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Hydrophones
Standard Article

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Abstract

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Theory

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HYDROPHONES

Hydrophones are devices used for the detection of sound in liquids (usually water). In theory, a hydrophone may convert an acoustic pressure or velocity into any measurable quantity. In practice, a hydrophone converts a sound or acoustic pressure or acoustic velocity signal into an electrical signal, which can then be measured by normal electronic means such as a voltmeter, lock-in amplifier, or other common electronic instrumentation. Most hydrophones measure pressure rather than velocity, and the discussion here will be limited to those devices. Very early hydrophones used other means of detection of acoustic pressure, such as modulating the plate separation and, therefore, the capacitance of an air-filled or fluid-filled capacitor. The development of the vast majority of modern hydrophones is intricately linked to the development of piezoelectric materials. The piezoelectric effect occurs in various classes of dielectrics, including single crystal, polymer, and ceramic materials. For hydrophone purposes, the direct piezoelectric effect relates linearly the dielectric displacement or electric field, E , developed by an element of a lossless dielectric when it is subjected to a mechanical stress as defined by the relationships

$$E = \text{voltage/thickness} = g \cdot T \quad (1)$$

$$D = \text{charge/area} = d \cdot T \quad (2)$$

where T is the applied stress and D is the dielectric displacement and is equal to the charge on the electroded surfaces divided by the area of the electrodes for materials with low dielectric loss. This latter requirement is a necessity for any commonly used piezoelectric material. Piezoelectric materials are intrinsically nonisotropic, and the magnitudes of the piezoelectric effect depend on the direction in which the electrical variables are measured as well as the directions in which the stress is applied. This will be described in more detail later. Most common acoustic signals are detected by employing the piezoelectric effect of certain types of ceramics, most often lead zirconate-titanate ceramics. This material, which is widely used for hydrophones, was developed in the 1950s and replaced more delicate piezoelectric single crystal materials used in Navy SONAR systems during and following World War II as well as barium titanate ceramics, which are commonly used today for electronic capacitors. Early hydrophones were made from piezoelectric single crystals such as Rochelle salt, potassium dihydrogen phosphate (*KDP*), adenine dihydrogen phosphate (*ADP*), and lithium sulfate. These materials are hygroscopic and tended to be environmentally unstable although they had high piezoelectric coefficients. Even today, research in new single crystals, which have extremely high piezoelectric coefficients, is conducted. Recently, a number of new types of materials have been developed for specific underwater sound detection applications, which gives the hydrophone designer a wider variety of materials to choose from depending on application. These include piezoelectric polymer, ceramic-polymer composite, and single crystal materials as well as more conventional piezoelectric ceramics and single crystals. Single crystal materials may have macroscopic piezoelectric effects because of the noncentrosymmetric symmetry along one or more of their crystallographic axes. Lithium sulfate serves as an example. Most piezoelectric materials commonly used today

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for hydrophones are also ferroelectric, which means that the polarization can be reoriented in direction by the application of an electric field of sufficient strength. This property generally gives the ferroelectric materials higher dielectric permittivities than the nonferroelectric piezoelectric materials. Dielectric permittivity, ϵ_{ij} , relates the charge or dielectric displacement to the electric field:

$$\mathbf{D}_i = \epsilon_{ij} \mathbf{E}_j \quad (3)$$

The subscripts designate direction ($i, j = 1, 2, 3$). D_i and E_j are first-rank tensors (vectors), and ϵ_{ij} is a second-rank tensor. For homogenous materials with a single unique polar direction, only ϵ_{33} and ϵ_{11} ($= \epsilon_{22}$) are independent and nonzero. Sufficiently high dielectric permittivity is often desirable to reduce the noise associated with insufficient capacitance relative to lead and stray capacitance effects, which cause reduction of the voltage signal and add extraneous noise. Ferroelectric materials, however, must be “poled” by applying a high electric field along a single direction in order to align the thermally disordered electric dipoles to the acceptable crystallographic direction nearest that of the applied electric field. This is the case for both ferroelectric single crystals and ceramics. Application of sufficient stress or temperature can again partially or completely randomize the dipoles, resulting in a loss of polarization and, consequently, of piezoelectricity. Materials used in hydrophones are, therefore, chosen according to the environmental conditions (pressure and temperature) at which the hydrophone is designed to operate.

Depending on the complexity of the signal, including the level of signal, the frequencies, and the types of signals (i.e., pulse, time-invariant sinusoidal, pulse sinusoid, etc.) that comprise the total signal, the detection systems can be either rather simple or extremely complex. If the level of noise in which the signal is being measured is high, the detection systems can become quite intricate, involving many hydrophones and their arrangement as well as sophisticated analog and digital electronics (used to detect the hydrophone signals and in the analog and digital signal processing of the resulting electrical signal). Technology developed recently also can convert the acoustic signal into optical signals generally by modulating a monochromatic laser beam by some means related to the acoustic pressure and then demodulating the optical signal by optical interferometric techniques into electrical signals. This has the advantage that the transmission of signals is nearly lossless, whereas the piezoelectric is a capacitive sensor and encounters signal loss due to cable capacitances being connected in parallel with the hydrophone. The cable, which has nonzero capacitance, in effect acts as a voltage divider with the hydrophone. Fiber-optic hydrophones avoid this problem and can be directly implemented with optical circuitry, a rapidly advancing technology.

Theory

Acoustic Waves. An acoustic signal can be represented by specifying the time dependence of either the acoustic pressure given by (1,2)

$$p(x, t) = p_0 \exp[-j(\omega t - \mathbf{k}x)] \quad (4)$$

or the acoustic particle velocity,

$$v(x, t) = v_0 \exp[-j(\omega t - \mathbf{k}x)] \quad (5)$$

where ω ($= 2\pi f$) is the angular frequency, f is the frequency, \mathbf{k} is the wave vector, and x is the coordinate along which the wave is propagating. For hydroacoustic signals, p_0 and v_0 are the scalar amplitudes of the pressure and velocity waves. The waves are longitudinal waves with particle displacement in the same direction as the

pressure gradient,

$$p(x, t) = -\rho_0 \frac{dv(x, t)}{dt} \quad (6)$$

where $v(x, t)$ is the particle velocity at a point in the fluid and ρ_0 is the density of the fluid.

