mechanical resonance, so that wave propagation in the ceramic can be neglected. For all practical purposes, the receiving sensitivity we are examining can be considered as a low-frequency estimate. Consider a very small rectangular block of piezoelectric ceramic of dimensions w, l, and t, shown in Fig. 2.8a, polled along the t-direction. Since the element is small compared to a wavelength, the acoustic pressure will have the same amplitude and phase on all sides. For such a situation, the receiving sensitivity can be determined using the piezoelectric voltage coefficients, g_{31} to account for the acoustic pressure on the side faces and g_{33} to account for the pressure on the electrode face. The receiving sensitivity will be (Wilson, 1988)

$$M_0 = \frac{V_0}{p} = (2g_{31} + g_{33})t. \tag{2.13}$$

Now let us consider the case in which all the non-electrode faces of the piezoelectric block are isolated by covering these faces with a acoustically reflective material. In this case, the acoustic pressure acts only on the electrode faces (see Fig. 2.8b), and the receiving sensitivity will be

$$M_0 = g_{33}t. \tag{2.14}$$

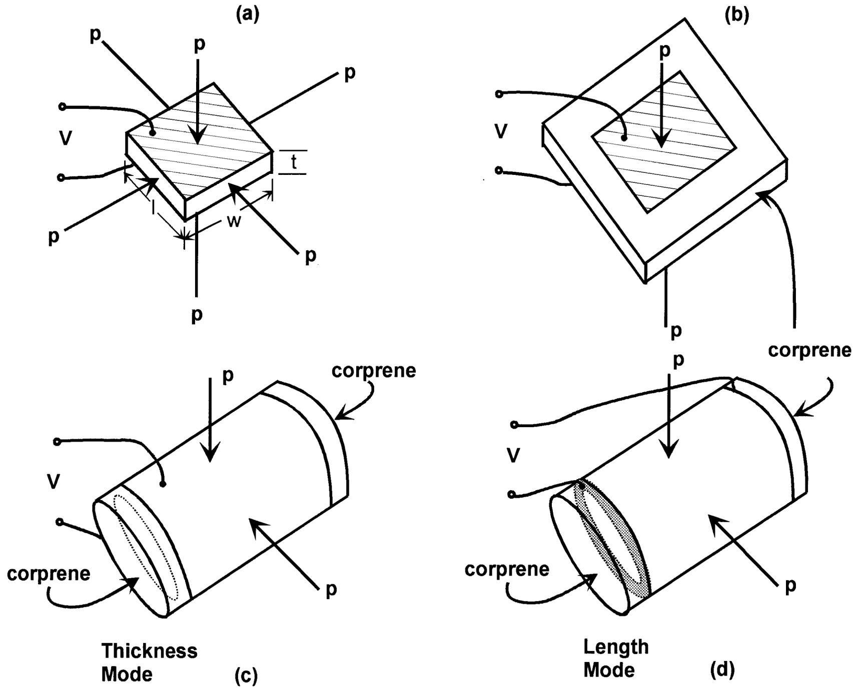

FIGURE 2.8. Simple geometry of piezoelectric elements for the calculation of hydrophone receiving sensitivity.

Equations (2.13) and (2.14) will also apply to a circular disk element, similar to that shown in Figs. 2.6a and 2.6b. The hydrophone depicted in Fig. 2.8b will be more sensitive than the one depicted in Fig. 2.8a, because g_{31} will have a negative value. For example, typical values of the piezoelectric voltage coefficients for a Navy Type 1 PZT material are $g_{31} = -10.5 \times 10^{-3}$ (volt-m/Newton) and $g_{33} = 24.5 \times 10^{-3}$ (volt-m/Newton). Therefore, for the element in Fig. 2.8a, $M_0 = 3.5 \times 10^{-3} t$ (volt-m/Newton) and for Fig. 2.8b, $M_0 = 24.5 \times 10^{-3}\ t$ (volt-m/Newton).

We will now consider hollow cylindrical piezoelectric elements with an inner radius of a and an outer radius of b. For a cylinder that is radially polarized as shown in Fig. 2.8c, and with the ends and interior surfaces acoustically isolated, the receiving sensitivity can be estimated with the equation (Wilson, 1988)

$$M_0 = b\left(g_{31} + g_{33}\left[\frac{1-\rho}{1+\rho}\right]\right), \tag{2.15}$$

where $\rho = a/b$. Since the piezoelectric voltage coefficients g_{31} and g_{33} have opposite signs, the sensitivity will depend on the ratio of both a/b and the piezoelectric voltage coefficients. The opposite signs of the g coefficients will cause the sensitivity to be equal to zero for certain values of ρ. Setting the expression within the parenthesis in Eq. (2.14) to zero, we get

$$\frac{1+\rho}{1-\rho} = -\frac{g_{33}}{g_{31}}. \tag{2.16}$$

Solving for ρ, we obtain values of ρ that will make the sensitivity equal to zero,

$$\rho = -\frac{1+(g_{33}/g_{31})}{1-(g_{33}/g_{31})}. \tag{2.17}$$

Using the g coefficients for the Navy Type I PZT material in the previous example, $g_{33}/g_{31} = -2.3$, so that the cylindrical element will have zero sensitivity when $a/b = 0.399$.

For a longitudinally polarized hollow cylinder in which the ends and interior are acoustically shielded (Fig. 2.8d), the receiving sensitivity can be estimated with the expression

$$M_0 = \frac{2\,Lg_{31}}{1-\rho^2} \tag{2.18}$$

(Wilson, 1988). This expression indicates that the sensitivity is proportional to the length L and inversely proportional to $(a/b)^2$. Therefore, the thinner the wall the greater the sensitivity.

