PIEZOELECTRIC TRANSDUCER DESIGN FOR MARINE USE

The Sonar Transducer

A sonar *transducer* is an underwater antenna; its sensitivity, radiation pattern and operating frequency will prescribe the information available to an echosounder for signal processing. An echosounder can perform no better than the transducer allows it to perform. Marine transducers are electromagnetic devices, and by definition, convert electrical energy to mechanical energy (sound pressure) and reciprocally, mechanical energy to electrical energy.

In a given underwater sonar system, a transducer may be employed as a transmitting device, a listening device, or both. When transmitting, the transducer is referred to as a *projector*. When listening, the transducer is referred to as a *hydrophone*.

In a typical sonar system, the transducer converts a high voltage electrical pulse at a given frequency into mechanical vibration. This creates a sound wave that is transmitted through the water in the desired direction according to the characteristic radiation pattern of the transducer. The sound wave intercepts one or more targets within its path (such as fish or the bottom) and a portion of the energy is reflected back to the transducer as an echo.

The received echo mechanically deflects the transducer, producing a low voltage return signal that is then amplified and processed by the receiver electronics (Figure 1). Since the speed of sound remains relatively fixed (at approximately 4800 feet per second in water), it is possible to determine the distance to the target by accurately measuring the time difference between the transmitted pulse and the received echo.

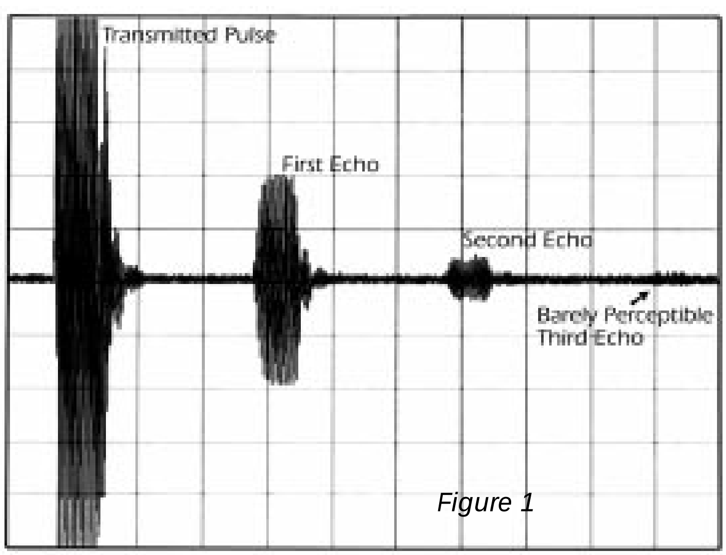

Figure 1

Piezoelectric Transducers

For most underwater applications, *piezoelectric* transducers present the best combination of efficiency, design flexibility and economy. Discovery of the piezoelectric effect in 1880 is credited to Jacques and Pierre Curie. This phenomenon is exhibited by certain materials which develop an electrostatic potential when subjected to pressure and, reciprocally, mechanically deform when subjected to an electrostatic potential. Certain naturally-occurring crystalline substances (for example, quartz) inherently exhibit the piezoelectric property. Synthetic piezoelectric materials can be manufactured using polycrystalline ceramics, or certain synthetic polymers.

Piezoceramics are manufactured by pressing a powder of a selected polycrystalline material to a desired shape (usually circular or rectangular) and then firing the parts in a kiln at a high temperature. Grinding and lapping usually is required to achieve desired mechanical or frequency tolerances. Electrodes typically of silver are applied next to allow the application of electrostatic potential. At this point, the ceramic is isotropic (uniform in all directions) and is composed of many crystals, in a random orientation, with each crystal cell behaving like a dipole. By applying a strong DC field at a high temperature, the dipoles are aligned parallel to the field thus making the ceramic anisotropic. This process is called *poling* and makes the ceramic piezoelectric.[1]

Applying an alternating current across the electrodes will cause the transducer to alternate in size at the applied frequency. Likewise, vibrating the ceramic mechanically will cause an AC voltage to appear at its electrodes.

In its simplest form shown in Figure 2, a marine transducer is fabricated by wrapping a resonant piezoceramic in a suitable pressure release material such as cork or foam, placing the ceramic in a suitable housing, connecting a shielded cable to the silvered electrodes on the ceramic, and filling the housing with an appropriate encapsulation material(s). Usually, the surfaces with electrodes are parallel to the water. (As a low-cost alternative, the ceramic may be bonded to the housing with encapsulated material applied as a backfill.)

Simplified Model

All piezoceramics have at least one series resonant frequency at which they vibrate most easily. This is dependent on the ceramic material, shape and dimensions. Around a given resonant fre-

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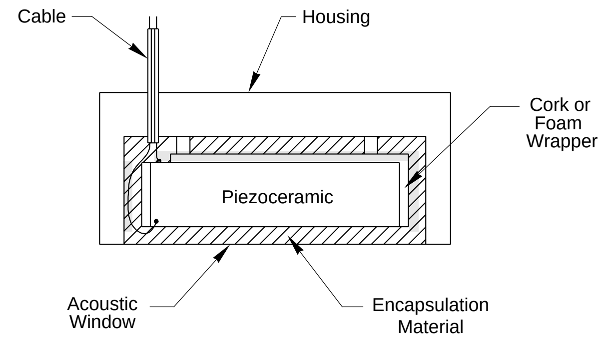

Figure 2
Encapsulation of Piezoceramic

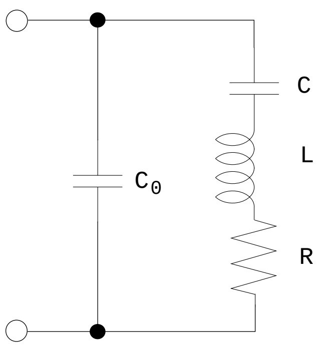

Figure 3

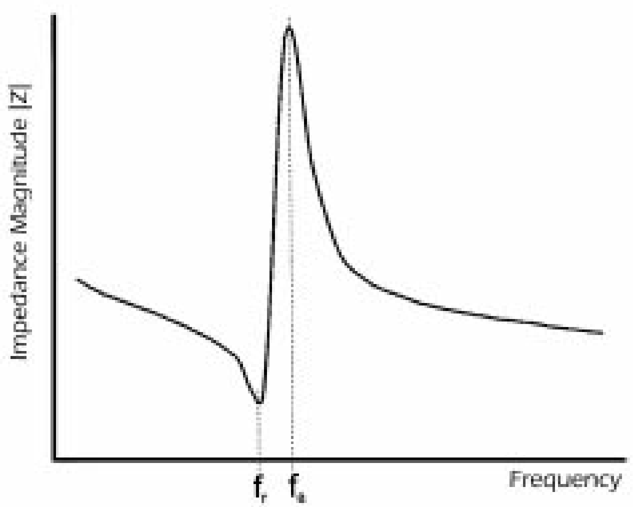

Figure 4

quency f_r, a piezoelectric transducer may be modeled by the equivalent circuit shown in Figure 3.

In this model, R, C, and L represent the mechanical resonance of the transducer. In particular, R represents the transfer of energy into the water, as well as mechanical losses of the transducer. At resonance, the energy stored in the transducer is being transferred back and forth between C and L, and the magnitude of the impedance is at a minimum determined by R. It is at a point very near this resonant frequency that the transducer is most efficient as a projector (that is, converting electrical energy to acoustic energy).

The equivalent parallel capacitor C_o represents the dielectric capacitance of the transducer. The combination of C_o, C, and L yields a parallel *antiresonance* at a frequency f_a, which for a piezoceramic is always above f_r (usually by a few kHz), and where impedance magnitude is near maximum. Near f_a, the transducer is most efficient as a hydrophone (that is, converting acoustic energy to electrical energy). The parallel antiresonant frequency is greatly influenced by external factors such as cable capacitance and acoustic window material, which serve to affect the total parallel capacitance in the system. For a piezoceramic, impedance magnitude vs. frequency is graphically presented in Figure 4.

The *quality factor*, or Q of the transducer at resonance, is defined as

$$Q = 2\pi f_r \cdot \left(\frac{\text{maximum energy stored in transducer at } f_r}{\text{power dissipated in transducer}}\right)$$

The Q of a transducer is related to its frequency response near resonance. It can be shown that

$$Q = \frac{f_r}{\Delta f}$$

where Δf is the -3dB (half power) bandwidth of the transducer, centered on the resonant frequency f_r. Transducers with a higher Q therefore have a narrower bandwidth around the resonant frequency. They also have a higher tendency towards ringing when transmitting.

Radiation Pattern and Beamwidth

The transducer *directivity*, or *radiation pattern*, is a function of the dimensions of the active transducer surface area and the transducer operating frequency. Piezoceramics have the property of *reciprocity*; therefore the transmitting radiation pattern of a given transducer is identical to its receiving radiation pattern. For a disc

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shaped element, the directivity of the element at a given angle α is

$$D(\alpha) = \frac{2CJ_1\left(\frac{2\pi rf\sin\alpha}{C}\right)}{\pi fd\sin\alpha}$$

where

$D(\alpha)$ = sound pressure at angle α

C = sound speed of water

J_1 = first order Bessel function of the first kind

f = frequency

d = piezoceramic diameter

The *beamwidth* θ of the transducer at -3dB (half power points) can be computed by letting $D(\alpha) = 1/\sqrt{2}$ and solving for α (= θ / 2). This reduces to the approximation

$$\theta \approx 1.02 \times \frac{C}{fd}$$

From this formula, we can see that transducer beamwidth is inversely proportional to both frequency and ceramic diameter. The -3dB beamwidth as a function of element diameter and frequency is shown in Figure 5. To increase beamwidth, it is obvious that the operating frequency and/or ceramic diameter must be decreased (and conversely). When piezoceramic diameter is reduced transducer sensitivity is also reduced.

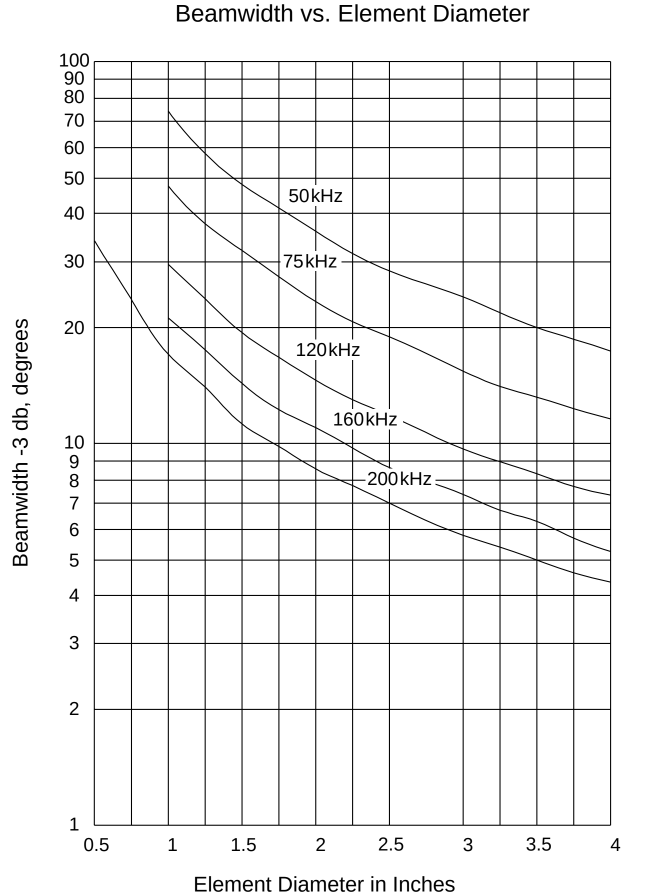

Figure 5
Performance Measurement of Transducers

Performance Measurement of Transducers

Various methods of transducer measurement are used by transducer manufacturers, instrument OEM's and marine electronics dealers. To further confuse this issue, various units are used by different manufacturers. Comparison of transducers measured in different units is difficult, but is still possible.

Of most significant interest is the measurement of transmitting voltage response, receiving voltage response, radiation pattern, and impedance. There are several methods for measuring acoustic response, but the easiest to use is the comparative method, whereby an unknown transducer is compared with a hydrophone of known and reliable calibration. A large number of calibrated hydrophones are available. Most measurements are performed at a distance of one meter between the unknown transducer and the hydrophone.