The ratio of the pressure to the particle velocity is termed the acoustic impedance,

$$z_a = \frac{p(x, t)}{v(x, t)} \quad (7)$$

and, in general, is complex depending on the geometry of the wave and the medium in which it travels. For plane waves in a liquid with density, ρ_0 ,

$$z_a = \rho_0 c \quad (8)$$

where c is the velocity of sound in the liquid. For water, c is approximately 1500 m/s. At low frequency (acoustic wavelength considerably larger than the dimensions of the hydrophone), Eq. 8 is a suitable approximation. For higher frequencies (where the wavelength is on the order or less than the largest dimension of the hydrophone), the response of the hydrophone becomes directional, the acoustic wave can no longer be treated as a plane wave, and the impedance is a function of the geometry and dimensions of the hydrophone as well as the direction of the acoustic wave (1,2)

Acoustic Transduction Requirements of Piezoelectric Hydrophones.

Voltage Sensitivity and Capacitance. In general, hydrophones are specified by their ability to detect both large and small signals over a specified range of frequency. They are often used with significant lengths of cable, and in order not to lose signal, the capacitance of the hydrophone must be significantly larger than that of the cable that is used to connect it to amplifier electronics. Also important is the environmental stability of the hydrophone with respect to pressure and temperature. These requirements, particularly pressure, must be addressed in the performance of a hydrophone. Extremely high pressures require thicker dimensions and materials that resist “depoling.” Often more sensitive designs tend to be more fragile, and again sensitivity must be traded for pressure stability as well as ruggedness.

Because of the lower noise associated with voltage electronics compared to charge electronics, voltage electronics are most often used to measure the output of piezoelectric transducers. Specifications for hydrophones that convert acoustic pressure into voltage include the free-field voltage sensitivity (M_0), which is defined as

$$M_0 = V/p_0 \quad (9)$$

where V is the voltage induced by the acoustic pressure, p_0 . Because of the large range of pressure measured by a typical hydrophone, voltage sensitivity is often expressed in decibels relative to an acoustic pressure of 1 μ Pa such that (in mks units) free-field voltage sensitivity (or *FFVS*) is often expressed as

$$\text{FFVS (in dB re 1 V/}\mu\text{Pa)} = 20 \log(M_0) - 120 \quad (10)$$

which is sometimes a useful specification when amplifiers are not included in the measured response of the hydrophone. However, since most signals from the hydrophone are amplified, and the amplifier gain can be made as large as desired, FFVS must be considered with regard to the noise of the hydrophone itself and the electronics (or optics) associated with detecting and measuring the output of the hydrophone. The bandwidth as well as center frequency are also, of course, primary concerns and are defined by the intended application.

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In general, sensitivity can be traded for bandwidth by varying the dimensions of the hydrophone element, just as the gain of an amplifier can be traded off for increased bandwidth. By making the sensitive element of the hydrophone smaller, smaller wavelengths (higher frequencies) can be accommodated before they become of size on the order of the dimensions of the acoustic element, thereby resulting in mechanical resonances, which strongly alter the response of the hydrophone. However, smaller dimensions result in lower voltage sensitivity and capacitance. Hydrophone specifications, therefore, include voltage sensitivity, capacitance, frequency range, maximum pressure of operation, temperature range, and noise levels as functions of frequency.

Piezoelectric Hydrophone Sensitivity Relative to Noise. The measure of performance of a hydrophone is its ability to detect acoustic pressure relative to noise. This is often defined as the minimal detectable pressure or noise equivalent pressure, p_{nep} , and can be considered the smallest acoustic pressure that can be detected in a noise-free environment given the self-noise of the hydrophone and the electronics associated with it. Noise in systems is a complicated subject, and many factors are involved, including the frequency range of interest, the capacitance, and the dielectric losses of the element. Also, the current and voltage noise of the electronics used to amplify the piezoelectric, random fluctuations in temperature and pressure in the environment and fluctuations of the polarization and capacitance of the piezoelectric element contribute to noise. Noise is typically dependent on frequency, temperature, and load (input resistance of the amplifier) as well as the frequency bandwidth over which the hydrophone is designed to operate. Environmental sources of noise depend on the platform on which the hydrophone is mounted and on the many possible noise sources in the ocean, which vary according to location.

The minimal detectable pressure is often calculated assuming that thermal noise is the dominant source of noise, which is not always the case. It is, however, a noise source that is always present and cannot be entirely eliminated. It represents the best-case situation, where electronic and other sources of noise have been lowered beneath this physical limit. The thermal voltage noise in a given frequency bandwidth, Δf , is given by the Nyquist equation, derivable from statistical mechanics as

$$V_n^2 = 4k\Theta|Z|\Delta f \quad (11)$$

where k is the Boltzmann constant, Θ is the absolute temperature, and $|Z|$ is the magnitude of the electrical impedance of the hydrophone. The impedance of the hydrophone is often assumed to be a Thevenin equivalent circuit with resistance, R , which represents the dielectric and conductive losses of the material connected in series with a lossless capacitance, C . The impedance is then given by

$$Z = R + (j\omega C)^{-1} \quad (12)$$

where the resistance is related to the dielectric loss tangent of the material by

$$R = \omega C \tan \delta \quad (13)$$

The ratio of signal to noise voltages is then given by

$$\frac{V^2(\text{signal})}{V^2(\text{noise})} = \frac{M_0^2 p_0^2 \omega C}{4k\Theta(1 + \tan^2 \delta)^{1/2}} \quad (14)$$

For a barely detectable pressure, this ratio is equal to unity. Then, solving for the pressure, p^2_0 (which is equal to the minimum detectable pressure),

$$p^2_0 = p^2_{\text{nep}} = \frac{4k\Theta(1 + \tan^2 \delta)^{1/2}}{M_0^2 \omega C} \quad (15)$$

When designing a hydrophone, it is desirable to minimize this value. A figure of merit (*FOM*) for a hydrophone may be defined by the reciprocal of p^2_{nep} , neglecting the factor $4k\Theta$, as

$$\frac{M_0^2 \omega C}{(1 + \tan^2 \delta)^{1/2}} = \text{FOM}_h \quad (16)$$

For any material of use with low losses at low frequency (far below any electromechanical resonances), $\tan \delta \ll 1$, and the figure of merit becomes

$$\text{FOM}_h = M_0^2 \omega C \quad (17)$$

In other words, the measure of performance of a piezoelectric hydrophone with respect to thermal noise is just the product of the square of voltage sensitivity and the hydrophone capacitance. Other noise sources, such as that from the environment or from the voltage and current noise of the amplifier, can also be included. The current noise often becomes significant at lower frequency and the voltage noise at higher frequencies. Often the environmental noise for an open-water ocean is given in terms of sea-state noise. This is defined in terms of measured noise pressure in a 1 Hz frequency band and is generally given in decibels relative to $1 \mu\text{Pa}/\sqrt{\text{Hz}}$. Figure 1 shows a plot of sea-state noise as a function of wind and sea conditions. Sea-state zero is most commonly used as a noise pressure reference. Since hydrophones are often specified to have self-noise at levels well below sea-state zero, thermal noise is often considered as the practical noise floor for hydrophones. The preceding figures of merit [Eqs. (16) and (17)] are, therefore, commonly used.