The final case we will consider is that of a hollow spherical piezoelectric element. Again, with $p = a/b$, the receiving sensitivity can be estimated by the expression

$$M_0 = \frac{b}{2(1+\rho+\rho^2)}\left[g_{33}(\rho^2+\rho-2) - g_{31}(\rho^2+\rho+4)\right]. \tag{2.19}$$

Like the radially polarized cylinder, the sensitivity of the spherical element will depend on both the piezoelectric voltage coefficients and the ratio of inner and outer radii. The sensitivity can also be zero for a certain ratio of a/b. However, this ratio cannot be easily derived with an analytical expression, but must be solved numerically using an iterative process.

2.4 Piezoelectric Polymer Material

Thus far we have considered only ceramics and crystalline materials as electroacoustic elements. Recently, a new technology has been developed, which is slowly gaining popularity as an underwater sensing element. Kawai

(1969) discovered that there were large useful piezoelectric pyroelectric effects in the polymer polyvinylidene fluoride (PVDF). This material comes in the form of a thin film, like a sheet of plastic, which is stretched and polarized with a thin layer of electrode electroplated on each side of the sheet. After polarization, the material exhibits a piezoelectric property that is stable over time, and can be used to project and receive sounds. PVDF elements have been applied to loudspeakers, headphones, and microphones, high-frequency broadband ultrasonic transducers, thermal detector for optical imaging systems, and a variety of force, pressure, acceleration, and strain transducer.

PVDF material has some distinct advantages over piezoelectric ceramics in underwater applications. Besides being relatively inexpensive, it is tough, flexible, lightweight and available in large sheets up to several square meters. Its specific acoustic impedance of 1.5×10^6 rayls is very close to water so that it will provide only a minimum distortion to a sound field. Its thin, flexible structure makes it easy to literally take a scissor and cut out any desirable aperture shape for a transducer element. The material can also be easily laid over and made to conform to structures of different shapes. Finally, PVDF films are inherently broadband devices that can operate in the megahertz frequency range. A PVDF element, because of its low compliance and flexible nature, is not subject to the various resonance modes depicted in Fig. 2.6, and is affected mainly by the thickness mode of resonance. However, PVDF materials also have some distinct disadvantages compared to piezoelectric ceramics. The piezoelectric constants of PVDF are significantly smaller than those of PZT ceramic, and the material cannot be used at temperatures much above 80°C because of the poor thermal stability of some of its properties (Wilson, 1988).

PVDF materials are used mainly as hydrophone elements because its transmission properties are relatively poor for generating underwater sounds. For a planar element of thickness t of almost any shape, the low-frequency open-circuit sensitivity is (Moffett et al., 1986)

$$M_0 = 20 \log |\mathrm{m}_0| - 120, \tag{2.20}$$

$$m_0 = g_\mathrm{h}\boldsymbol{t}, \tag{2.21}$$

where $g_\mathrm{h} = g_{31} + g_{32} + g_{33}$ is the volume expansion piezoelectric constant. The constant of 120 in Eq. (2.20) is used to convert the reference from Pa to μPa. The unit for M_0 is dB re 1 V/μPa.

Besides being available as plain sheets, PVDF are often supplied as planar elements attached to stiffening electrodes, as shown in Fig. 2.9a,b, and as cylinders, as shown in Fig. 2.9c. The stiffening electrodes are used to minimize the in-plane or transverse (g_{31} and g_{31}) sensitivity and to maximize g_h. The elements depicted in Fig. 2.9b are connected in parallel to increase the overall

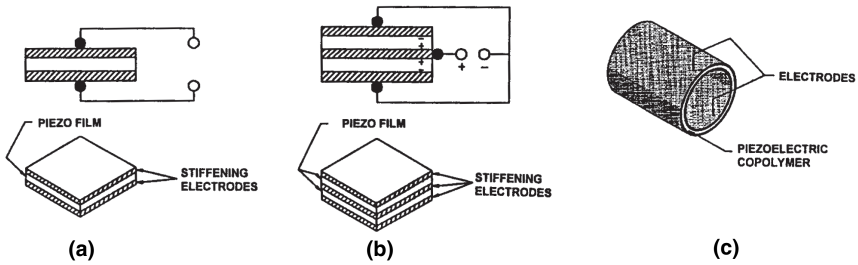

FIGURE 2.9. **(a)** PVDF material with stiffening electrodes; **(b)** PVDF material in parallel with stiffening electrodes; **(c)** PVDF material in a cylindrical form.

capacitance of the element, which in turn will give the element a greater capacity to drive cables of longer lengths. The capacitance of PVDF material is usually provided by the manufacturer in term of Farad per unit area. Its sensitivity will be the same as the single element. The sensitivity of the cylindrical element having a wall thickness of t can be calculated from Eqs. (2.20) and (2.21). Its capacitance is given by the expression

$$C = 2\varepsilon L/\log(b/a), \tag{2.22}$$

where L is the length of the cylinder, ε is the permittivity of the PVDF material, a is the inner radius and b is the other radius.

There are some synthetic rubbers that have been demonstrated to have piezoelectric properties after proper polarization. However, this technology is still in its infancy, and considerable work needs to be done before it can be used as a hydrophone. Therefore, we will not discuss this topic any further.