The *transmitting voltage response* (TVR) of the unknown transducer is the sound pressure produced in the center of the radiated beam pattern at a given distance from the transducer per unit voltage into a hydrophone. Commonly, TVR is reported in decibels (dB) above 1 micropascal (µPa) per volt at 1 meter.

The *receiving voltage response* (RVR) of the measured transducer is the voltage generated across its leads by a plane wave of unit acoustic pressure. When the measured transducer works into a very high impedance, this measurement is called *open circuit voltage* (OCV) response. Common units are dB relative to 1 volt per µPa.

Both TVR and RVR are measured as a function of frequency to determine the peak responses (transmit and receive). A *figure of merit* (the sum of TVR and RVR) is useful in providing a relative gauge of the performance of various piezoceramics. Figures 6, 7, 8 show TVR, RVR and Figure of Merit, respectively, for an Airmar 200 kHz 1.75" diameter PZT-4 piezoceramic which is com-

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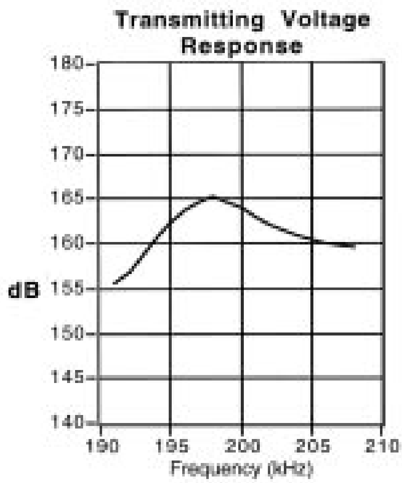

Figure 6

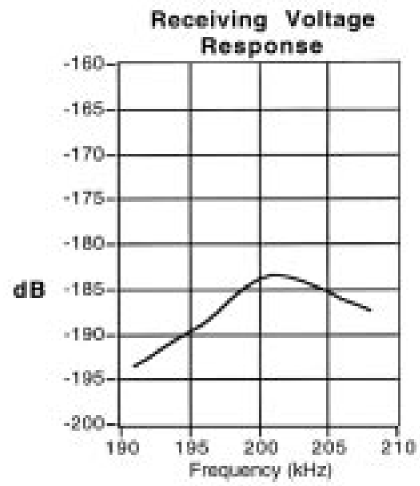

Figure 7

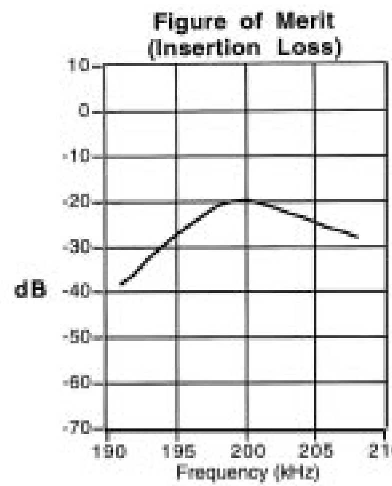

Figure 8

monly used in recreational echosounders. Note that peak TVR is at 198 kHz while peak RVR occurs at 202 kHz. Peak TVR occurs approximately at the resonant frequency of the ceramic (f_r, the minimum impedance point; refer to Figure 4) whereas peak RVR occurs approximately at the anti resonant frequency (f_a, the maximum impedance point). The figure of merit (Figure 8) provides a good representation of transducer bandwidth and the best operating frequency for the transducer (when not tuned).

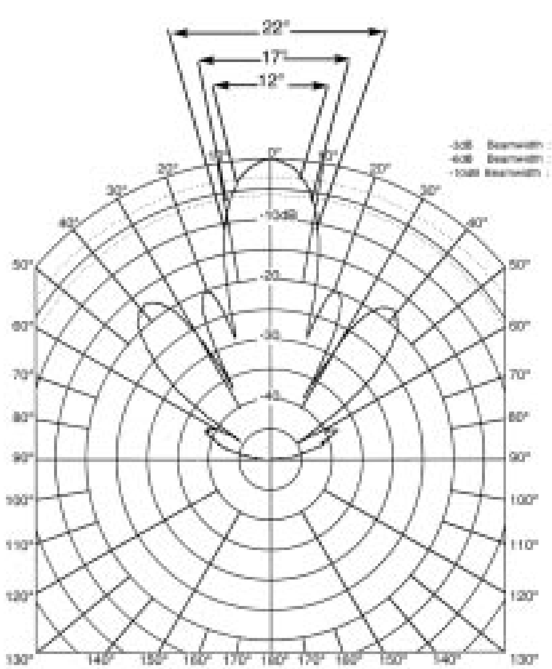

Figure 9

The *transmit radiation pattern* is normally measured at the best transmitting frequency by applying a signal to the transducer and measuring the signal received with a hydrophone as the transducer is being rotated. Measurements can be made continuously or in finite increments of 1˚ or so. The measured data is normalized relative to the peak response and usually plotted on a polar grid such as shown in Figure 9. The beam angles at -3dB, -6dB, and -10dB are highlighted. Note that the first sidelobe is at -20dB and the second sidelobe is well suppressed as well at -17dB. Spurious radiation is negligible and this is mainly attributable to the the fact that this ceramic was mounted in a bronze housing.

Impedance data is measured while the transducer is immersed in water. No echo should be received by the transducer during this measurement which, in theory, would require an infinitely large tank. Depending on the equipment used, impedance is measured as a function of frequency in one of the representations of impedance: impedance magnitude and angle ($|Z|$ and Θ), series resistance and reactance ($R_s + jX_s$), equivalent parallel resistance and capacitance (R_p and C_p), or conductance and susceptance ($G + jB$). These are mathematically related by the following formulas:

$$|Z| = \sqrt{R_s^2 + X_s^2} \qquad \Theta = \operatorname{atan}(X_s / R_s)$$

$$R_p = |Z|^2 / R_s \qquad C_p = X_s / 2\pi f_r |Z|^2$$

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$G = R_s / |Z|^2 \qquad B = -X_s / |Z|^2$

While the theory of transducer measurement is simple, it is relatively difficult and expensive to make accurate absolute measurements. A water tank of sufficient size must be used. Tank sizing is dependent on the frequency to be measured. Detailed recommendations on tank design and measurement equipment systems are outside the scope of this article, but valuable information may be obtained by referring to literature published by Bruel & Kjaer Instruments, 2364 Park Central Blvd., Decatur, GA 30035-3987.

A block diagram of the equipment used for transducer measurement is shown in Figure 10. A good comparative evaluation of small transducers in the 50 kHz to 200 kHz frequency range can be performed with less sophisticated equipment, but still must be done in a tank of adequate size. As a general recommendation, the hydrophone and transducer should be 1 meter apart to avoid being in the Fresnel zone. The tank should be at least 4 feet deep to control surface reflections, and the transducer and hydrophone should be at least 1 foot from the tank walls. Wood tanks work well; the high reflectivity of steel (unless lined) makes for a poor tank. Small diameter tubes are not suitable measurement tanks because of standing wave reflections. Measurement in air of marine transducers is not recommended for many reasons. Most basic is that marine transducers are designed to couple the maximum amount of energy to water. For any specific design, the transducer may or may not exhibit good coupling to air depending on a number of factors.

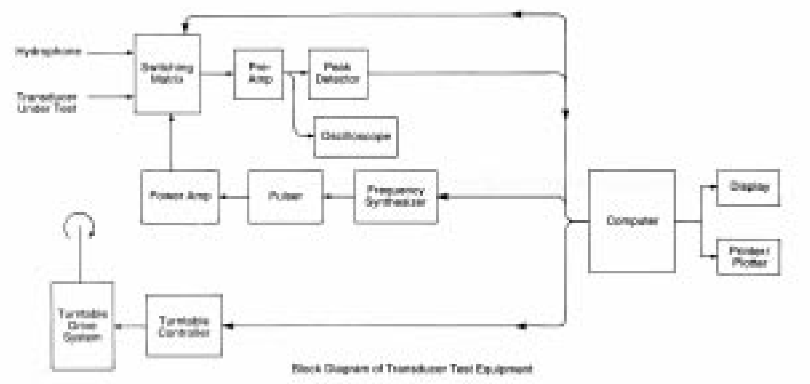

Figure 10

Piezoceramic Resonance Modes

Piezoceramics are usually used at one specific resonant frequency. However, all ceramics contain multiple resonances and the resonant frequencies are a function of the geometry and type of piezoceramic material. Because piezoceramics are three dimensional solids, they can resonate in elongation in several planes and also resonate in shear. These different resonances are called *modes*. For each mode of resonance and each material type, there is a specific *frequency constant* and *coupling coefficient.*

The frequency constant is usually given in kHz/mm and is the product of frequency and the dimension in millimeters at which a piezoceramic resonates in a certain mode. For example, for a specified frequency constant of 2MHz/mm, a ceramic resonating in the thickness mode at 200 kHz would be about 10mm thick.

The *coupling coefficient*, k, is a dimensionless measure of piezoceramic performance and is defined by

$$k = \sqrt{\frac{\text{energy stored mechanically}}{\text{total energy stored electrically}}}$$

The coupling coefficient is not to be confused with transducer

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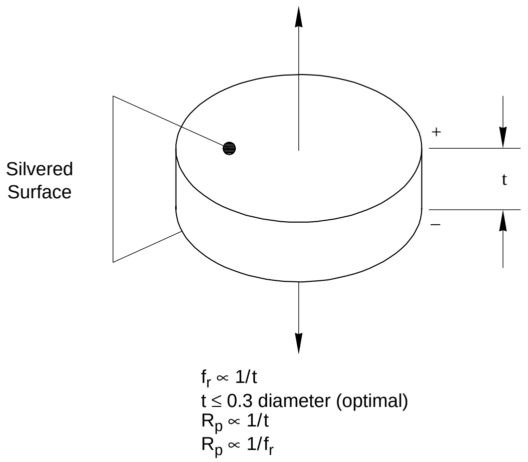
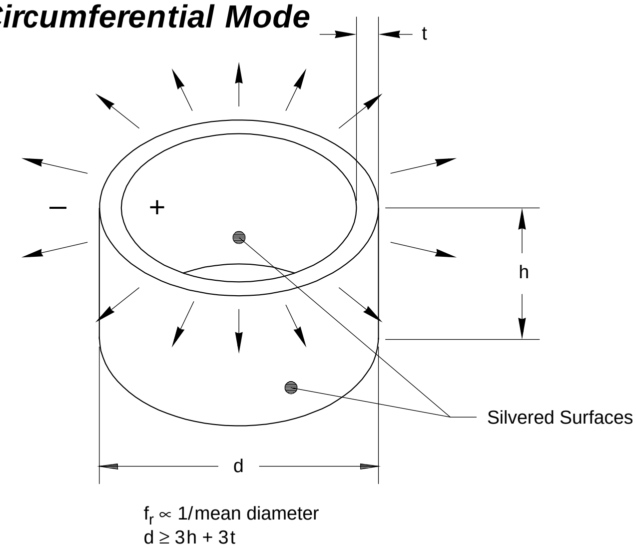
Axial (Thickness) Mode



Circumferential Mode



efficiency, but higher coupling coefficients yield higher efficiency transducers.

Thickness Mode

The *thickness mode* is the most commonly used resonance mode above 100 kHz.

Advantages:

- Resonates in the direction of the water
- Piezoceramic can be manufactured at low relative cost
- Simple transducer construction
- Generally low spurious radiation if properly constructed
- Low to moderate impedance if $t \leq 0.35d$

Disadvantages:

- Less than desirable characteristics if $t \geq 0.4d$ (typical of 1.0" to 1.3" diameter piezoceramics at 150 kHz to 200 kHz)
- High impedance
- Low to moderate sensitivity
- Unwanted resonance modes often near desired resonant frequency

Circumferential Mode

The *circumferential mode* is primarily used in applications below 75 kHz. Piezoelectric rings resonating in circumferential mode are commonly used to generate quasi-omnidirectional radiation patterns. A typical application is underwater communications.