The frequency range or bandwidth of a hydrophone is also of primary importance. The bandwidth can be limited by either the mechanical resonances of the hydrophone or the electronic circuits used to detect the signal. Mechanical resonances cause the sensitivity of the hydrophone to vary drastically and, therefore, hydrophones are designed to operate generally below any fundamental resonance or sometimes in a region above the fundamental resonance and below higher-frequency resonances.

From a piezoelectric materials perspective, figures of merit are also often used. First, however, a brief introduction into the definitions of piezoelectric coefficients and their application to hydrophone technology is required.

Piezoelectricity. The piezoelectric effect is defined by the equations in full tensor notation as (3)

$$D_i = d_{ijk} T_{jk} \quad (i, j, k = 1-3) \quad (18)$$

and

$$E_i = g_{ijk} T_{jk} \quad (i, j, k = 1-3) \quad (19)$$

where the dielectric displacement is defined as the charge developed on the electrode faces perpendicular to the k -direction of the material divided by the area perpendicular to the k -direction for a stress applied down the i -axis to the plane described by the normal vector \mathbf{k} (Fig. 2). The piezoelectric charge coefficient, d_{ijk} ,

so that T_1 , T_2 , and T_3 refer to tensile or compressive stresses along the x -, y -, and z -axes and T_4 , T_5 , and T_6 refer to shear stresses applied to faces perpendicular to the x -, y -, and z -axes. For poled piezoelectric ceramics, Eq. (18) has the form

$$[\mathbf{D}_1 \mathbf{D}_2 \mathbf{D}_3] = d_{ij} T_j = \begin{matrix} 0 & 0 & 0 & 0 & d_{15} & 0 & T_1 \\ 0 & 0 & 0 & d_{15} & 0 & 0 & T_2 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 & T_3 \\ & & & & & & T_4 \\ & & & & & & T_5 \\ & & & & & & T_6 \end{matrix} \quad (21)$$

where $d_{31} = d_{32}$ and $d_{24} = d_{15}$ because the 1 and 2 directions are equivalent. The g_{ij} matrix has the same form relating the E_i coefficients to the stress, T_j . Hence, under hydrostatic pressure, which defines the low-frequency case where the acoustic wavelength λ is much larger than the largest dimension of the hydrophone,

$$p = -T_1 = -T_2 = -T_3 \quad (22)$$

the dielectric displacement perpendicular to the electrode faces of the element is given by

$$D_3 = d_{31}T_1 + d_{32}T_2 + d_{33}T_3 = -d_h p \quad (23)$$

where then the hydrostatic piezoelectric coefficient is defined as

$$d_h = d_{33} + d_{31} + d_{32} \quad (24)$$

For most poled ceramics, as well as many single crystals, the last two coefficients are equal in sign and magnitude. Furthermore, the signs of the d_{31} and d_{33} coefficients are opposite and the magnitude of d_h is substantially lower than either d_{33} or d_{31} . A similar piezoelectric voltage coefficient is defined for low-frequency (hydrostatic conditions) applications as

$$E_3 = -(g_{33} + 2g_{31})p = -g_h p \quad (25)$$

The dielectric displacement and electric field are related through the dielectric permittivity as given by Eq. (3), so that from Eq. (3), (23), and (25),

$$d_h = g_h \epsilon_{33}^T \quad (26)$$

where the superscript T indicates that the permittivity is measured under conditions of constant stress, which is the proper boundary condition for low-frequency applications. For higher frequencies, where the wavelength of the acoustic wave is on the order of the dimensions of the transducer, the stresses are not generally equal to the opposite of the pressure and they must be solved for by applying the wave equation to the structure in order to solve for the stress or strain as a function of time and position in the hydrophone with appropriate boundary conditions. The piezoelectric response can then be calculated by integrating the response of each point in the hydrophone structure over the volume of the hydrophone. For applications such as large-area hydrophones, which will be discussed later in conjunction with use of polymer and piezoelectric composite materials, this is necessary. The calculations are beyond the scope of this article, but information has been given elsewhere on

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such calculations (2). For most applications, however, the hydrostatic coefficients are the most critical measure of performance of a material, as are the voltage sensitivity and capacitance for a hydrophone. The equations given previously are for piezoelectric ceramics with a single unique axis. For many single crystals, the situation is more complicated, and full derivation of the piezoelectric matrices can be found in the textbook by Nye (3).

Figures of Merit for Piezoelectric Hydrophone Materials. The performance of a hydrophone material is derived from the hydrophone figures of merit by replacing the hydrophone geometry (4). For a lossless piezoelectric material, the electric field is related to the voltage of a planar piece of material with planar surface area A and thickness t by

$$E = V/t = -g_h p \quad (27)$$

so then the material voltage sensitivity is related to hydrophone voltage sensitivity by

$$M_0 = g_h t = -E_3/p \quad (28)$$

The dielectric permittivity is related to the capacitance by

$$\epsilon_{33}^T = Ct/A \quad (29)$$

Similarly, the charge sensitivity of the material,

$$d_h = -D_3/p = \epsilon_{33}^T g_h = CM_0/A \quad (30)$$

which, when solved for C and put into the hydrophone figure-of-merit equation [Eq. (16)], yields

$$\text{FOM}_h = \frac{M_0^2 \omega C}{(1 + \tan^2 \delta)^{1/2}} = \frac{\omega d_h g_h (At)}{(1 + \tan^2 \delta)^{1/2}} \quad (31)$$