2.5 Transducer Configuration

In the preceding sections, we discussed transducers from a single-element point of view. However, many, if not most, transducers are configured with an array of elements, usually connected in parallel. The use of multiple elements serves three purposes: first, as a means to construct electroacoustic devices with large apertures that will have a desired directivity property (directivity will be covered in the next chapter) but still have a desired bandwidth; second, to lower the output impedance of the parallel connected element so that the array will be able to drive a longer cable than a single element; and third, to lower the output impedance of parallel connected elements so that the input impedance of a preamplifier can be kept low and therefore reduce the noise limit of a hydrophone–amplifier pair. From the equivalent circuit Fig. 2.3 in which we neglect the leakage resistance of an element, each element in a parallel-connected configuration acts basically as a charged capacitor. Therefore, a number of

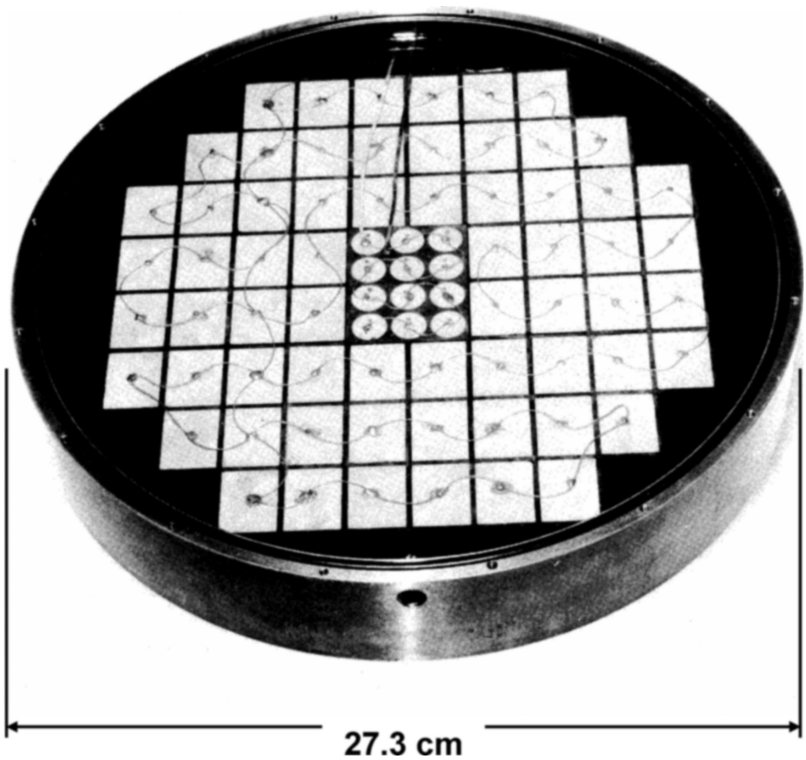

FIGURE 2.10. Piezoelectric ceramic element array, USRD type F33 transducer (adapted from Bobber, 1970).

capacitors connected in parallel will cause the total capacitance of the array to be larger, so that the total capacitance will be the sum of the individual capacitance of each element. Since the electrical impedance is inversely proportional to capacitance, an increase in the output capacitance will mean a lower output impedance and the ability to drive a longer cable. An array of parallel elements will also circumvent resonance problems that would be inherent in a single, large ceramic element. The resonance frequency of an array of elements will be determined by the resonance frequency of each individual element. Therefore, an array of elements will have a higher resonance frequency (leading to greater bandwidth) than a single, large element of comparable size as the array of elements. Finally, using an array of parallel elements is often more cost-effective than trying to produce a large, single piezoelectric ceramic element. The discussion so far does not apply to PVDF since PVDF is usually made in relatively large sheets and does not tend to resonate in other than the thickness mode. However, as stated in Section 2.4, PVDF is not usually used for the projection of sounds, but is used mainly in hydrophones.

Piezoelectric elements with circular and rectangular cross-sectional area, as well as cylinders (and rings), are usually used in multi-element transducers.

An example of a circular-shaped transducer composed of both rectangular and circular piezoelectric elements is the USRD F-33 transducer shown in Fig. 2.10. The inner array is composed of nine circular PZT disks, and the outer array is constructed of 64 BaTi rectangular disks. The individual arrays can be used separately or joined together. Each of the ceramic plates are cemented to a steel backing embedded in butyl rubber. Pressure release corprene is used between the individual ceramic elements. Both sections are sealed in transparent polyurethane with castor oil, providing the coupling between the polyurethane potting material and the butyl rubber acoustic window. An example of PZT ceramic rings configured in an array is the Atlantic Research LC-32 hydrophone shown schematically in Fig. 2.11. The rings are separated by a narrow gap with pressure-release corprene occupying the inner portion of the rings. The array is encapsulated in a degassed polyurethane compound. These two examples are just part of an imaginable number of a different transducer configuration that is in existence.

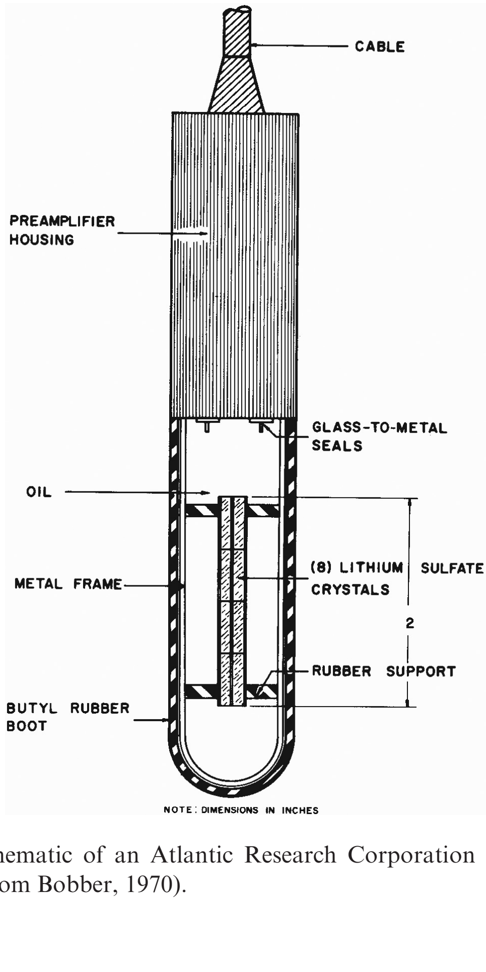

FIGURE 2.11. Schematic of an Atlantic Research Corporation type LC32 hydrophone (adapted from Bobber, 1970).