Transverse Wall Mode

The primary application of the *transverse wall mode* is from 100 kHz to 300 kHz. By controlling t, impedance can be, by design, low to moderate allowing low impedance transducers in a wide range of diameters, d.

Advantages:

- Good sensitivity
- Allows narrow and wide beam, high frequency transducers at low to moderate impedance
- Moderate cost

Disadvantages:

- Higher sidelobes in some cases
- Higher spurious radiation requires more expensive construction

Planar (Radial) Mode

The *planar mode* in circular disks typically exhibits very high coupling, high Q and high ringing. The principal application of the planar mode is for dual mode, dual frequency transducers, and mass loaded low frequency assemblies of ≤120 kHz. This can be most easily demonstrated with an example. In the planar mode, lead zirconate titanate (PZT) resonates at 50 kHz, when the diameter is about 1.75". PZT cannot be poled easily when thicker than 0.8”, precluding the thickness mode. (Even if it could be, its impedance would be quite high!) So metal wafers are bonded to both sides of the piezoceramic disk to lower its resonant frequency. When wafers of approximately $\lambda/4$ thickness are bonded to a thin ceramic, it becomes a thickness mode resonant assembly.[2] In our 50 kHz example, when 1.75” diameter steel wafers and aluminum approximately 0.75” thick are bonded to a 1.75” diameter thin PZT wafer, an assembly is created which resonates

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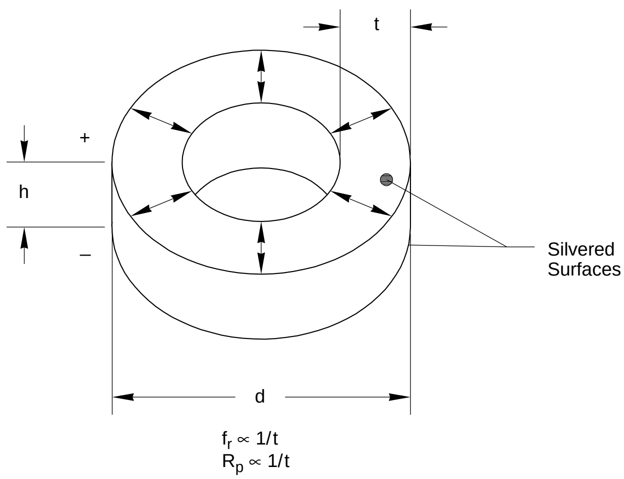
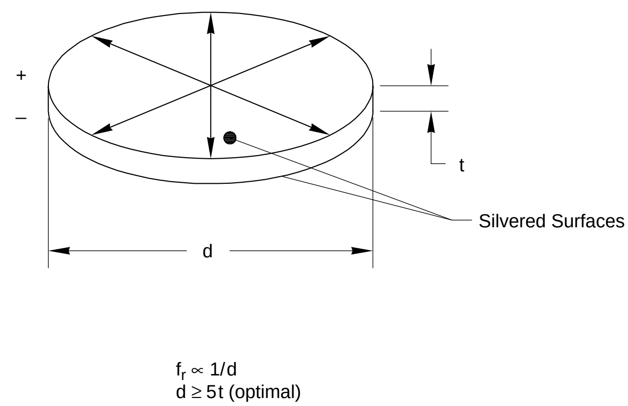
Transverse Wall Mode



Planar (Radial) Mode



simultaneously in the thickness and planar modes. Such an assembly is said to be *mode coupled* and tends to be very efficient. Various material combinations and shapes can be used for the radiating head (wafer closest to the water) and tailpiece (wafer away from the water). The principal application of coupled planar/thickness mode assemblies is in the range from 24 kHz to 120 kHz. Cost is moderate considering the available alternatives at lower frequencies.

Piezoceramic Material Comparison

There are many piezoceramic materials that could be used for marine transducers, but the trade-off of ceramic cost and performance have dictated the use of two material families, barium titanate and lead zirconate titanate (PZT). Comparison of barium and the most commonly used variant of lead zirconate titanate, PZT-4, is shown below.[3]

Resonance Mode	*Coupling Coefficient* Barium	PZT-4
Axial (Thickness)	.46	.71
Circumferential	-.19	-.36
Transverse Wall		-.54
Planar (Radial)	-.32	-.60

Resonance Mode	*Frequency Constant, kHz/in.* Barium	PZT-4
Axial (Thickness)	106	79
Circumferential	58	41
Transverse Wall	91	65
Planar (Radial)	124	87

As can be seen, PZT-4 exhibits superior coupling in all modes and generally yields superior transducers. Barium is desirable in certain situations where its higher frequency constant can yield a more desirable beamwidth and better thickness to diameter ratio. Consider a 75 kHz mode coupled transducer of laminated construction. Barium titanate is resonant in the planar mode at 1.65" diameter whereas PZT-4 is resonant at a diameter of 1.16". For most applications, barium is used because it yields a larger assembly, narrower beamwidth and better absolute sensitivity despite its lower coupling coefficient.

Other forms of PZT are used in marine transducers. PZT-5 is used primarily in receive only applications whereas PZT-8 has high transmit power capabilities.

Use of Various Modes

In marine applications, how does one decide when to use one resonance mode over another? At a given frequency, there may exist a market need for a selection of radiation patterns. Table 1 shows a good example of using different resonance modes to achieve a family of transducers of varying beamwidths at 120 kHz.

Use of these resonance modes can create a selection of transducers which are reasonably impedance compatible. If a single mode were used, the impedance variation would be much greater and transducer sensitivity compromised. Radiation patterns shown in Figure 11 graphically illustrate the great variation in beam patterns that can be achieved.

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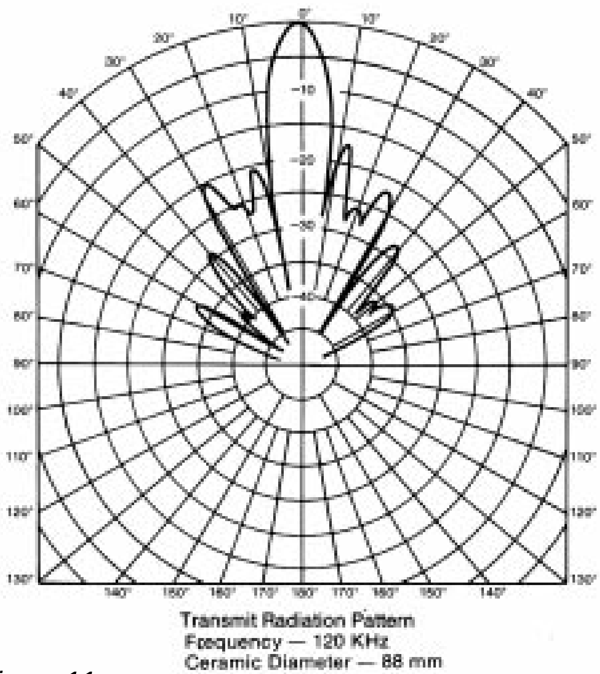

Figure 11a

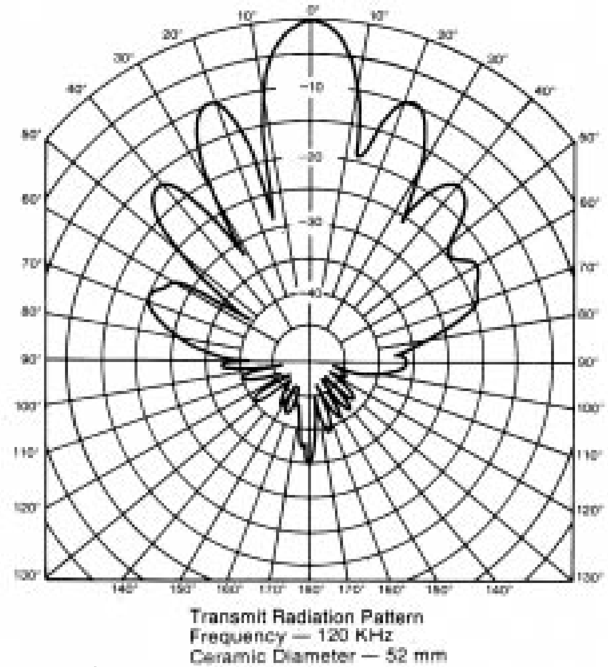

Figure 11b

Multi-Beamwidth Transducers

By creating an impedance compatible family of transducers at one frequency, it is obvious that two or more of these piezoceramics can be packaged in one housing allowing different characteristics to be obtained. For example, at 120 kHz a 2.1"/15 degree beamwidth can be used for bottom detection to 1000 feet and medium depth fishfinding whereas a 0.75" diameter/40 degree beamwidth is an excellent choice for shallow water fishfinding and will present fish targets as "arches". A multi-beamwidth transducer allows the fisherman to select the beamwidth best suited to the situation. For a discernible difference to be obtained on the echosounder screen, there must be a significant difference in beamwidth and transducer characteristics. For example, a 9/17 degree, 200 kHz dual beamwidth transducer, while easy to construct, does not present a significantly different picture to the fisherman viewing the echosounder.

Table 1: Various Modes at 120 kHz

Piezoceramic Diameter	3.5"	2.1"	1.45"	0.75"
Beamwidth @ -3dB	9	15	20	40
Material	Barium	PZT	PZT	PZT
Resonance Mode	Thickness	Transverse	Thickness	Coupled Planar/ Thickness
Power Capability Watts, RMS	1000+	600	350	56
Transmitting Voltage	1000+	600	350	200
Response dB	71	66	62	56
Impedance, Rp, ohms	320	200	200	500

Multifrequency Transducers

All ceramics have multiple resonances of varying strengths. A circular disc with a center hole might have the resonance modes shown in Figure 12. Depending on its various dimensions, a given ceramic can exhibit virtually any combination of thickness, circumferential, transverse wall, and/or planar modes.

In single frequency piezoceramic applications, the ceramic is designed for one strong resonance with other resonances as far away in frequency and as weak as possible. Unwanted resonances that are close in frequency to the desired resonance are parasitic

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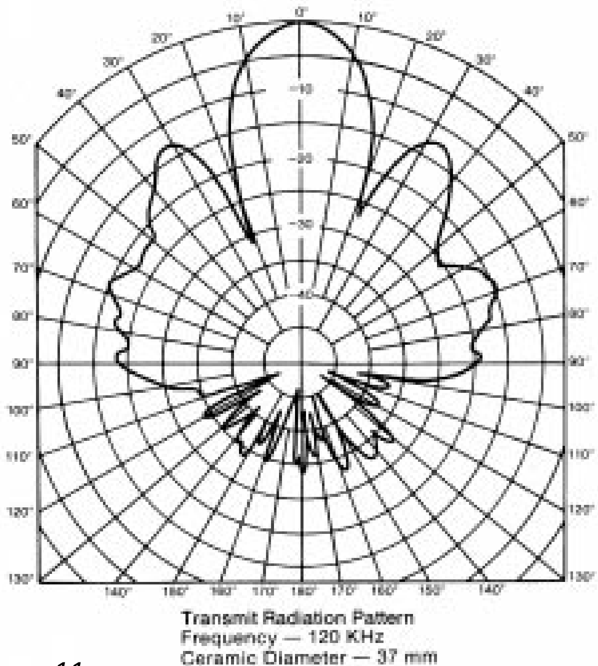

Figure 11c

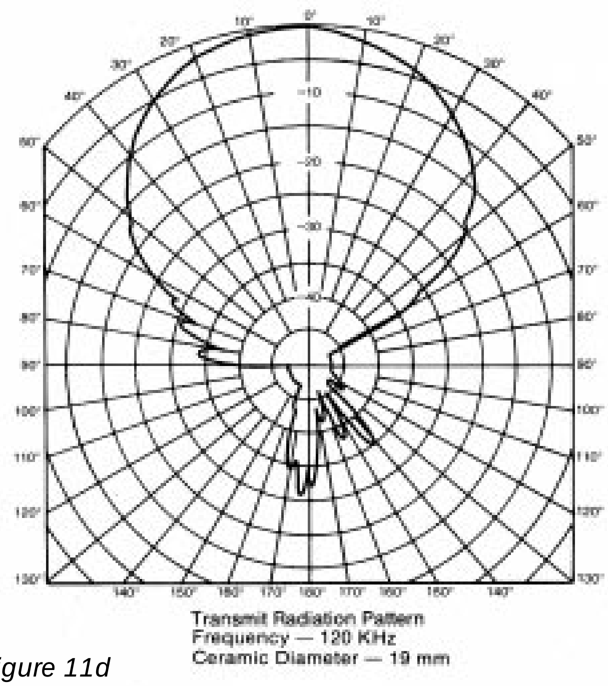

Figure 11d

and tend to diminish the strength of the desired resonance. Rather than separate resonances, another approach sometimes used is to cross couple (in frequency) the two resonances to achieve greater piezoelectric activity.