The materials FOM is then

$$\text{FOM}_m = \frac{\text{FOM}_h}{\omega(tA)} = \frac{d_h g_h}{(1 + \tan^2 \delta)^{1/2}} \quad (32)$$

where the product, tA , equals v , the volume of the element. Since the product of charge and voltage equals the electrical energy, the hydrophone FOM gives the energy converted from the acoustic signal to the electrical signal per unit acoustic pressure squared, whereas the material FOM gives the energy converted per unit volume of material, both at frequency ω . For low loss materials, this reduces simply to the product

$$\text{FOM}_m = d_h g_h \quad (33)$$

which defines the signal-to-noise performance of a low-loss hydrophone material. It is maximum when the conversion from acoustic energy to electrical energy is maximized. The mechanical work done per unit volume on the material is

$$w_m = \frac{1}{2} S_i T_i = \frac{1}{2} s_{ij} T_i T_j \quad (i, j = 1-6) \quad (34)$$

where S_i is the elastic strain, s_{ij} is the elastic compliance matrix, and the repeated subscripts are summed over the possible values for i and j (3). Similarly, the electrical energy is given by

$$w_e = \frac{1}{2} D_i E_i = \frac{1}{2} \eta_{ij} D_i D_j \quad (i, j = 1-3) \quad (35)$$

where

$$\eta_{ij} = [\epsilon_{ij}]^{-1} = E_i / D_j \quad (36)$$

is the dielectric impermeability. Using Eq. (18) and taking the ratio of Eqs. (34) and (35) defines the electromechanical coupling coefficient, k_{ij} ,

$$\frac{w_e}{w_m} = \frac{\eta_{ij}^T d_{ij}^2}{s_{ii}^E} = \frac{d_{ij}^2}{\epsilon_{ii}^T s_{ij}^E} = \frac{d_{ij} g_{ij}}{s_{ij}} = k_{ij}^2 \quad (37)$$

This coefficient represents the energy conversion efficiency and is in itself an important figure of merit for hydrophones as well as acoustic projectors. For the 3–1 transverse mode discussed earlier, $i = 3, j = 1$, while for the longitudinal mode, $i = j = 3$ in Eq. (37). For the hydrostatic mode, the coupling coefficient becomes

$$k_h^2 = \frac{d_h g_h}{\chi E} \quad (38)$$

where χ is the bulk compressibility given by (3)

$$\chi = s_{iikk} = s_{33} + 2(s_{11} + s_{12} + 2s_{13}) \quad (39)$$

For poled piezoelectric ceramics the compressibility matrix is given by

$$S_i = s_{ij} T_j = \begin{array}{ccccccc} s_{11} & s_{12} & s_{13} & 0 & 0 & 0 & T_1 \\ s_{12} & s_{11} & s_{13} & 0 & 0 & 0 & T_2 \\ s_{13} & s_{13} & s_{33} & 0 & 0 & 0 & T_3 \\ 0 & 0 & 0 & s_{44} & 0 & 0 & T_4 \\ (i, j = 1-6) & 0 & 0 & 0 & s_{44} & 0 & T_5 \\ 0 & 0 & 0 & 0 & 0 & s_{66} & T_6 \end{array} \quad (40)$$

From Eq. (38), it is seen that softer materials should give lower electromechanical coupling, yet in many instances they give higher values of the $d_h g_h$ materials figures of merit to maintain high coupling. The coupling factor is intrinsically tied to the achievable bandwidth of the material of a particular dimension as well as the sensitivity to stress and, therefore, it is an important measure of a materials performance as well.

Directivity. So far we have assumed the acoustic pressure is virtually hydrostatic. For higher frequencies and shorter acoustic wavelengths of operation relative to the shape and dimension of the hydrophone and its acoustic sensing element, the sensitivity of a hydrophone may depend on direction relative to an oncoming acoustic plane wave (5). Note that the case where the acoustic wavelength, λ , is on the same order as the largest dimension of the hydrophone element is considered. The directivity function $H(\theta, \phi, \omega)$ is defined as the ratio

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of the sensitivity in a particular direction in spherical coordinates (θ, ϕ) to that obtained in the direction where the sensitivity is maximum, which is referred to as the acoustic axis of the hydrophone, or

$$H(\theta, \phi, \omega) = \frac{M_0(\theta, \phi)}{M_0(\max)} \quad (41)$$

and the frequency, ω , is included to indicate that it is generally a strong function of frequency when the acoustic wavelength is on the order of the dimensions of the hydrophone. At low frequencies, $H(\theta, \phi, \omega)$ approaches unity. The directivity is defined as

$$D = \frac{4\pi}{\int_{4\pi} H^2(\theta, \phi, \omega) d\Omega} \quad (42)$$

where Ω is the solid angle and H^2 is integrated over its domain.

Again, the tradeoff between sensitivity and bandwidth must be made according to the desired performance criteria (frequency, bandwidth, voltage sensitivity, capacitance, pressure sensitivity, temperature sensitivity, and noise) as well as mechanical ruggedness requirements. Note that the directionality of a planar hydrophone element increases as the frequency increases with the pattern being omnidirectional at low frequencies (where $\lambda \gg a$, a being the longest dimension of the hydrophone) but becomes increasingly directional as the wavelength is increased and becomes of the same order as the physical dimension of the element. Depending on geometry and properties of the element, there may be one or more main lobes of the radiation pattern at higher frequency. (See the section on piezoelectric hydrophones.)

Bandwidth. The frequency range of a hydrophone is usually determined by the region of use where the voltage sensitivity of the hydrophone is constant. In some cases the electronic detection system also limits the frequency range. Normally, but not always, the frequency range is below the fundamental resonances of the piezoelectric, or fiber-optic sensing element, although in the cases of piezoelectric structures such as spheres, cylinders, and composites, the frequency ranges between the various electromechanical resonances (where the sensitivity is constant) are often used. The resonant frequency depends on element geometry, the dimensions of the element, and its elastic properties and density. The frequency constant is defined as

$$N = f_r \cdot d \quad (43)$$

where f_r is the resonant frequency and d is the correct dimension of the element. (For simple thickness mode transducers made using a disk of piezoelectric material, d is the thickness. For radial mode, d is the radius.) For complex geometries, the exact dimension can be complex to calculate as for spheres or cylinders of finite thickness.