2.6 Projection of Low-Frequency Sound

Our discussion so far has been on piezoelectric transducers, and have not considered transducers operating on electrodynamic principles. Moving-coil transducers that operate like airborne speakers can be very effective in producing low-frequency acoustic signals from tens of Hertz to approximately 10–20 kHz. There is often a need to produce low-frequency sound to measure the hearing sensitivity of marine animals and to perform playback experiments using the natural sounds of whales, dolphins, and other marine mammals. Moving-coil transducers are more effective in producing low-frequency underwater sound than piezoelectric ceramics, because of the inherently high-resonance frequencies of piezoelectric elements that would require a transducer to be very large in order to achieve resonance at low frequencies.

A well-known and well-used moving-coil transducer is the J-9, developed at the U.S. Navy's Underwater Sound Reference Detachment in Orlando by

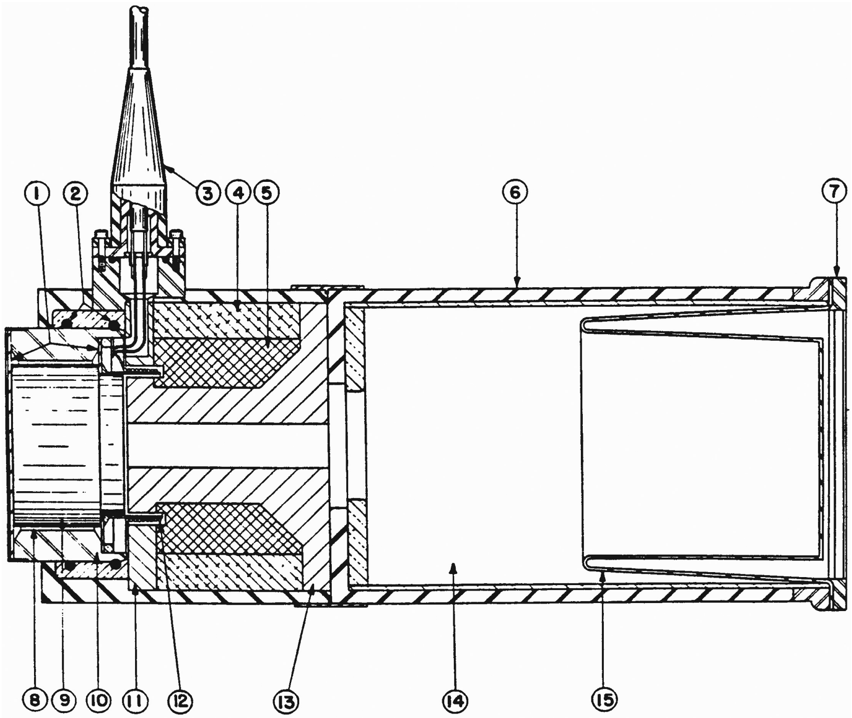

FIGURE 2.12. Assembly drawing of the USRD J9 transducer; 1, rubber seals; 2, rubber O-rings; 3, cable gland; 4, magnet; 5, lead; 6, rubber jacket; 7, grille; 8, slit filled with silicone oil response 9, magnesium diaphragm; 10, diaphragm housing; 11, front pole pieces; 12, coil; 13, back pole piece; 14, compensating air chamber; 15, rubber compensating bag. Overall length, 11 in.; diameter, 4-1/2 in. (adapted from Bobber, 1970).

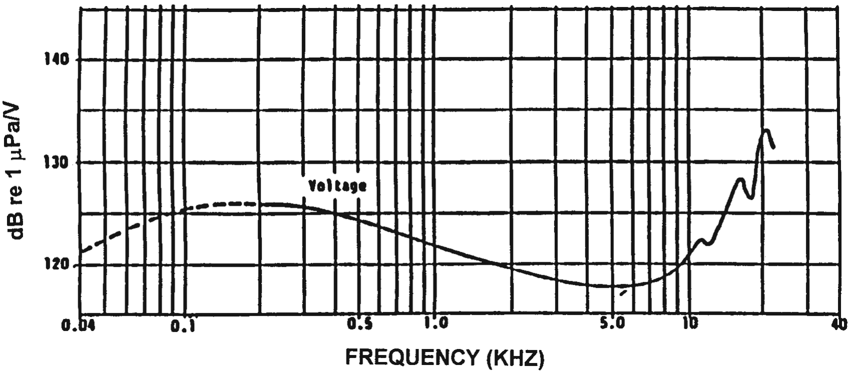

FIGURE 2.13. Typical transmitting voltage response of the J9 transducer.