Since all ceramics have a number of resonance modes, a multifrequency transducer can be created using a single ceramic. The optimization of a multifrequency transducer is a difficult process, and involves compromises since good sensitivity is desired at two or more frequencies. Usually, the relative performance at one frequency will be better than at the others. Multifrequency transducers are often desirable for applications where transducer size (and therefore housing drag) is an important consideration. For commercial fishing, multifrequency transducers are certainly desirable but since size is not usually a dominant consideration, optimum performance can best be achieved using specialized piezoceramics for each frequency. In this way sensitivity, beamwidth, impedance, and sidelobes can be tailored to the intended application.

Acoustic Window

There are many construction variables which affect transducer performance and reliability but the most important is the material used for the *acoustic window.* Referring to Figure 2, the window material occupies the space between the piezoceramic and the water.

When an acoustic wave encounters an interface between two materials, some energy propagates through the interface, and some is reflected back. As acoustic energy is transferred from piezoceramic to the acoustic window material and into the water (and back again as an echo), it passes through several interfaces. At a given frequency, a given material has a characteristic *acous-*

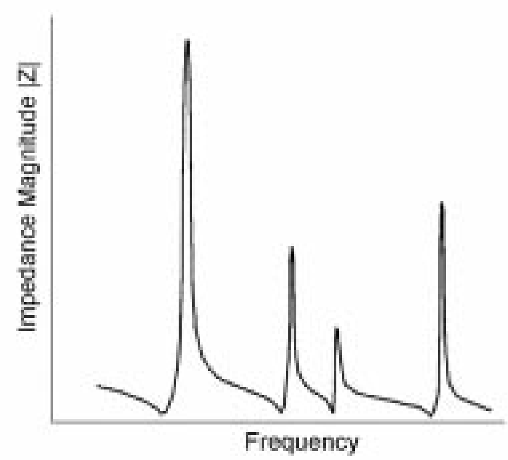

Figure 12

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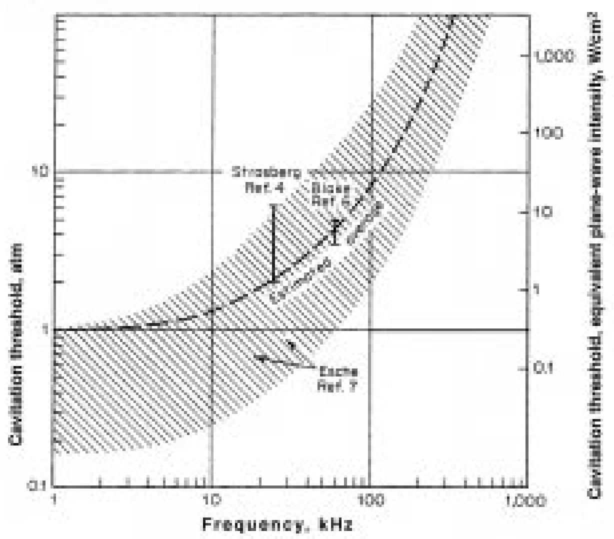

Figure 13

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tic impedance. A good window material will provide an efficient matching layer between the ceramic and the water. In addition, an impedance mismatch may be effectively "tuned out" by controlling the thickness of the acoustic window relative to the wavelength at the frequency of interest.

Most marine transducers use one of the following materials for the acoustic window:

1. Urethane - Flexible material generally with good adhesion, excellent hydrolytic stability and soundspeed close to that of water. Low impedance. Low acoustic transmission losses. Medium to high cost material.
2. Neoprene - Flexible material usually used in conjunction with vulcanized housing construction. Relatively expensive. Other characteristics similar to urethane.
3. Epoxy - Usually a hard material with fillers. Varying hydrolytic stability. High soundspeed relative to water. Good adhesion characteristics. Low material cost. Often used to form a $\lambda/4$ wave matching layer which results in lower Q, lower ringing, and higher impedance.
4. Plastic - Typically, ABS, polycarbonate, or polyester. High soundspeed relative to water. Usually yields a transducer with higher impedance. Generally used for 150-200 kHz. Very low cost and smooth. Repeatable, but compromised performance relative to other materials.

Neoprene and urethane can be used in the frequency range from very low frequencies to 2MHz. Because the soundspeed of the window is close to that of water, thickness is not critical generally, affording design flexibility. Urethanes are relatively expensive and difficult to handle, being toxic and hydroscopic and often requiring a high temperature cure cycle. Maximum acoustic performance and maximum power ratings are achieved using neoprene and urethanes. The flexibility of urethanes is especially important in bronze housings since urethanes are less likely to separate from housing walls during thermal cycling.

Epoxies are inexpensive and their process control is relatively simple. Acoustic window thickness is somewhat critical when constructing a matching layer. Epoxy windows are susceptible to delamination at high power and separation from bronze housings during cold cycling due to the inherent rigidity of the material. Epoxies are not often used in low frequency commercial transducers. They are also not very suitable for multifrequency or multibeamwidth transducers. However, cast epoxy housings with integral matching layer can provide excellent performance (low Q, low sidelobes) in 1-3 kW transducers.

Plastic windows are confined to low cost, high frequency transducers; this construction is especially suited to in-hull transducers since the relatively hard plastic window provides an excellent bonding surface to the relatively hard hull material. Plastic windows are also commonly used on transom mount transducers because the smooth plastic surface can provide very good high speed performance.

Power Rating

Most transducers are rated for a maximum input power usually stated in watts, RMS. Maximum power input is constrained by cavitation of the transducer and by catastrophic failure of the transducer.

Cavitation occurs on the surface of a projecting transducer as transmitting power is increased. As the transducer vibrates, the acoustic pressure generated alternates between a positive and a negative pressure. When the pressure on the negative portion of the cycle exceeds a certain *cavitation threshold*, bubbles begin to form on the face and just in front of the transducer. As the transducer is driven harder, various detrimental effects begin to occur, including a loss of acoustic power as the energy is scattered by the cavitated bubble cloud, a deterioration in the transmitting radiation pattern, and a mismatch of acoustic impedance between the transducer face and the water.

Cavitation is a limiting factor usually at lower frequencies (<50 kHz) (see Figure 13). The cavitation threshold may be raised, thus allowing more acoustic power to be radiated, by increasing the frequency, decreasing the transmit pulse length, increasing the active surface area and/or increasing the depth (hydrostatic pressure) of the transducer.[4] As shown in Figure 13,

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the cavitation threshold in watts/cm^2 is not precisely defined at each frequency since the onset of cavitation is dependent on the presence of bubbles, particles and biomass in the water, water temperature and dissolved oxygen. For example, the data in Figure 13 shows that the cavitation threshold at 50 kHz can vary from 0.4 to 40 watts/cm^2 with the estimated average being 6 watts/cm^2. Typical sportfishing transducers are operated at power densities as high as 43 watts/cm^2. Commercial fishing transducers operate in the range of 6 to 23 watts/cm^2. While transducers (especially those used in sportfishing) are often operated above the cavitation threshold, the effect is seldom noticed since water flowing over the transducer carries the cavitated bubbles away.

The other limiting factor in determining the power rating of a transducer is the catastrophic failure of the device. Failure modes include

- Piezoceramic fracture
- Silver electrode failure
- Excessive heat, causing depoling
- Delamination of loading wafers
- Separation of acoustic window from resonant assembly

The most common failure modes at high power are delamination or acoustic window separation.

A transducer with a power rating of 500 watts will accept a 500 watt input and survive. It is not necessarily the best transducer for a 500 watt echosounder. There is no direct correlation between power rating and transducer acoustic response or overall acoustic efficiency. Unfortunately, power rating is frequently the selection criterion for matching a transducer to an echosounder. This is analogous to selecting the smallest available propulsion unit for a vessel and yet expecting maximum performance.

Frequency Selection

A recurring trade-off is the optimum operating frequency for a variety of applications. Higher freqencies have narrower beamwidths yielding greater bottom definition but detecting fewer midwater targets. Attenuation of sound in water increases with frequency according to the graph shown in Figure 14. Note that attenuation in saltwater is significantly greater below 500 kHz than freshwater primarily due to the presence of magnesium sulfate. Because there is lower roundtrip attenuation of lower frequency signals, lower frequencies must be used to achieve greater working depths. However, lower frequencies have the disadvantage of greater beam angle and spreading losses for a given transducer size. Also, there is increasing ambient noise at the lower end of the frequency spectrum and this reduces the signal to noise ratio when using lower frequencies. Due to the longer wavelength inherent with lower frequencies, smaller targets such as feedfish may not be detected. This can be an advantage or disadvantage. Finally, the lower the transducer frequency, generally the higher the transducer cost.

The fact that different size targets and different bottom compositions have a different appearance on an echosounder display at different frequencies, has precipitated the transition to multifrequency echosounders especially for commercial fishing.

Ringing

A bell, when struck, resounds at its resonant frequency, decaying over time. A transducer exhibits this behavior as well, in both transmit and receive modes of operation. The amplitude of ring is generally much lower than the amplitude of the causative “strike.” In a system with one transducer acting as both projector

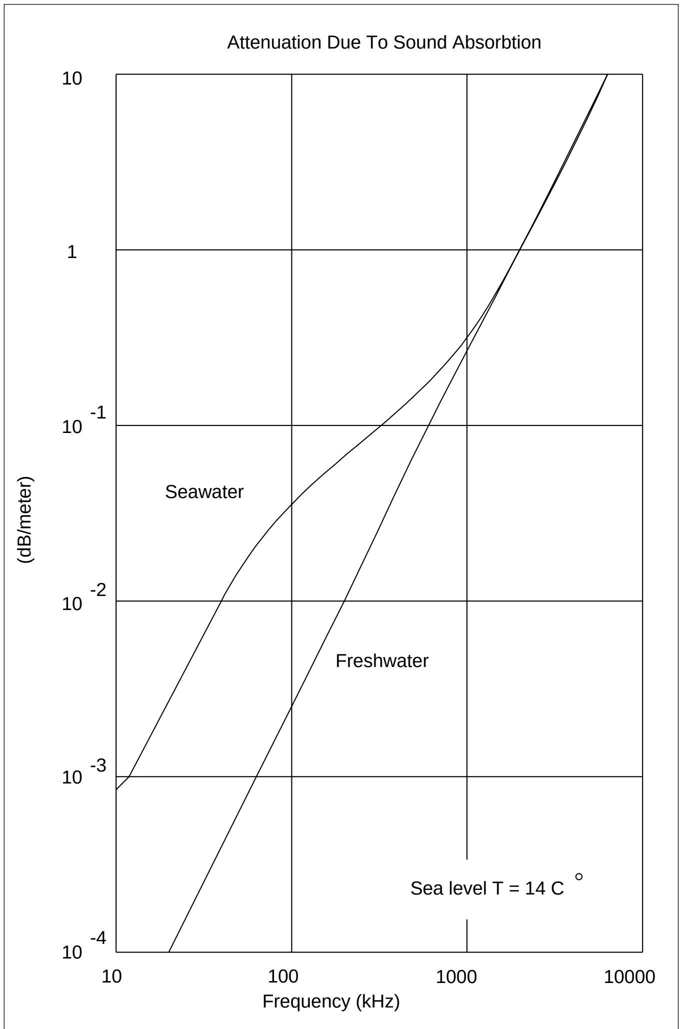

Figure 14

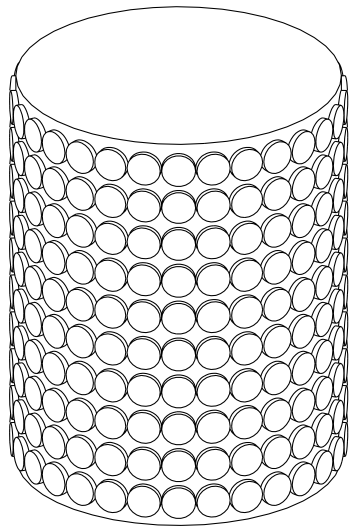

Figure 15

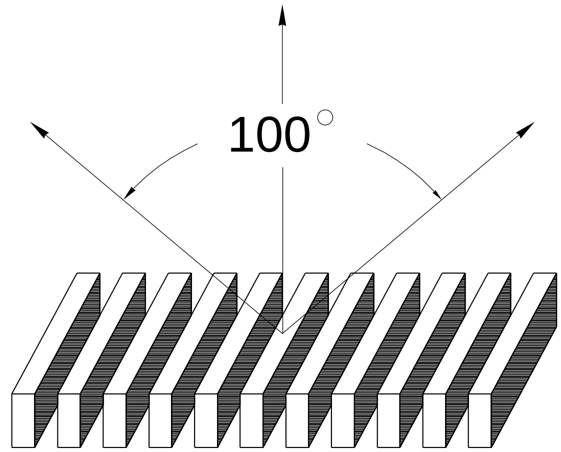

Figure 16

and hydrophone, the ringing occurring as a result of the transmit pulse can prevent the receiver from “seeing” near-range echoes. Various methods may be used to counteract the effects of ringing:

- To reduce ringing of the transmitted pulse, use a transducer with a lower Q.
- To reduce the ringing of received echoes, use a transducer with a lower figure of merit.
- Use separate transducer elements for transmit and receive. If the elements are well isolated from each other, the ringing of the transmit element will not affect the received signal.
- If using a single element for both transmitting and receiving, apply a low impedance load across the transducer immediately after the transmit pulse to dissipate the ringing energy. This is analogous to grabbing the bell with your hand immediately after it is struck.
- If the ringing profile of the transducer immediately after transmit is measured and stored in the signal processing module of the receiver, the expected amplitude of the ringing at each point in time can be subtracted from the total signal detected, thus resulting in only the external signal of interest. The dynamic range of the receiver in this case would need to be wide enough such that the total amplitude of ringing + signal would not saturate the receiver.

System Losses

Many articles and books cover the system losses in echosounders. Prediction of system losses can be determined using the sonar equation and its application is well documented in several texts and papers.[4, 5] This paper focuses on transducer performance, but this is only one component in the sonar equation. Others include water path attenuation along the soundpath (Figure 14), reflection loss of the target, acoustic noise, and electrical noise on board the vessel. Because of these variables, it is very difficult to evaluate initially a transducer in the field environment. Too many other variables can mask subtle differences among transducers. While transducers ultimately must work in the field environment, there is no substitute for the controlled environment of a test tank.

Transducer Selection Criteria

In most echosounder systems sold today, the transducer represents less than 10% of the system cost. It should be obvious that an optimal transducer can markedly enhance echosounder performance; a minimal transducer can severely limit performance. Believing that all transducers of similar power rating are the same can lead to unhappy customers. Various manufacturers produce transducers with different impedance and using different piezoceramic materials and different acoustic window materials.

In commercial fishing applications, the operating frequency(s) will be determined by intended use. Once the frequency(s) is determined, transducer selection criteria should be maximum acoustic response (figure of merit), an impedance which matches the echosounder, and a beam angle compatible with the intended application. Usually, the optional, more expensive transducer is the better choice because of its better acoustic response and narrower beam angle.

For recreational fishing, the selection criteria are slightly different. Since most pleasure fishing is done in shallow waters, beam pattern can be a dominant factor along with operating frequency. Once these are determined, the transducer offering best acoustic response and compatible impedance should be selected. For recreational navigation, narrow beam angle transducers are preferred. Maximum required depth will determine the operating frequency. Again, acoustic response should be maximum. Post

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transmission ring and pulse width will affect minimum depth capability. Spurious radiation and transducer sidelobes should be evaluated carefully for digital depth sounder applications.

PVDF

The piezoelectric homopolymer *PVDF* (polyvinylidene fluoride) is emerging as a low cost alternative to piezoceramics in certain applications. A sheet of isotropic PVDF is poled by stretching it while being exposed to heat and a high electrostatic field. It is then plated with copper on both sides. The copper is selectively etched using the same method as for printed-circuit boards, yielding a pair of electrodes. The shape of the electrodes determines the transducer's radiation pattern, and is designed using the principles of antenna theory. This approach presents the opportunity to design a transducer with a unique radiation pattern, such as an elliptical shape or one with very low sidelobes. PVDF has a broader frequency response than do piezoceramics, and is therefore not limited for use at a specific frequency. PVDF can be shaped to conform to unusual requirements. Multiple elements may be etched onto a single sheet, taking advantage of the intrinsic uniformity of the sheet, yielding arrays of elements well matched in amplitude and phase.

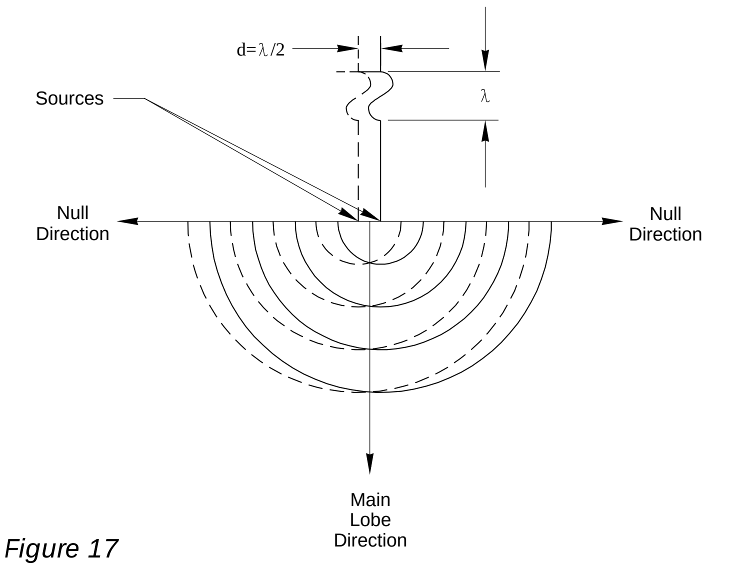

Figure 17

Phased-Array Systems

Single frequency, single beam transducers limit the information available to the echosounder to the underwater volume within the transducer beam pattern. A wide beam transducer can cover an increased volume in shallow water, but provides less resolution and sensitivity. Multifrequency and multi-beamwidth transducers are becoming popular because they can provide significantly more information on the echosounder display. But these transducers generally use a vertically directed soundbeam and provide no acoustic information on targets lying in front of and to the side of the vessel.

Ideally, an echosounder would cover a very large area fore, aft, port, and starboard of the vessel, and have good resolution, sensitivity and discrimination. These characteristics are provided by *phased-array* systems.

The unique characteristic of the phased-array system is the ability to electronically and rapidly steer the acoustic beam in a selected direction. This allows the echosounder to display near-real-time images of targets in their actual locations, and accurate, to-scale bottom contours, rather than a historical graph of objects that have been passed over.

A phased-array system consists of a transducer containing multiple elements, and a beam former, which consists of multiple transmitters and receivers and the phase delay circuitry required to steer the beam.

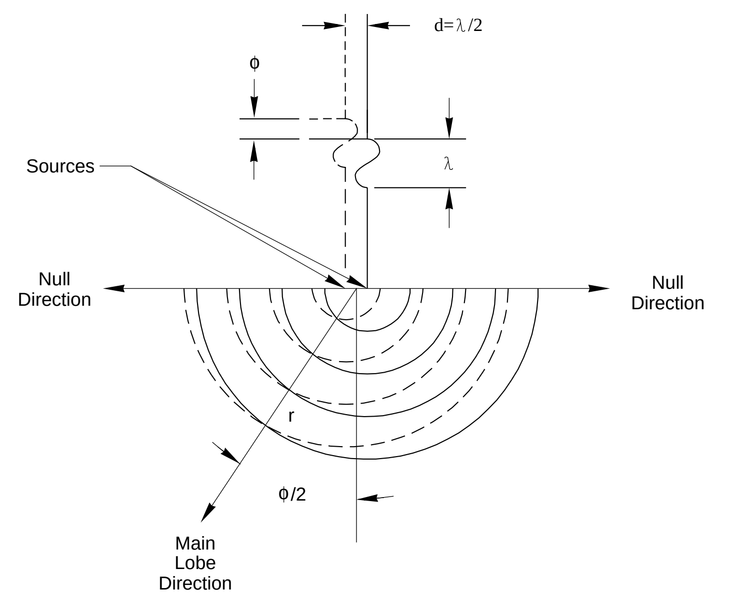

Figure 18

The complexity of the system is determined by the application. Some military systems use very large cylindrical or spherical arrays to obtain 360-degree steering capabilities with very high resolution and sensitivity. Some large commercial systems use larger planar or curvilinear arrays for beam steering on either one or two axes.

Curvilinear arrays such as the one shown in Figure 15 are used in omni-sonars on large fishing vessels. Phase shifting is used to tilt the beam on the vertical (elevation) axis. (These arrays also can form a single or multiple beams on the horizontal (azimuth) axis.)

Planar arrays (Figure 16) can steer a beam on one or two axes through plus or minus 50 degrees from an axis normal to the planar surface. The concept can work at any ultrasonic frequency commonly in use, but some frequency bands present greater transducer fabrication difficulties and result in higher cost.

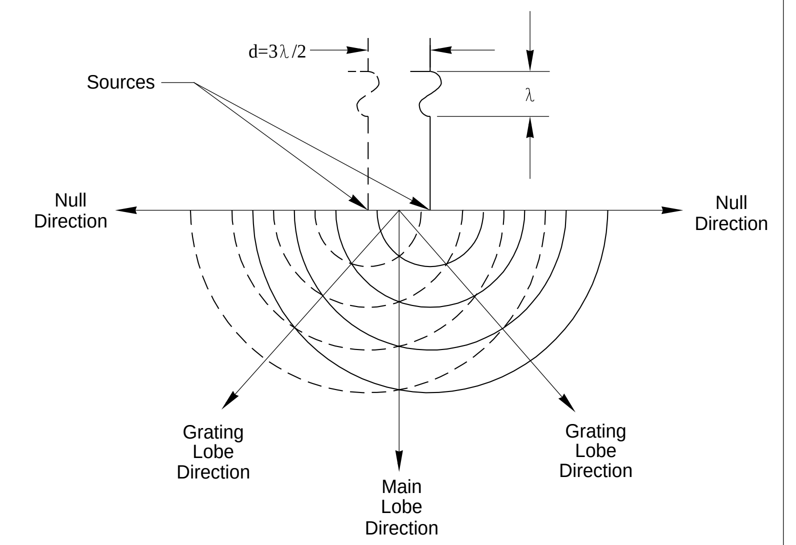

Figure 19

The principle of beam steering may be illustrated by considering the simple case of two point sources, each radiating hemispherically, driven synchronously by a sinusoid of wavelength λ, and separated from each other by a distance of $\lambda / 2$, as shown in Figure 17. The sound waves emanated from each will also be synchronous and sinusoidal, and are represented by concentric semicircles one wavelength (λ) apart, corresponding to the same point on each wave. Where the dotted and solid lines cross, the sound waves are in phase, adding to produce a main lobe; when the two lines are $\lambda / 2$ apart, or 180 degrees out of phase, the sound waves cancel, creating a null. For Figure 17, the main lobe is directed perpendicular to the plane of the two sources.

To steer the beam, we create a time delay, or phase shift ϕ, between the input signal to each source, which in turn produces a phase shift between the sound waves as shown in Figure 18. Now the sound waves add along a line at an angle $\phi / 2$ from the perpendicular. In phased-array technology, this basic principle is extended to the different array types discussed earlier.

What happens if we change the spacing between sources? Figure 19 demonstrates that if the spacing is greater than $\lambda / 2$, there will be more than one line along which the sound waves add. These "grating lobes" are unacceptable in a scanning sonar system because actual positions of targets become uncertain. If the spacing is less than $\lambda / 2$, then the waves are never 180 degrees out of phase, so there is no null along the plane of the sources as there is in Figure 17. This is also undesirable.