For thickness (TE) mode transducers, the resonant frequency is related to the thickness, t , of the element, elastic stiffness, c_{33}^D , and density, ρ , by

$$N_t = f_r \cdot t = (c_{33}^D/\rho)^{1/2} \quad (44)$$

where N_t is a dimensionless material property. For broadband high-frequency transducers, the amount of energy per unit bandwidth is limited by the total amount of acoustic energy that can be converted to electrical energy, which is related to the electromechanical coupling factor. For a particular vibrational mode the

$$\text{bandwidth} = \Delta f = (f_s/f_p) \tan^{-1}((2/p)k^2 f_s/f_p) \quad (45)$$

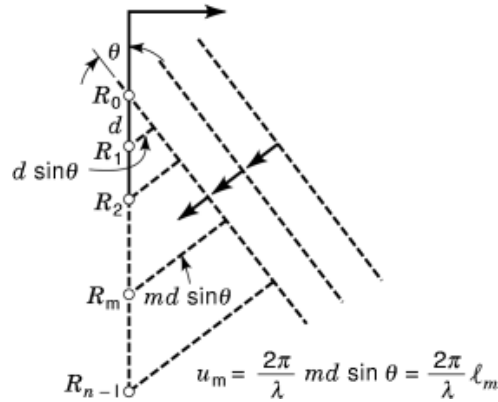


Fig. 3. Hypothetical line array of n hydrophones. (Figure reproduced from Ref. 5.)

where k is the electromechanical coupling coefficient for the appropriate vibrational mode and f_p and f_s are the parallel and series resonance frequencies, respectively.

Hydrophone Arrays. To detect an object in a fluid some distance away, one must detect both the angles at which the object is located relative to the receiver and the distance from the receiver, thereby determining the location in spherical coordinates (r, θ, ϕ) . It is easy to conceptualize that this can be done by an array of highly directional hydrophones (5) with the direction of the acoustic axis (the most sensitive direction) of a number of elements being distributed over 2π radians in both angular directions (θ, ϕ) . The signal from the source will then interact most strongly with the hydrophone elements whose directivity coincides with the direction of the source and that are closest to the source. The direction of the source can then be calculated. For low-frequency signals, the hydrophone directivities are omnidirectional. The location of an acoustically radiating object can still be determined. A plane wave that interacts with elements separated by a distance r_1 from the source will experience a time delay and corresponding phase change relative to each other. Since the frequency and wavelength of the signal is determined by each hydrophone, information about the distance of the source from the receiver and its motion can be determined by calculating the cross-correlation coefficients of the signals from the different hydrophone elements and determining the coherence of the signals from the different hydrophone elements of the array. In general, the hydrophone signals are coherent with one another; there is a specific mathematical relationship between them in terms of the phase delays relative to each other. Noise, in general, is not correlated and the relationships between the signals from the various hydrophone elements are random. Consider a simple line array of n hydrophones, of length L ; $d (= L/n)$ is the distance between hydrophones, as in Fig. 3. Given that the hydrophones have identical sensitivity, M_0 , the output from the hydrophones can be summed with each other as a function of time delay, Δt , corresponding to a phase delay

$$\Delta\theta_d = \omega \Delta t - kr \quad (46)$$

where r is the distance to the array when the array is far from the source. Then all elements are essentially equally distant from the source and differences in distance are negligible. This condition is referred to as

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far-field conditions. The output voltage of the array is given by (1)

$$\begin{aligned}
 V(r, \theta, t, \omega) &= M_0 p [1 + \exp(i\theta_d) + \exp(2i\theta_d) \\
 &\quad + \cdots + \exp((n-1)i\theta_d)] \\
 &= M_0 p \exp(\omega \Delta t - kr) \exp(-i(kL/2) \sin \theta) \quad (47) \\
 &\quad \sum_{j=1}^n \exp(i(j-1)kd \sin \theta)
 \end{aligned}$$

which, using trigonometric identities, transforms to

$$V(r, \theta, t, \omega) = M_0 p \exp(\omega \Delta t - kr) \frac{\sin[(nkd/2) \sin \theta]}{\sin[(kd/2) \sin \theta]} \quad (48)$$

at a distance far from the source (far-field conditions). This latter function can be separated as

$$V(r, \theta, t, \omega) = V_0 H(\theta) \quad (49)$$

where the maximum voltage amplitude is given as a function of distance, r , and frequency, ω , along the acoustic axis by

$$V_0(p, r, \omega) = M_0 p \exp(\omega \Delta t - kr) \quad (50)$$

and the angular dependence of the signal is given by the directivity function

$$H(\theta) = \frac{\sin[(nkd/2) \sin \theta]}{\sin[(kd/2) \sin \theta]} \quad (51)$$

As a simple example of how an array functions, consider a source that is omnidirectional, radiating an acoustic wave of pressure p_0 at low frequency, ω (wavelength λ), to two identical hydrophones separated from the source by distances r_1 and r_2 , respectively. The distance between the hydrophones is

$$R = r_1 - r_2 \quad (52)$$

and is known. Assuming plane-wave conditions, the voltage output from the first hydrophone is

$$V_1 = M_0 p_0 \exp[ikr_1 - \omega \Delta t_1] \quad (53)$$

and

$$V_2 = M_0 p_0 \exp[ikr_2 - \omega \Delta t_2] \quad (54)$$

from the second hydrophone. Subtracting Eq. (53) from Eq. (54) yields the expression

$$\begin{aligned}
 V_2 - V_1 &= M_0 p_0 \exp[k(r_1 - r_2)] \exp(-\omega \Delta t) \\
 &= M_0 p_0 \exp[-kR] \exp(-\omega \Delta t) \quad (55)
 \end{aligned}$$

where

$$\Delta t = \Delta t_2 - \Delta t_1 \quad (56)$$

If voltages V_2 and V_1 are measured and the sensitivity M_0 and distance R are known, the frequency of the incoming wave, which determines the wave vector $\mathbf{k} = (\omega/c)$, and the time delay Δt can be determined directly in a manner similar to measuring the frequencies and phase difference of two sine-wave signals on an oscilloscope with a time base. The pressure amplitude at the source can then be calculated as

$$p_0 = \frac{V_2 - V_1}{M_0 \exp[kR]} \exp(-i\omega \Delta t) \quad (57)$$

and by putting this value into Eqs. (53) and (54), values for r_1 and r_2 can be solved for giving the distance to the radiating object. Similarly, since n , the number of hydrophone elements; \mathbf{k} , the wave vector; and d , the distance between elements, are all known, Eq. (48) can be solved for angle θ provided the directivity function of the array, $H(\theta)$, is known. Since both r and θ relative to the object are determined, the object is located in two dimensions and its signal strength is also known. Extension of this example to three dimensions is straightforward. When calibrating a hydrophone, generally the free-field voltage sensitivity (FFVS) and directivity function $H(\theta)$ are measured as functions of frequency. Hydrophones are usually designed to make these two parameters as insensitive as possible to signal strength (the voltage/pressure relationship must be linear over wide ranges of acoustic pressure) and environmental variables (pressure, temperature, and time).