C. C. Sims (1959). This transducer was designed to be operated in the infrasonic and audio frequency range from 40 to 20 kHz. A cut-away diagram of the J-9 is shown in Fig. 2.12, and the voltage transmit sensitivity is shown in Fig. 2.13. Being an electrodynamic or moving-coil transducer, it can provide the large volume displacement of water needed to produce low-frequency sound pressures without resorting to a very large radiating area that would be needed for piezoelectric ceramic transducers. When the transducer is submerged, water enters the rear compensation chamber and compresses the butyl rubber bag until the internal air pressure is equal to the external water pressure up to a depth of about 24 m. At deeper depths, a scuba bottle must be used. The compliance of the air inside the transducer is important for the highly damped resonance below 200 Hz. Changes in this compliance cause the response below 200 Hz to be a function of depth. The peak in the response at 20 kHz is due to a flexure resonance in the diaphragm. At still higher frequencies, other resonance causes wild fluctuations in the response curve. Although the J-9 is reversible, its performance as a hydrophone is relatively poor so that it is used almost exclusively as a projector.

The maximum input power to the J-9 is 24 W at frequencies above 200 Hz. If higher power is required, several J-9 can be clustered together or a larger projector can be used. The J-9 has several larger “brothers,” the J-11 and J-13. Both of these transducers operate on the same principle, but are much larger and heavier than the J-9. For example, the in-air weight of the J-9 is 20 lbs while the J-11 weighs 125 lbs and the J-13, 121 lbs. The maximum input power to the J-11 and J-13 are approximately 80 and 150 watts, respectively.

2.7 Calibration of Transducers

There are special facilities that have anechoic properties or are large enough so that reflections from boundaries will not seriously affect any transducer calibration. However, many of us will not have the access to a large and deep testing facility but will be restricted to relatively small tanks in which to calibrate transducers. Therefore, in order to do meaningful and accurate calibration of transducers, we must use pulsed pure tone signals so that the direct signal from the projector can be separated out from the reflected signal. However, when using pulsed tone signals, special consideration of the *Q* of the projector needs to be taken into account. The duration of the signal must be long enough for a steady-state condition to be reached in the projector. A typical example of a received hydrophone signal from a projector driven by a pulsed tone signal is shown in Fig. 2.14a. At the beginning of the pulse there is a transient effect present before steady state is reached. At the end of the pulse, there is another transient oscillation, which in this case is smaller than the steady-state response, but in some higher *Q* transducer this oscillation may be larger than the steady-state response. The transducer should be calibrated using the steady-state portion of the signal. The transient period will generally consist of *Q* cycles (Bobber, 1970). The signal of Fig. 2.14a was turned on and off at a zero crossing, which would minimize transient effects. Some signal generation system will gate a continuous wave (cw) signal to produce a pulsed tone signal without regard to the zero crossing of the cw signal. Such a signal may produce considerable more transient effects, since the turn-on time from zero volt to a specific level and the turn-off time from a specific level to zero volt are instantaneous. The presence of a turn-on and turn-off transient can be extremely important when measuring the hearing sensitivity of a marine animal, since it could cue the animal to the onset of the signal. One method to reduce or even eliminate the transient effects is to turn the signal on and off gradually. The hydrophone signal in Fig. 2.14b is for the similar situation as in the trace above it, except the signal was turned on gradually using a trapezoidal amplitude-modulated signal.

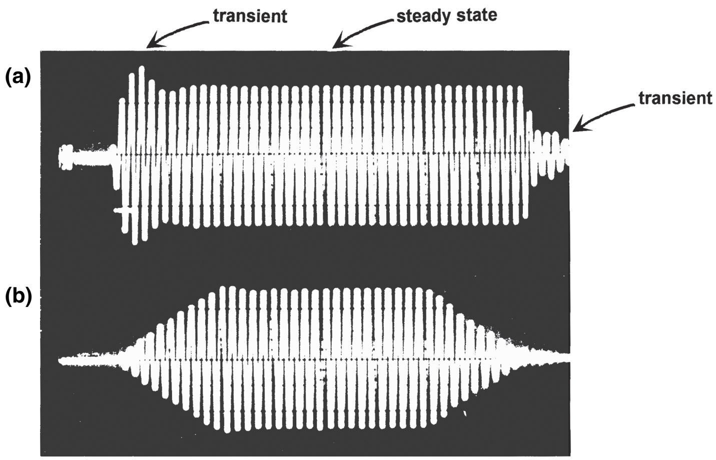

FIGURE 2.14. (**a**) Received hydrophone signal from a projector driven by a pulsed tone signal that is turned on and off abruptly; (**b**) received hydrophone signal form projector driven by a trapezoidal modulated signal.

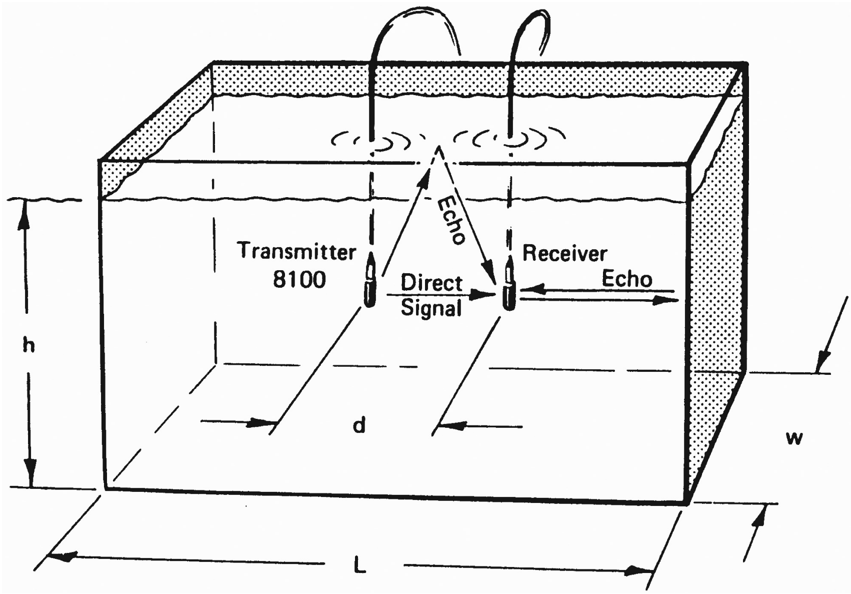

FIGURE 2.15. Sketch of acoustic propagation in a small tank showing some of the paths of propagation from a projector to a hydrophone.