Having chosen $\lambda / 2$ as the best spacing, we accept that each element must be less than $\lambda / 2$ in width for ease of manufacture. To construct a transducer of reasonable sensitivity, the width of each element should be at least $\lambda / 4$. The number of elements used is based on the overall beamwidth desired.

Due to the complexity of the transducer and the need for multiple receivers, transmitters, and a beam former, a phased-array echosounder is understandably more expensive to produce than a fixed-beam echosounder. The prevailing trend is to design and use transducers which will acquire more underwater information. As more features are added to new echosounders, phased-array systems will inevitably become more prevalent in the sportfishing and other recreational markets.■

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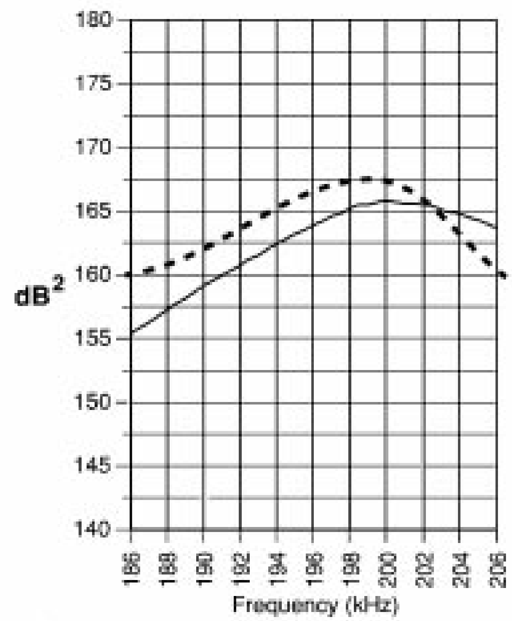
COMPARISON OF URETHANE VS. PLASTIC FOR ACOUSTIC WINDOW MATERIAL

For 120, 150, 200, and 235 kHz transducers, Airmar offers two different acoustic window materials: a soft, low durometer urethane window, and a harder plastic window. Each has advantages. A transducer with the urethane window will have maximum sensitivity and lower impedance. The plastic window will have a broader frequency response, higher impedance, and typically less sensitivity. The low durometer urethane offers superior hydrolytic stability which translates to lower water absorption and longer life for thru-hull transducers. The flexibility of the softer material also reduces the window separation from the housing, which can occur due to the temperature extremes transducers may be subjected to in northern climates. Transducers with plastic windows wet more quickly and generate less acoustic noise at high boat speeds. Plastic windows are more desirable for in-hull mounting and for use on trolling motors, trailered boats, and high speed boats. ■

Transmitting Voltage Response

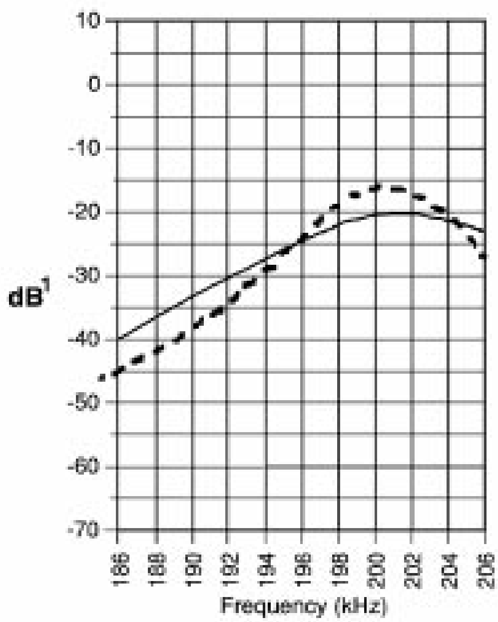


Performance Comparison of Window Material

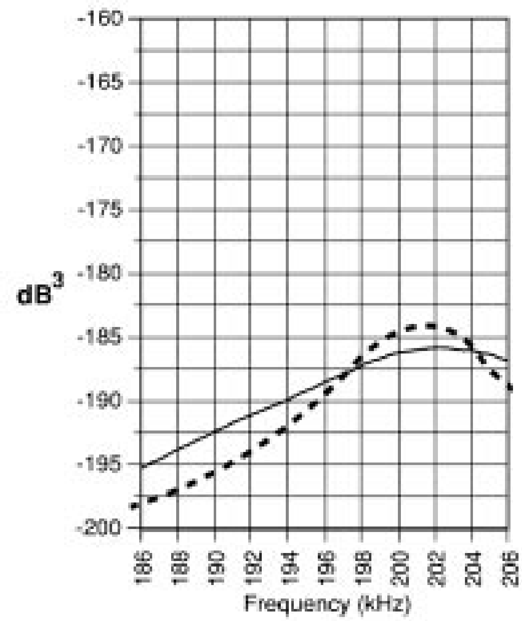
Urethane Window - - - - - - -

Plastic Window ———————

Figure of Merit
(Insertion Loss)



Receiving Voltage Response



1. Sum of transmitting voltage response and receiving voltage res
2. dB re 1 µPa per volt at 1 meter, subtract 100 dB for µbars
3. dB re 1 volt per µPa, add 100 dB for µbars

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IMPEDANCE OF PIEZOCERAMIC TRANSDUCERS

Review of Impedance Concepts

In DC circuits, Ohm's Law states that the resistance R of a device is the ratio of the DC voltage V across its terminals to the current I flowing into the device:

$$R = \frac{V}{I}$$

where R is measured in ohms, V is in volts, an

In AC circuits, we broaden this concept of resistance to include information regarding the phase relationship between the time-varying voltage and current. Impedance Z is the AC equivalent of resistance, and is the ratio of voltage to current:

$$Z = \frac{V(t)}{I(t)}$$

where voltage V(t) and current I(t) both vary as a function of time. Like resistance, impedance is measured in ohms. Unlike resistance, impedance is described using complex numbers. A complex number is any number of the form A+jB. It has two components: a real component A, and an imaginary component jB. By definition, $j = \sqrt{-1}$. That is, j is that number which, when multiplied by itself, results in negative one. The term imaginary is sometimes misleading: it does not mean that the quantity being described is any less physical or tangible than a real quantity; only that it is mathematically represented in a different geometric dimension than a real value. While ordinary real numbers may be plotted on a number line in a single dimension, complex numbers are plotted on a 2-dimensional complex plane.

Impedance is represented in the complex plane by the vector

$$Z = R + jX$$

where R (resistance) is the real component of impedance, X is the imaginary component of impedance, known as reactance, both of which are measured in ohms, and j is the complex operator $\sqrt{-1}$. Impedance of a device in the complex plane is shown in Figure 1.

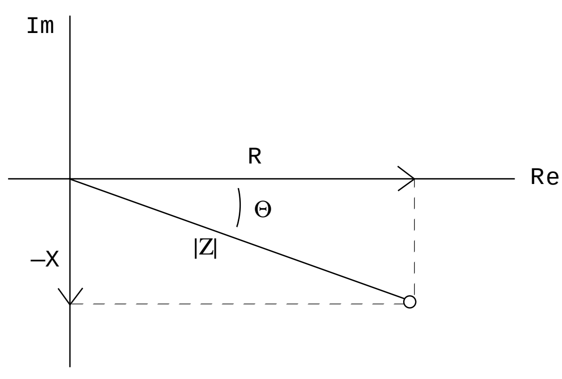

Figure 1

An ideal capacitor has the capacitive reactance

$$X_C = \frac{-1}{2\pi fC}$$

and an ideal inductor has the inductive reactance

$$X_L = 2\pi fL$$

where f is the frequency in hertz, C is the capacitance in farads, and L is the inductance in henrys. Noting the sign in the above two equations, we see that positive reactances are inductive, and negative reactances are capacitive.

The magnitude of impedance Z is

$$|Z| = \sqrt{R^2 + X^2}$$

and its phase angle is

$$\Theta = \operatorname{atan}\frac{X}{R}$$

Impedances connected in series are additive, that is

$$Z_{series} = Z_1 + Z_2$$

and impedances connected in parallel are combined according to

$$\frac{1}{Z_{parallel}} = \frac{1}{Z_1} + \frac{1}{Z_2} \qquad \text{or} \qquad Z_{parallel} = \frac{Z_1 Z_2}{Z_1 + Z_2}$$

Admittance Y is the reciprocal of impedance: Y = 1 / Z, and is

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measured in siemens (S, also known as mhos, the reciprocal of ohms). As with impedance, admittance is represented as a complex value:

$$Y = G + jB$$

The real and imaginary components of admittance are conductance G, and susceptance B, respectively, where

$$G = \frac{R}{|Z|^2} \quad \text{and} \quad B = \frac{-X}{|Z|^2}$$

Both conductance G and susceptance B are measured in siemens.

Transducer Equivalent Circuit

Over a relatively narrow frequency range, a piezoelectric transducer can be modeled by the equivalent circuit shown in Figure 2.

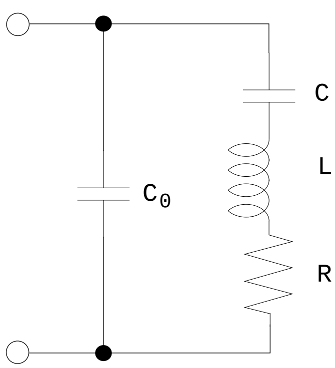

Figure 2

The series elements L and C yield a natural resonance at a specific series resonant frequency f_r of the transducer. This frequency may be expressed in terms of the equivalent values of L and C:

$$f_r = \frac{1}{2\pi} \cdot \sqrt{\frac{1}{LC}}$$

At this frequency, the capacitive reactance X_C of equivalent series capacitor C exactly cancels the inductive reactance X_L of inductor L, and the magnitude of the transducer impedance |Z| is therefore at a minimum determined by R. Near f_r, the transducer is most efficient as a projector (transmitting device).

Parallel capacitor C_0 combines with C and L to produce a second resonance known as the parallel antiresonant frequency f_a, which for a piezoceramic is usually a few kHz above f_r. f_a is related to the equivalent circuit elements by

$$f_a = \frac{1}{2\pi} \cdot \sqrt{\frac{C + C_0}{LC_0C}}$$

At this antiresonant frequency, the impedance magnitude is at a maximum. It is near this frequency that the transducer is generally most efficient as a hydrophone (listening device). Note that the parallel capacitance of the entire system, including the cable, connectors, and echosounder driver circuitry, serve to add to the total parallel capacitance, and so tends to shift the antiresonant frequency. Note also that this total parallel capacitance acts as an AC load, reducing the amplitude of the received signal, and/or requiring the transmitter driver amplifier to provide more current. (The effect of this total shunt capacitance may be minimized at a given frequency by proper selection of a suitable series or parallel inductor.) External parallel capacitance has no effect on the series resonant frequency f_r.

Quality Factor

The quality factor, or Q of a transducer, is a measure of its energy storage property relative to its energy dissipation property. Q is measured at resonance, where the total stored energy in the transducer is constant. Q may be expressed in terms of our equivalent circuit elements:

$$Q = \frac{X_L}{R} = \frac{2\pi f_r L}{R} \quad \text{and} \quad Q = \frac{-X_C}{R} = \frac{1}{2\pi f_r CR}$$

The Q of a transducer is related to its frequency response near resonance. It can be shown that

$$Q = \frac{f_r}{\Delta f}$$

where Δf is the -3dB (half power) bandwidth of the transducer, centered on the resonant frequency f_r. Note from this equation that a transducer with a higher Q at a given frequency will have a narrower bandwidth.

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Net Impedance of a Transducer at its Terminals

It is often required to characterize the net impedance vs. frequency of a transducer at its terminals. For this purpose, our equivalent circuit may be simplified further. At a given frequency (except at resonance), either C or L is predominant. Therefore, at that frequency the transducer will appear at its electrodes to be either capacitive or inductive, and may be represented by either Figure 3 or Figure 4.

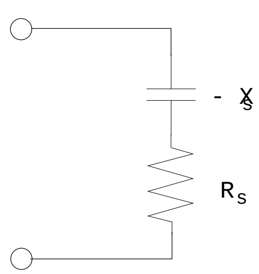

Figure 3

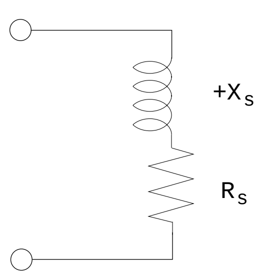

Figure 4

where R_s = series resistance
X_s = series reactance

Note that the values of both R_s and X_s are highly frequency dependent.