The previous example was an extremely simple one based on a number of assumptions, which are often incorrect. The array elements were assumed to measure pressure independent of the other hydrophones. In practice, individual elements diffract the sound waves, impinging on them (which alters the field on surrounding hydrophones in the arrays, thereby altering the response of the hydrophone). Thus the individual hydrophones, which are often in close proximity or even physical contact, such as in extended-area hydrophones for towed-array applications, interact with each other. Minimizing these interactions and accounting for the remaining interactions is fundamental to producing a useful hydrophone array. In terms of material parameters, for extended hydrophones, the cross coupling is often strongly related to the transverse piezoelectric coefficients, g_{31} and d_{31} , and it is important to reduce the effect of these coefficients through either material or hydrophone design. Also, plane waves or far-field approximations were assumed, and the question of the noise in the environment was not even considered here. There are many noise sources in an ocean environment, such as reverberations, which are frequently nonisotropic and can contribute significantly to the computed cross-correlation coefficients of the various elements of the array. Such contributions generally degrade the performance of an array. Thus the performance of an array is a function of the noise environment in which it operates. One particular type of noise that has received a great deal of attention recently is flow noise. Flow noise results from turbulence and nonlaminar flow over the surfaces of the hydrophone, which induces pressure fluctuations on the hydrophones. Flow noise is generally a broad-spectrum noise source that depends on the velocity of flow, the hydrophone dimensions, and the array configuration. The broad spectrum of the noise tends to particularly excite vibrational modes of the hydrophones and arrays where the sensitivity of the system is high and can mask incoming acoustic signals. The noise tends to be largest at shorter wavelengths and can be averaged out by using larger area hydrophones. Longitudinal (3–3) modes and transverse (3–1) modes of the hydrophones can both be excited. The size and shape of hydrophone elements and arrays must be designed in consideration not only of the acoustic requirements, such as bandwidth, noise, voltage sensitivity, capacitance, and directivity, but also in consideration of sources of noise, such as flow noise. Operating conditions of a structure on which the hydrophones and arrays are mounted, such as a submarine, including its velocity and its hydrodynamic characteristics, must therefore also be considered.

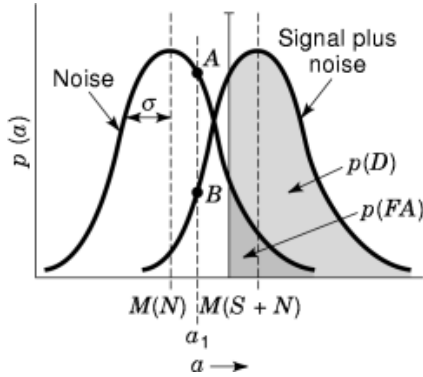


Fig. 4. Probability density distributions of noise and signal plus noise. (Figure reproduced from Ref. 5.)

There are numerous methods of correlating and processing the outputs of an array of hydrophones. If the outputs of pairs of hydrophones are correlated in pairs for m hydrophones in $m(m - 1)/2$ correlators and then added, the power signal-to-noise ratio of the array in isotropic noise is given by

$$(S/N)_{\text{array}} = m(m - 1)Bt(S/N)_{\text{hydrophone}}^2 \quad (58)$$

where B is the bandwidth of the receiver and t is the time over which the signal is processed. The performance of an array, therefore, strongly depends on the signal-to-noise ratio of the hydrophone as well as the number of hydrophones in the array and the achievable bandwidth of the array as well as the time interval over which the signals are processed. The detection index, D_1 , is defined as the square of mean amplitude of signal and noise, M_{S+N} , minus the mean amplitude of just noise, M_N , divided by the variance of the noise present, σ_n^2 , or

$$D_1 = \frac{(M_{(S+N)} - M_N)^2}{2\sigma_n^2} \quad (59)$$

The probability density of the noise is assumed to be Gaussian. The detection threshold (D_T) is defined as the level of a signal that is just detectable at a predetermined probability of accurate detection versus a false detection (Fig. 4). This is given as

$$D_T = 10 \log(S/N) = 10 \log(D_1/(2t\Delta f)) \quad (60)$$

where the noise power is defined as that in the frequency band Δf , which is generally defined as 1 Hz. The detection threshold is the measure of a performance of a hydrophone array.

The performance of an array can be altered by “shading” the different hydrophones by varying their sensitivity and directivity patterns. Weighting the sensitivity of the hydrophone elements is frequently used to further increase the signal-to-noise-ratio of the hydrophone array. For arrays that use identical elements, this can be done electronically by varying the sensitivity of each element through changes in the gain of the amplifiers associated with the hydrophones (amplitude shading), by digital computation after sampling of the analog signal, or by introducing phase delays in the elements either electronically (either by analog or digital means) or by varying the size and position of the array elements (phase shading). The first technique (amplitude shading) is used extensively in sonar systems. The latter technique (phase shading) has been applied in radar systems but is not widely used in sonar. Amplitude shading is particularly important for use in systems where

the noise field is not uniform and isotropic, such as on submarine systems. It is beneficial in such cases to lower the sensitivity of elements exposed to greater noise relative to those in quieter locations.

Multiplicative arrays are also possible where the outputs of the hydrophones are multiplied with each other rather than added. This technique can reduce the size and number of elements in an array and is useful in environments with high signal-to-noise ratios well above unity. In such arrays, the D_I and D_T must be considered together because the signal processing and the array design are closely intertwined with each other.

The design of hydrophones is then intimately tied to the design criteria for arrays and systems in which they are used and to the specific application and its physical environment. In the past, there were few options in the design of hydrophone materials in order to tailor the properties of the material to the application. Recently, a number of piezoelectric materials have been developed that can be designed for very specific hydrophone requirements. The interaction of material design, hydrophone design, and array design is critical in designing an acoustic detection system.