A typical tank situation for calibration is depicted in Fig. 2.15 showing some of the paths that one must be concerned about. One important constraint on the minimum size of a tank is the necessity of having the hydrophone located in the far field of the projector. The far field of a transducer will be discuss in the next chapter; it suffices here to state that the far field of a transducer exists at distance greater than a^2/λ, where a is the largest active dimension of the transducer, and λ is the wavelength in water. The size of a tank could impact on the minimum pulse duration that can be used, since it would be most desirable to have reflective components arrive after the direct signal has completely passed the receiver. An example of the acoustic condition in a 2.44-m diameter, circular tank having a depth of 1.83 m is shown in Fig. 2.16. Both the projector and the hydrophone were at mid-depth and separated by 1.2 m. The top trace shows the signal fed to the projector and the bottom signal the received hydrophone signal. The first received pulse is from the direct path, and the following pulses are the results of propagation along the reflective paths. Since a small tank can be highly reverberant, the pulse repetition rate must be slow enough for the reverberation in the tank to totally decay.

2.7.1 Calibration with a Calibrated Hydrophone

There are several methods by which a transducer can be calibrated; the simplest method uses a calibrated hydrophone. In order to measure the

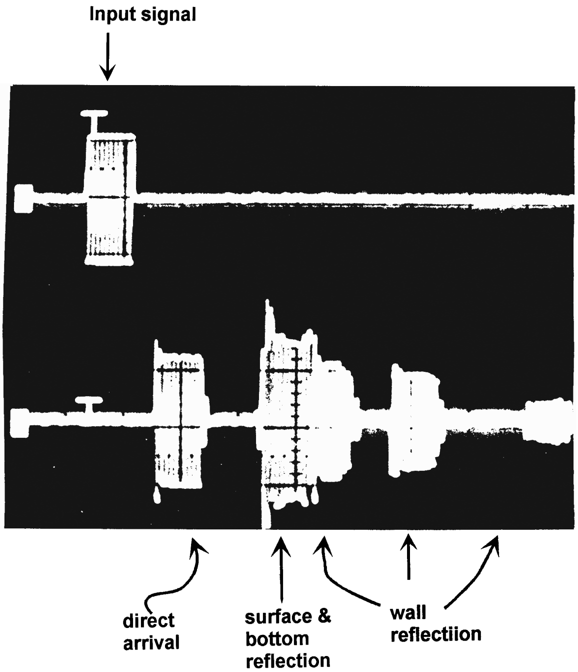

FIGURE 2.16. *Top* trace shows the signal sent to a projector and the *bottom* trace shows the received signal from a hydrophone that is 1.2 m from the projector. The first pulse is the direct signal from the projector, the next pulse is the surface reflected signal, and the remaining pulses are echoes from different parts of the circular tank boundary.

receive response of an uncalibrated hydrophone, the calibrated and uncalibrated hydrophone can be situated side by side with a projector emitting an acoustic signal of a specific frequency at both of them. Both hydrophones will receive the same acoustic signal so that, from Eq. (2.1), the received sound pressure level will be

$$\mathrm{SPL} = |M_1| - G_1 + 20\log V_1 = |M_{\mathrm{unk}}| - G_2 + 20\log V_2, \qquad (2.23)$$

where the subscript 1 is used for the calibrated hydrophone and subscript 2 for the uncalibrated hydrophone, and G is the gain of the receiving system in dB. Solving for M_{unk}, we get

$$|M_{\mathrm{unk}}| = |M_1| - (G_1 - G_2) + 20\log\left(\frac{V_1}{V_2}\right). \qquad (2.24)$$

The receive sensitivity will be a negative quantity, and absolute values are used to avoid confusion in using Eqs. (2.23) and (2.24). Typically, the response characteristics is given in terms of rms voltage; however, since the ratio of V_1 and V_2 is measured, the peak-to-peak values can be read off an oscilloscope.

The voltage projection or transmit sensitivity of a transducer can easily be measured using a calibrated hydrophone. Suppose a signal V_{in} directed to a projector to be calibrated and the calibrated hydrophone is at a distance r from the project, we have from Eqs. (2.1) and (2.3),

$$\text{SPL} = |M_1| - G_\text{i} + 20\log V_1 = S_{\text{unk}} + 20\log V_{\text{in}} - 20\log r, \tag{2.25}$$

where again, the subscript 1 refers to the calibrated transducer. Rearranging Eq. (2.25), we have for the transmit sensitivity

$$S_{\text{vunk}} = |M_1| - G_1 + 20\log\left(\frac{V_1}{V_{\text{in}}}\right) + 20\log r. \tag{2.26}$$

The transmit sensitivity is usually a positive quantity. In a similar manner, the current transmit sensitivity can be measured, using Eqs. 2-1 and 2-3 to get

$$\text{SPL} = |M_1| - G_1 + 20\log V_1 = S_{\text{iunk}} + 20\log I_{\text{in}} - 20\log r. \tag{2.27}$$