The series model does not conveniently lend itself to calculations involving parallel tuned matching circuits. Therefore, it is often more convenient to convert the circuits of Figure 3 and Figure 4 to their exactly equivalent parallel circuits, Figure 5 and Figure 6.

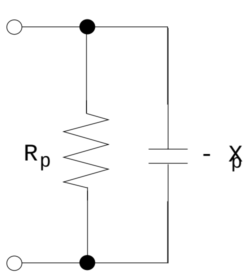

Figure 5

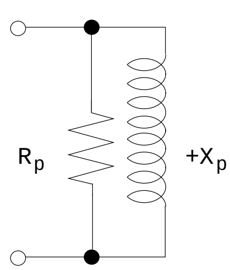

Figure 6

where R_p = parallel resistance
X_p = parallel reactance

The values of R_p and X_p are related to R_s and X_s by the equations

$$R_p = \frac{R_s^2 + X_s^2}{R_s} = \frac{|Z|^2}{R_s}$$

and

$$X_p = \frac{R_s^2 + X_s^2}{X_s} = \frac{|Z|^2}{X_s}$$

As with R_s and X_s, R_p and X_p vary with frequency.

If X_p is assumed to be capacitive, the value of the corresponding equivalent parallel capacitance would be

$$C_p = \frac{1}{2\pi f X_p}$$

The above equation can be used even if X_p is in fact inductive; in this case the value computed for C_p will be a negative number.

The impedance vs. frequency characteristic of a given transducer may be represented using the units most convenient to the task: impedance magnitude and angle (|Z| and Θ), series resistance and reactance ($R_s + jX_s$), equivalent parallel resistance and capacitance (R_p and C_p), or conductance and susceptance (G + jB). Airmar provides impedance data for sample transducers in tabular form showing all of these pairs of values as a function of frequency.

Note that the impedance of a transducer in air is significantly different than in water; therefore when characterizing the impedance of a marine transducer, the device must be immersed in water.

Finding Transducer Resistance at Resonance

The following procedure will allow you to determine the approximate resistance R of a transducer at its resonant frequency (note that at resonance, $R = R_s = R_p$). Though limited, this procedure will produce sufficiently accurate results for field use. Note the following:

- With this procedure a transducer can only be measured unbalanced (i.e. having one side of the transducer grounded).
- If the transducer does not become resistive at the frequency of minimum voltage, the value obtained will be closer to the

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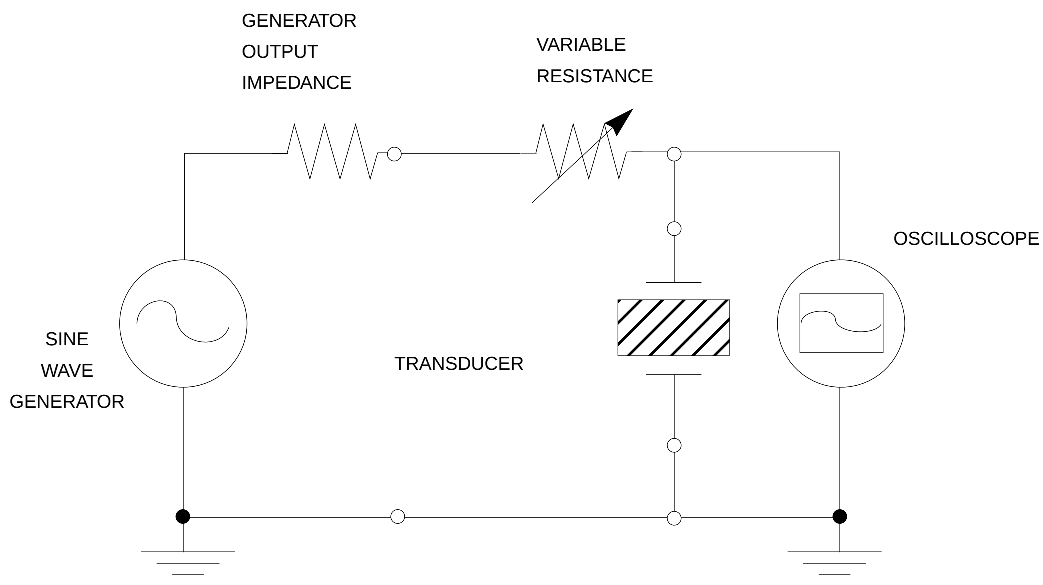

Figure 7

impedance magnitude |Z| at that frequency than to R, but no indication is given of the angle (capacitive or inductive).

Equipment required:

- Sine wave generator
- Variable resistor or a selection of fixed resistors between 50 and 5,000 ohms
- Oscilloscope
- Ohmmeter

Procedure:

1. Configure the equipment as shown in Figure 7. Set the variable resistor to approximately 1000 ohms. Immerse the transducer in water.
2. Adjust the frequency of the sine wave generator until the signal across the transducer seen on the oscilloscope is at a minimum. This is the resonant frequency, and should be within a few kHz of the nominal operating frequency of the transducer.
3. Open one connection to the transducer and set the variable resistor to 0 ohms (shorted). Record this “open circuit” voltage measured by the oscilloscope.
4. Re-connect the transducer. Vary the resistor until the voltage measured by the oscilloscope is exactly one-half of the open-circuit voltage.
5. Remove the variable resistor from the circuit and measure its resistance with the ohmmeter. The resistance of the transducer at the chosen frequency is the resistance of the variable resistor plus the output impedance of the sine wave generator.■

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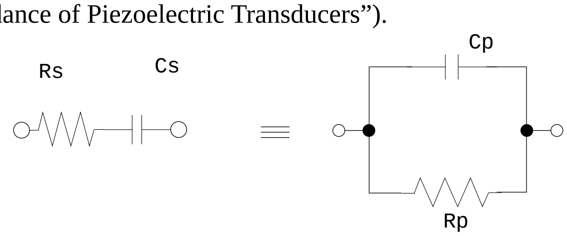
NOTES ON THE DESIGN OF MATCHING SYSTEMS FOR PIEZO ELEMENTS

These notes describe a simplified approach to match a piezoelectric device to a source of power. The optimum matching circuit will result in maximum transmitted energy which will result in stronger echoes.

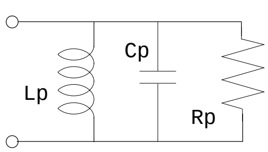
Delivering power to a piezo device, such as a transducer for a depth sounder, is relatively simple in a normal situation. If the fundamentals are understood, then special circumstances can also be accommodated in a straightforward manner.

Like most reactive loads, a piezo device can be represented by a series resistor and capacitor. The values of both these elements will vary with frequency.

By means of the classic transformation, the series values may be transformed to an exactly equivalent parallel resistor and capacitor combination. Unfortunately, the values of these components also vary with frequency (see the separate application note, "Impedance of Piezoelectric Transducers").



The solution to these variations with frequency of operation is to use the values at the desired frequency. In the case of a depth sounder, it is the "Best Echo Frequency". At exactly this frequency, the resistance and capacitance values of the piezo device are obtained either by measurement or from the manufacturer of the device.



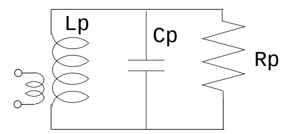
$X_L = X_C$

The simplest matching method is to use an inductor to tune out the reactance of the parallel capacitance, yielding a purely resistive load very nearly equal to the parallel resistance. If the resulting load resistance is too high to directly match the driving source, the inductor may also be used as a tuned transformer to provide a lower, more convenient driving point.

The procedure now follows classic RF matching methods. First, the Q (figure of merit) of the inductor load must be reasonable (5-7 is acceptable)

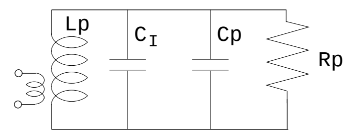
.

$$Q = \frac{R_P}{X_L} = \frac{X_L}{R_S}$$

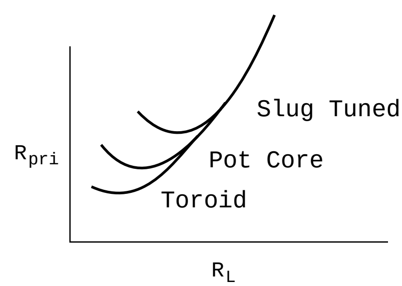


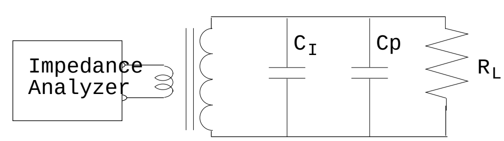
If the Q is too low, place a capacitor C_I across the load and reduce L until the load is again resistive.

$$X_L = \frac{X_{CI}(X_{CP})}{X_{CI} + X_{CP}}$$



A low impedance winding may now be added to provide a match to the driving source. The turns ratio is the square root of the impedance ratio. However, there is a limit to how high the turns ratio can be. For the usual universal wound inductor with a ferrite adjustment slug and ferrite shell, a ratio of 22 to 1 is about the maximum that can be achieved. Higher ratios may be achieved if toroidal forms are used for the inductor. This is because tighter coupling is achieved with toroids than is available with other types of inductors. Pot cores are between toroids and slug-tuned coils in coupling.





The foregoing discussion of matching assumes that the coil is lossless, at least compared to the R_p of the desired transducer load. Often this is not the case.

To evaluate whether there is a problem, a sample coil of the cal-

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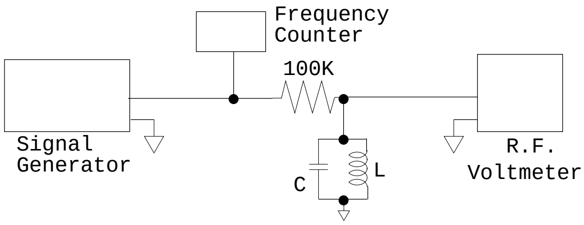
culated inductance must be obtained. If an impedance analyzer is available, the R_p of the coil may be measured by placing the calculated total capacitance across the coil and adjusting the frequency for zero phase angle. The instrument will indicate the R_p directly.

If an impedance analyzer is not available, the s
obtained by another technique.



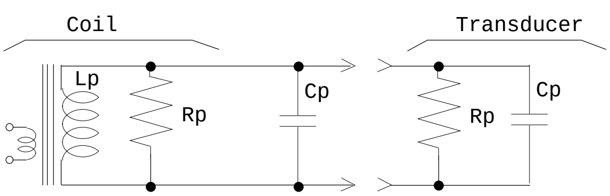
Find the frequencies at which the response of th
down 3dB from peak response.

$$Q = \frac{\left(\frac{F_H + F_L}{2}\right)}{F_H - F_L}$$

F_L= lower -3dB frequency
F_H= higher -3dB frequen

$$R_P = QX_C$$

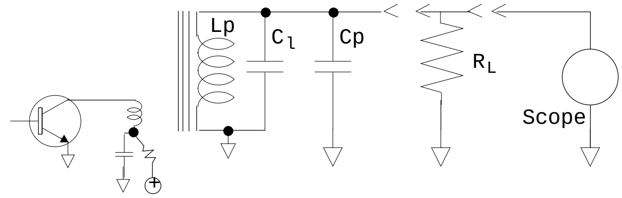
The R_P of the coil should now be considered to be
of the transducer



The coil inductance and resonating capacitance must now be recalculated based on the lower load resistance presented by the parallel combination of the R_P of both the coil and transducer.

Also, the division of the available output power must be considered. If the two R_P's are equal, only one half the power developed is available to the transducer to put into the water. So it is desirable that the R_P of the coil be as high as possible compared to the R_P of the transducer.

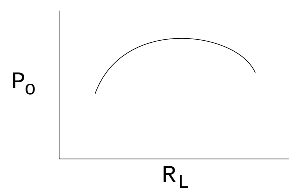
Once the coil is designed and in place, the effectiveness may be checked by placing the equivalent parallel capacitance of the piezo device across the inductor.