Conventional Piezoelectric Hydrophones

Single Crystal Materials and Hydrophones. Before about 1955, many hydrophones were based on the use of single crystal materials, which have significant hydrostatic piezoelectric coefficients (d_h or g_h). Disadvantages of using single crystals are their mechanical fragility and the limited size achievable by single crystal growth methods. The cost of single crystals is also prohibitive because of the time and sophisticated equipment required. Several purely piezoelectric (nonferroelectric) crystals have very high voltage sensitivity (g_h) but low dielectric permittivity and, therefore, low charge coefficients (d_h). A classic material in this family is lithium sulfate monohydrate ($\text{Li}_2\text{SO}_4\text{-H}_2\text{O}$). This material is still used for a few hydrophones that require high voltage sensitivity and where an amplifier can be physically located very near the single crystal element so that significant capacitive losses due to the cable connecting the crystal to an amplifier can be prevented. Ferroelectric crystals, such as ammonium dihydrogen phosphate (ADP), potassium dihydrogen phosphate (KDP), and Rochelle salt, were extensively used in early hydrophone development because they had higher dielectric permittivity, which lowers the cable loss. Properties of these crystals are given in Appendix 1 (6,7). Hydrophones and arrays built from these crystals were often simple in nature, using one or more crystals mounted on acoustically soft polymer or corprene (rubberized cork) in order to isolate it from vibrations of the transducer housing. By simply providing electrical leads to either a transformer or amplifier, the output voltage of the crystals could be measured and, depending on the size and manner in which the crystals are connected (series and parallel), the voltage sensitivity and hydrophone capacitance could be adjusted to fulfill the design criteria.

Recently, a new class of materials, the lead magnesium niobate–lead titanate (*PMN-PT*) single crystals, were developed and give extremely high dielectric permittivity ($\sim 50,000\epsilon_0$) and piezoelectric charge coefficients (d_{33} , d_{31} , d_h) and moderate piezoelectric voltage coefficients, which yield significant material FOM ($d_h g_h$) (8). Application of these materials has only recently begun. The high dielectric permittivity makes the material appropriate for remote acoustic sensors where amplifiers are not in close proximity of the sensor. The large d_h can also be used for acoustic sources, while the voltage sensitivity is sufficient for hydrophone applications, making the material intriguing for pulse-echo and other reciprocal transducer applications. Being single crystals, the materials suffer from mechanical shock limitations and are limited to small sizes, but the sensitivity and dielectric permittivity of the material may make them useful for very compact hydrophone applications.

Ceramic Hydrophone Materials and Conventional Hydrophone Designs. The most commonly used piezoelectric material for hydrophones is lead zirconate-titanate (*PZT*) ceramic. This material was developed by B. Jaffe and coworkers at Clevite Corporation (now a division of Morgan-Matroc Corp., Cleveland, OH) in the mid-1950s. The classic textbook, *Piezoelectric Ceramics*, by B. Jaffe, W. Cook, and H. Jaffe (9) describes the common ceramic compositions of PZT and their properties. Several compositions are so commonly used

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in Navy systems that they are referred to as Navy Type I, Navy Type II, and Navy Type III piezoceramic corresponding to trade names of PZT-4, PZT-5, and PZT-8. There are many other compositions, but these first two are most commonly used in hydrophones. PZT-8 is almost exclusively used in acoustic source (projector) applications. The properties of these materials are listed in Appendix 2. As can be seen in Appendix 2, these materials have high piezoelectric charge coefficients, d_{33} , d_{31} , and d_{15} when the stress (compressive or shear) applied is along a single direction. However, for low-frequency applications, the stress is hydrostatic and the hydrostatic piezoelectric coefficient, d_h , is rather low due to the opposite signs of the d_{33} and d_{31} coefficients [Eq. (24)]. The voltage sensitivity is extremely small due to the very high dielectric constants in addition to the difference in sign. Therefore, the object of most hydrophone design is to transform or eliminate either the longitudinal (T_3) stress and maintain or increase the transverse (T_1 and T_2) stresses or to eliminate the transverse stresses and increase or maintain the longitudinal stress. Hydrophones, which are based on the latter technique, are termed 3–3 or longitudinal mode transducers, while those based on the former strategy are called 1–3 or transverse mode transducers. The Russian monograph by Ananeva (10) provides descriptions on the design of transducers using piezoceramics, although it principally discusses barium titanate ceramic hydrophones, more commonly used in early Russian transducers. The most common method for accomplishing the stress transformation is to form the ceramic into either a hollow sphere or a piezoelectric ceramic tube. Usually, the spherical shell is poled radially. For a radially poled spherical shell with inner radius a and outer radius b , the tangential stresses are amplified, whereas the radial stresses are nearly negligible and the hydrostatic voltage response (voltage/hydrostatic pressure) is given by (10)

$$\frac{v_3}{p} = \frac{b}{\eta^2 + \eta + 1} \left[\frac{\eta(1 + \eta)}{2} (g_{33} - g_{31}) - (g_{33} + 2g_{31}) \right] \quad (61)$$

where $\eta = a/b$. Thus, for very thin shells, η approaches unity and this equation becomes simply

$$\frac{v_3}{p} = \frac{bg_{31}}{3} \quad (62)$$

A very thin shell hydrophone, of course, cannot withstand high pressure or shock; often, the shell must be made thicker, which reduces the sensitivity of the hydrophone. Recalling that the g_{33} and g_{31} coefficients have opposite signs, it is apparent that the two terms tend to cancel each other in the far right-hand term [Eq. (61)]. For small η (thick shell), the first term in the brackets is zero and the response simply becomes equal to the hydrostatic response of the piezoceramic,

$$g_h = g_{33} + 2g_{31} \quad (63)$$

as expected.

Spherical hydrophones have the advantage of being omnidirectional up to higher frequencies compared to planar or cylindrical hydrophones. They are generally used for applications where space is restricted or where it is impossible to align the element properly, such as in small acoustic test facilities. The sensitivity of a hydrophone based on a spherical ceramic element is omnidirectional up to near the fundamental resonance of the spherical element. The unamplified FFVS of a series of spherical hydrophones is shown in Fig. 5.

The sensitivity, however, is lower than that of a hollow-cylindrical PZT hydrophone (by a factor of 4.5 for thin-walled elements) for elements of similar volume. The cylindrical hydrophone (directivity is shown in Fig. 6) is more commonly used because of its higher capacitance, higher sensitivity per unit volume, and more convenient shape for arrays. The voltage response (FFVS) of a hollow cylindrical hydrophone, poled radially

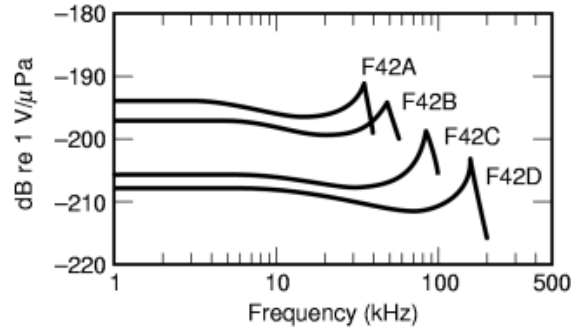


Fig. 5. FFVS of a series spherical hydrophones (NUWC-USRD Models F42 A-D) with OD dimensions of ceramic elements: A: 5.0 cm, B: 3.91 cm, C: 2.54 cm, D: 1.27 cm). (Figure reproduced from Ref. 11.)