The input current can be measured by measuring the voltage across a resistor R placed in series with the input so that

$$S_{\text{iunk}} = |M_1| - G_1 + 20\log\left(\frac{V_1}{V_r}\right) + 20\log R + 20\log r. \tag{2.28}$$

A hydrophone can also be easily calibrated with a calibrated projector. From Eqs. (2.1), (2.2) and (2.3), we have in this case

$$\text{SPL} = S_1 + 20\log V_{\text{in}} - 20\log r = |M_{\text{unk}}| - G_2 + 20\log V_2. \tag{2.29}$$

Solving for the unknown hydrophone response, we get

$$|M_{\text{unk}}| = S_1 + G_2 + 20\log\left(\frac{V_{\text{in}}}{V_2}\right) - 20\log r, \tag{2.30}$$

where again, the subscript 1 refers to the calibrated transducer and subscript 2 to the uncalibrated hydrophone, and r is the separation distance between the projector and the hydrophone. Although we can calibrate a hydrophone with a calibrated projector, the same projector cannot be used to calibrate another projector, only a calibrated hydrophone must be used.

2.7.2 Spherical Reciprocity Parameter

Transducers can be calibrated in the absence of a calibrated transducer by making use of the reciprocity property of most electroacoustic devices. To be a reciprocal transducer, the element must be linear, passive, and reversible. These conditions are satisfied by piezoelectric ceramics. Let us use a spherical transducer as a projector driving it with a harmonic input current I_{in}, which causes the surface of the spherical element to vibrate with a velocity u and producing a spherical acoustic signal p at a distance r from the element as shown in Fig. 2.17a. Keep in mind that the input is harmonic or sinusoidal, so that u and p will also be sinusoidal. Now let us use this spherical element as a receiver so that an acoustic force F produces a voltage V_{0c} at the terminal as depicted in Fig. 2.17b. The electroacoustic reciprocity theorem states that

$$\frac{I_{in}}{u} = \frac{F}{V_{0c}}. \tag{2.31}$$

It will be more convenient to invert Eq. (2.31) so that

$$\frac{u}{I_{in}} = \frac{V_{0c}}{F}. \tag{2.32}$$

Now we need to snatch an expression for the relationship of a vibrating sphere and the resulting acoustic pressure. From Kinsler et al. (1982) and almost any physical acoustics book, we find that the transmitted pressure at a distance r produced by a sphere of surface area A vibrating at a frequency f is given by the expression

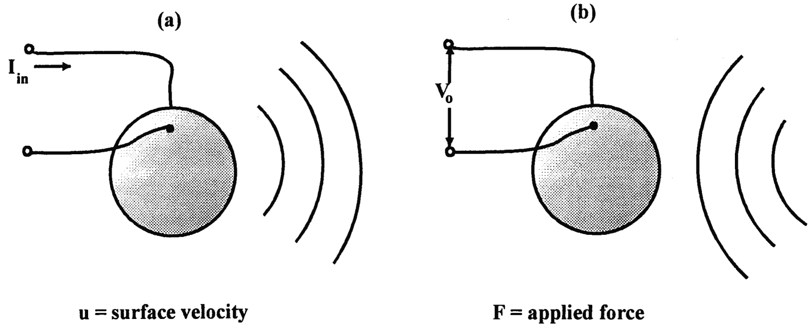

FIGURE 2.17. (**a**) A spherical transducer as a projector driven by a harmonic current I_{in} causing the surface of the sphere to vibrate with a velocity u and producing an acoustic pressure p_t; (**b**) an acoustic force F causing the voltage V_0 at the hydrophone terminals.

$$p = \frac{\rho c}{2r\lambda} Au, \tag{2.33}$$

where ρ is the density and c is the sound velocity in water. Since the acoustic force in Eq. (2.31) is nothing more than the incident acoustic pressure p times the area of the sphere ($F = pA$), Eq. (2.32) can be rewritten, using the relationship of Eq. (2.33) as

$$\frac{p}{I_{\mathrm{in}}}\left(\frac{2r\lambda}{\rho c A}\right) = \frac{V_{0\mathrm{c}}}{F} = \frac{V_{0\mathrm{c}}}{pA}. \tag{2.34}$$

From the definition of voltage receive sensitivity ($M_{\mathrm{h}} = V_{0\mathrm{c}}/p$) and current transmit sensitivity ($p = S_{\mathrm{i}} I_{\mathrm{in}}$), Eq. (2.34) can be rewritten as

$$S_{\mathrm{i}}\left(\frac{2r\lambda}{\rho c}\right) = M_{\mathrm{h}}. \tag{2.35}$$

The spherical reciprocity parameter was defined earlier as the ratio of M_{h} and S_{i} in Eq. (2.9), so that from Eq. (2.35) we have

$$J = \frac{M_{\mathrm{h}}}{S_{\mathrm{i}}} = \frac{2r\lambda}{\rho c} = \frac{2r}{\rho f}. \tag{2.36}$$

The reciprocal parameter J can now be used in the calibration of transducers without the necessity of having a calibrated transducer present.

The reciprocal parameter is slightly different for cylindrical and planar elements and can be found in Urick (1983). However, if the calibration is done in the far field, i.e., $r >> L^2/\lambda$ for cylindrical elements and $r >> A/\lambda$ for planar elements, then the spherical reciprocal parameter could still be used with little error. This means that both the frequency of calibration and the distance between elements must be seriously considered. The reciprocity parameter can now be used in the calibration of transducers without the necessity of having a calibrated transducer present.

2.7.3 Three-Transducer Spherical Wave Reciprocity Calibration

Three transducers are needed in this reciprocity calibration technique to determine the free-field sensitivity of a hydrophone; the hydrophone H, a projector P and a reciprocal transducer T. Three measurements are also required as depicted in Fig. 2.18. In the first and second measurements, a current I_{P} is fed into projector P to produce an acoustic pressure of p_{P} at

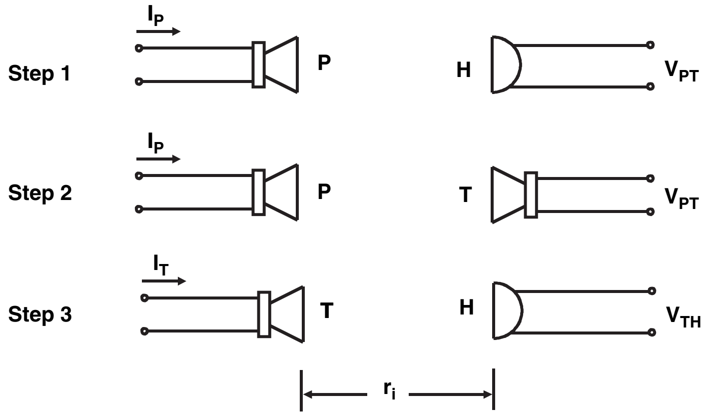

FIGURE 2.18. The three steps used in the three-transducer reciprocity calibration method.

a distance r_1, producing the following voltages at the terminals of hydrophone H and transducer T. From these measurements we have

$$V_{PH} = M_H p_P = \frac{M_H I_P S_P}{r_1} \tag{2.37}$$

,

$$V_{PT} = M_T p_P = \frac{M_T I_P S_P}{r_1}, \tag{2.38}$$

where M_H and M_T are the received responses of transducers H and T, respectively, and S_P is the transmit sensitivity of transducer P. Dividing Eq. (2.37) by Eq. (2.38), we get

$$\frac{V_{PH}}{V_{PT}} = \frac{M_H}{M_T}. \tag{2.39}$$

For the reciprocal transducer T, we have from Eq. (2.36)

$$J = \frac{M_T}{S_T} = \frac{2r_1\lambda}{\rho c}. \tag{2.40}$$

Substituting Eq. (2.40) into Eq. (2.39), we get

$$M_H = JS_T \frac{V_{PH}}{V_{PT}}. \tag{2.41}$$

For the third measurement, the reciprocal transducer T is driven by current i_T to produce an acoustic pressure p_T, which will be received by the hydrophone H to produce open-circuit voltage

$$V_{TH} = M_H p_T = \frac{M_H i_T S_T}{r_1}. \tag{2.42}$$

Solving for M_H from Eqs. (2.41) and (2.42), we arrive at the following expression

$$M_H = \left(\frac{V_{TH} V_{PH}}{V_{PT} i_T} Jr_1 \right)^{1/2}$$

The current I_T can be measured as a voltage drop across a series resister R so that

$$M_H = \left(\frac{V_{TH} V_{PH}}{V_{PT} i_T} RJr_1 \right)^{1/2}. \tag{2.44}$$

Since the four voltages appear as a dimensionless ratio, they can be measured by an uncalibrated voltmeter that is linear.

2.7.4 Two-Transducer Reciprocity and Self-Reciprocity

If two transducers are identical, one can be used as a hydrophone and the other as a reciprocal transducer so that only one measurement is needed, which is depicted in step three of Fig. 2.18. With transducer T driven by current I_T an open-circuit V_0 will be produced across the terminals of hydrophone H, so that from Eq.(2.43) along the assumption that $M_H = M_T$, we have

$$M_H = \left(\frac{V_{TH}}{I_T} rJ \right)^{1/2}. \tag{2.45}$$

Once again, I_T can be measured by a voltage drop V_T across a series resister R so that

$$M_H = \left(\frac{V_{TH}}{V_T} rRJ \right)^{1/2}. \tag{2.46}$$

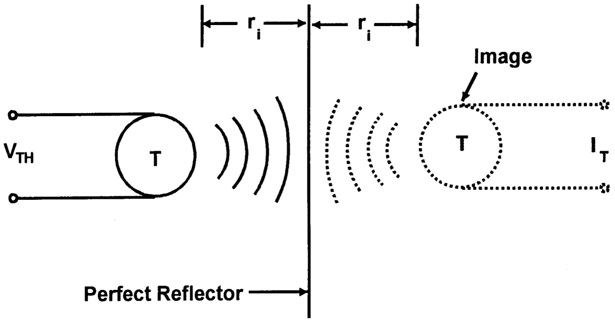

FIGURE 2.19. Schematic for a self-reciprocity calibration of a transducer.

This calibration should be considered as estimate unless one can show that the two transducers are indeed identical. This can be done by using a third transducer to project an acoustic signal that the first two transducers can measure. The results should be identical if the first two transducers are identical.

The two-transducer reciprocal method can be a true primary method if the same transducer is used as both a hydrophone and a projector. This can be done by reflecting a transmitted signal back to the transducer so that it receives its own signal. The self-reciprocity calibration is shown schematically in Fig. 2.19 where the mirror image can be considered as a second transducer at the same distance from the reflecting surface. The reflection must be perfect so that the transmitting current response of the image is identical to that of the real transducer. Pulsed sounds must be used in this technique. The receiving sensitivity is given by Eq. (2.46), where $r = 2r_1$. Patterson (1967) used this method to calibrate a transducer at sea, transmitting the signal toward the surface and receiving the reflection from the surface. He obtained an accuracy of 2 dB. However, using the sea surface requires the presence of a calm sea with a flat surface and the absence of a prominent supporting platform over the transducer.

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