with stiff-capped ends, is given by (10)

$$\frac{v_R}{p} = \frac{b\xi g_{33}}{1-\xi} + \frac{3-2\xi g_{31}}{2-2\xi} \quad (64)$$

where $\xi = (b - a)/2b$, a is the inner diameter and b is the outer diameter of the cylinder. For thin-walled cylinders, this expression becomes

$$\frac{v_R}{p} = \frac{3bg_{31}}{2} \quad (65)$$

Capacitance can be increased by increasing the length of the tube depending on bandwidth requirements. The response of a cylindrical end-capped hydrophone (NUWC-USRD Model H56) used for calibration purposes is shown in Fig. 7. It has FFVS of -164 dB re $1 \mu\text{Pa}$, which includes about 30 dB of amplifier gain. The response of the hydrophone is seen to be flat from 10 Hz to near 50 kHz. The FFVS must be considered relative to the noise (the noise equivalent pressure) and is essentially the reciprocal figure of merit for hydrophones. The noise-equivalent pressure of an H56 hydrophone is shown in Fig. 8 (11). For a comparison to other materials technology, the materials FOM $= (p_{\text{nep}}^2 V)^{-1}$ for a hollow cylinder, where V is the volume of this cylinder, is calculated to be $2 \times 10^{15} \text{ m}^2/\text{N}$ based on the measured noise equivalent pressure, p_{nep} . Directivity patterns for several frequencies are shown in Fig. 6 for the x - z plane. The directivity patterns are omnidirectional for the x - y plane below the fundamental resonance of the hydrophone. The directivity patterns show that the cylindrical transducer becomes directional below the fundamental resonance in the hydrophone. Note the difference of sensitivities, although this must be considered in light of the volume of the ceramic element in the hydrophone.

Perhaps the most widely used reversible transducer for Naval underwater applications is the Tonpizl stack, which is a variation on the piezoceramic cylinder (12). This transducer is made from stacks of rings electroded on the flat surfaces and electrically connected in parallel, which can either be poled longitudinally or radially (3-3 or 1-3 mode) and are electrically insulated from each other held together with a stress rod made of very stiff steel. By varying the ring geometry, the number of rings, the static stress maintained by the stress rod, as well as the poling direction, the Tonpizl stack transducer can be designed with a wide range of voltage sensitivity, capacitance, and resonance frequencies and can serve as both acoustic source and hydrophone.

Flexensional Hydrophones. An alternative family of transducer designs most often used for acoustic sources, but which can also be used as hydrophones, are not classic 1-3 or 3-3 mode transducers but are referred

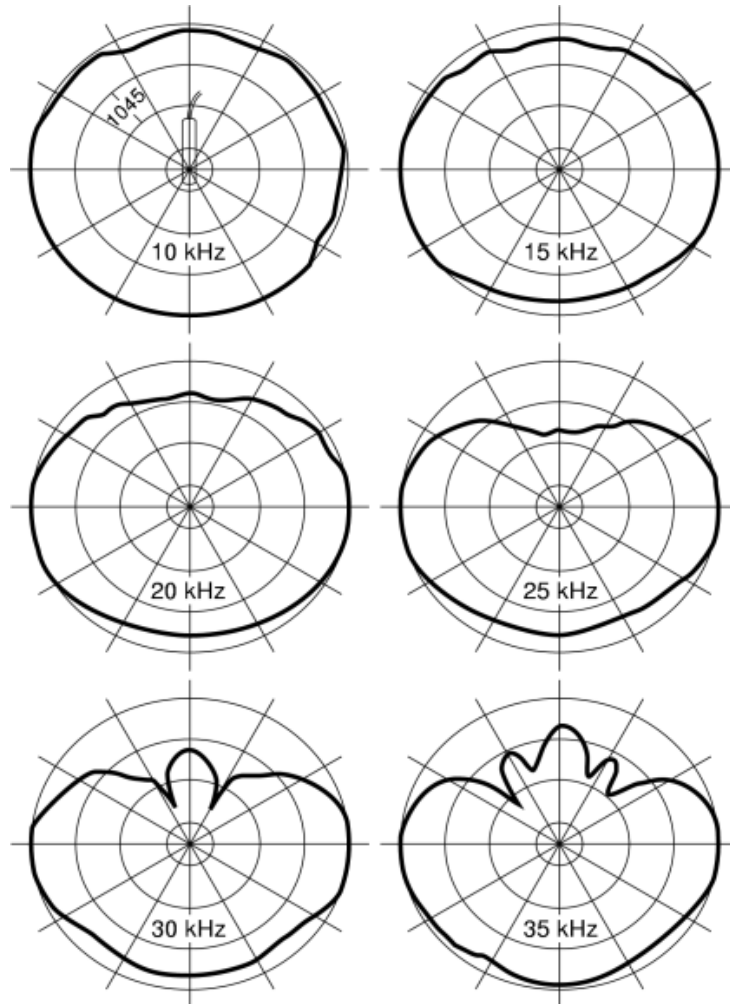


Fig. 6. Directivity of NUWC Model H56 cylindrical tube PZT hydrophone for several frequencies (dimensions of ceramic element : OD—0.518", ID—0.446", L—0.375"). (Figure reproduced from Ref. 11.)

to as flextensional hydrophones (13,14,15). Unlike the piezoceramic sphere and cylinder hydrophones, which use their own geometry to achieve a high level of acoustic sensitivity, the flextensional hydrophone uses a mechanical shell, generally made of metal such as steel or brass, to transform hydrostatic stress to a stress along one or more of the sensitive axes of a single piezoelectric plate or a stack of piezoelectric ceramic plates or rings. Recent application of a flextensional design generates a high sensitivity because it is possible to convert hydrostatic stress to activate the contributions from two or even all three independent piezoelectric coefficients (d_{33} , d_{31} , and d_{15}). The various responses sum together with the same sign, thereby making the hydrophone sensitivity greater than is possible with a perfect 33-mode or 31-mode design.

Class I–V Flextensionals. The classification of different flextensional transducer designs depends on the geometry of the outer shell and are described elsewhere. Class I flextensional transducers have “football-shaped” shells that are driven into resonance by a piezoelectric stack, while Class II transducers use a spherical or oval shell attached to a longer stack and can generate more power. Class III flextensional transducers use