Then various resistors are placed across the inductor and the

$$P_o = \frac{\left(\frac{V_{P-P}}{2.83}\right)^2}{R_L}$$

power dissipated is then calculated. A broad peak should be achieved at the value of the parallel resistance of the piezo device. If the power peak does not occur at the value of parallel resistance which the piezo device has at the frequency of interest, small adjustments in the turns ratio and/or the Q should be made.



The advantages of this method of matching are:

- Minimum components — minimum cost
- Highest impedance in the connecting cable, hence the lowest I^2R losses
- If the cable must be extended, a simple removal of fixed capacitance is all that is required

Another method which might be considered is using the series equivalent values of the piezo device. To do this, an inductor is placed in series with the piezo device whose reactance is equal to the reactance of the equivalent series capacitance. This method presents the value of series resistance to the driving source. The disadvantage is that a second inductor is required because in the usual case, the series resistance is still higher than the required load impedance of semiconductor power sources. Also, the current through the load must pass through the effective series resistance of this (series) inductor, which increases the I^2R losses, resulting in a net loss of power delivered to the load in the usual case.

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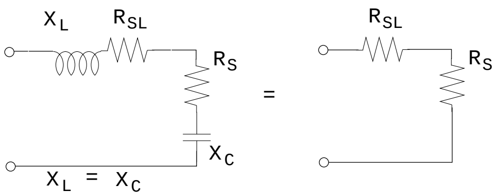


Example:

Assume that a transducer is to be matched whose “Best Echo Frequency” is 196.0 kHz and the series R and X have been measured at that frequency as 151 – j239 (C = 3398pf).

$$R_P = R_S + \frac{X_S^2}{R_S} = 151 + \frac{(239)^2}{151} = 529.3\text{ohms}$$

$$X_P = \frac{R_S R_P}{X_S} = \frac{151(529.3)}{239} = 334.4\text{ohms}$$

$$(C_P) = 2428\text{pf}$$

Since at resonance $X_C = X_L$, the inductor will have a reactance of 334.4 ohms

Calculate Q of this situation

$$Q = \frac{R_P}{X_L} = \frac{529.3}{334.4} = 1.58$$

This is too low so capacitance must be added. Let us calculate on the basis of a loaded Q of 6

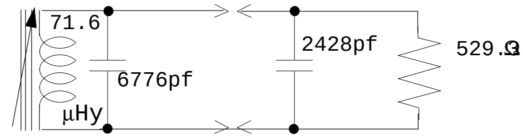
$$X_L = \frac{R_P}{Q} = \frac{529.3}{6} = 88.22\text{ohms}$$

$$L = \frac{X_L}{2\pi f} = \frac{88.22}{6.28(196 \times 10^3)} = 71.6\mu\text{Hy}$$

Total C is now

$$C = \frac{1}{2\pi f X_L} = \frac{1}{6.28(196 \times 10^3)(88.22)} = 9204\text{pf}$$

Added capacitance must then be $9204 - 2428 = 6776\text{pf}$



The required primary impedance is calculated as 3.6 ohms to match the driving transistor

$$N_R = \sqrt{\frac{529.3}{3.6}} = \sqrt{147} = 12.1$$

This is low enough so a slug tuned coil may be used. If a coil of 71.6µHy required 55 turns, then the primary would use 4.5 turns;

$$T_{PRI} = \frac{Tsec}{N_R} = \frac{55}{12.1} = 4.55$$

The primary should be wound as tightly over the secondary as possible to obtain the best coupling. Use the start of the secondary coil as the high impedance end.

Power into a piezo device:

If the parallel resistance is known, power calculation is straightforward:

$$P = \frac{E^2}{R}$$

E is RMS volts
R is the parallel resistance of

Of course the voltage across the load will probably be measured with an oscilloscope and read as peak to peak voltage. If the transmitted pulse is a sine wave, then it must be divided by 2.83 to change to RMS voltage.

If parallel resistance is not used in the calculation, series resistance may be used. But the calculation is a bit more involved:

1. Impedance

$$|Z| = \sqrt{R_S^2 + X_S^2}$$

2.

$$I_L = \frac{E}{|Z|}$$

E is RMS voltage across the load as previously shown

3.

$$P = I^2 R_S$$

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4. The above equations are combined into a single e

$$P = \frac{R_S E^2}{R_S^2 + X_S^2}$$

Considerations for Matching Systems During Receive Mode:

Once the matching has been accomplished for transmit, what are the considerations for receiving? If the input impedance of the receiving section is higher by a large margin, then it may be tied directly across the tuned circuit used to match in transmit.

If the receive input impedance margin is not large or is even small, then other methods must be used to achieve the maximum performance of which the piezo device is capable. Also, provisions must be made to prevent the transmit voltage from destroying the input device(s) of the receiver.

If the coupling of the transformer is high, a lower "Q" may operate satisfactorily. Reduce the capacitance added in steps, increasing the inductance of the secondary in steps to maintain resonance. Keep the primary inductance constant. In the extreme it may be possible to resonate with just the capacitance of the transducer without adding any external capacitance. This will yield higher turns ratios and if the coupling is tight enough, will also yield more output voltage (power).

Note, however, that at Q values of 7 or less, the equation $X_L = X_C$ no longer holds. Until such time as an application note describing techniques of calculating such low Q matching systems is developed, proceed carefully, step by step, in developing these matching systems by empirical methods.

Balanced versus Unbalanced

The method of driving transducers is a choice made by the designer of the echo sounder. Unbalanced systems are simpler and easier to make electrical measurements on. An unbalanced configuration requires a higher matching capacitance across the transducer element. Balanced systems often require a third winding on the output transformer to feed an unbalanced signal to the receiver. Balanced lines usually pick up less noise than unbalanced, assuming that the shielding in each case has identical leakage.

Airmar normally uses shielded, twisted pair cable for connection to the piezoceramic element. The transducer may be wired either balanced or unbalanced, as required. The lead designated as transducer "low" is connected to the piezo element surface closest to the water; the transducer "hot" lead is connected to the piezo element surface further from the water.■

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MEASUREMENT OF ECHOSOUNDER POWER OUTPUT AS A FUNCTION OF TRANSDUCER IMPEDANCE

To determine the optimum transducer impedance value, it is useful to know the power output of an echosounder as a function of impedance. The ability of the echosounder to handle a range of impedances is best approached by modeling the transducer as a parallel equivalent circuit comprised of a resistor and capacitor.

The data is obtained by using ordinary 5% carbon resistors and an oscilloscope. The steps are as follows:

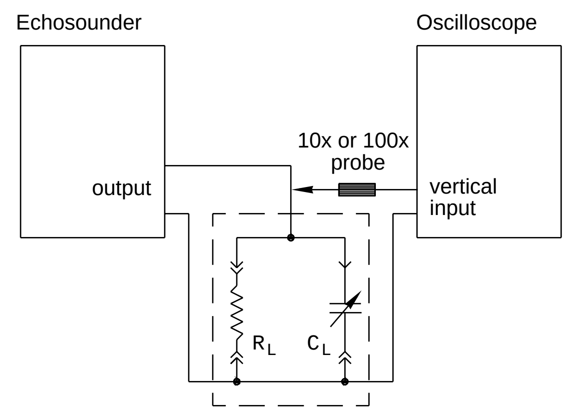
1. Connect equipment as shown in Figure 1.
2. With nominal R_L connected, vary C_L for a maximum voltage transmit pulse on the oscilloscope.
3. Connect various values of resistors at R_L. Record volts peak to peak as read from the oscilloscope. (Select a range of values of R_L so as to find maximum power and several data points on either side.)
4. Calculate RMS power during the transmit pulse.
5. Plot on a graph the Output Power (RMS watts) vs. Parallel Load Resistance (ohms).
6. Set R_L to the value yielding maximum output power. Vary the capacitance, C_L, and record volts peak-to-peak.
7. Calculate RMS power out during the transmit pulse and plot Output Power (RMS watts) vs. Parallel capacitance (pf).

Figures 2 and 3 show the power output curves for a typical echosounder.

With these graphs, the optimum values of parallel load resistance and capacitance are determined and the sensitivity of the echosounder to changes in load may be determined easily.

The transducer data sheets provided by Airmar list the equivalent parallel resistance R_p and capacitance C_p for each model at best transmit frequency. Upon request, we also can provide a table showing R_p and C_p as a function of frequency.■

Figure 1



Equivalent Parallel Circuit of Transducer

Figure 2

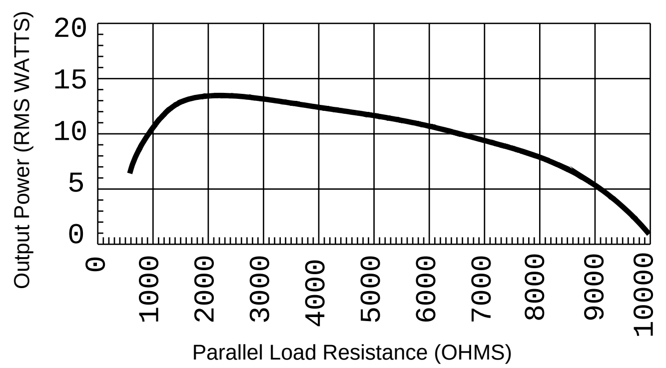
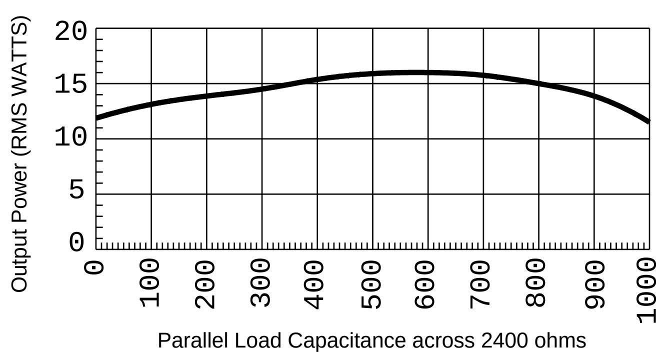


Figure 3



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Bench Testing of Marine Transducers

Without a large tank and sophisticated test equipment, it is difficult, if not impossible, to make measurements that yield absolute sensitivities of marine transducers. However, it is not too difficult to make a comparison between a “known good” transducer and a suspected/questionable unit. Note that this is a comparative test and is valid only for transducers having the same element size and sensitivity.

The equipment requirements are; a test tank, frequency source, pulse generator, a transmit/receive (T-R) switch and an oscilloscope.

Test tank:

A plastic cylindrical tank is recommended, the larger the better. As an absolute minimum, use a 55 gallon steel drum. The drum should have a very flat bottom. This can be done in either of two ways. In the steel drum, about 1” of epoxy will provide a satisfactorily flat bottom. Alternatively, in either the steel or plastic drum, a metal plate can be cut and placed in the bottom of the drum. A 1/8” plate of stainless steel is ideal; aluminum or steel is less so because of corrosion. In addition, the walls of the drum should be lined with a sound absorbing material to reduce reflections. The material we have used is single skin, closed cell neoprene foam fastened with contact cement.

Frequency Source:

A sine wave generator with a range of 50 to 220 kHz and supplying 10 Volts peak-to-peak from a source impedance of 600 ohms or less is adequate. It is desirable to have a frequency counter to provide an accurate frequency readout.

Pulser:

This unit is connected to the frequency source and forms the transmit pulses. If a commercial model is not available, then a pulser may be constructed. A schematic for a fairly simple unit is shown in Figure 1.

Oscilloscope:

Almost any scope will be satisfactory. A dual channel, 15 or 20MHz bandwidth with external trigger input, is satisfactory. Among similar oscilloscopes a unit which has higher accelerating potential on the cathode ray tube will give a brighter, more visible presentation.

Figure 1. gives the schematic of the T-R switch and indicates the connections to the other components of the test set-up.

Test Procedure

1. The transducer should be connected to the T-R switch grounding the wire attached to the ceramic surface closest to the water. (Usually the black wire in shielded twisted pair cable or the braid in coax cables).
2. The transmit pulse voltage should be set to a reference level, say 10 Volts peak-to-peak.
3. Wet the transducer face, place in the tank, and aim at the tank bottom. Adjust the position and direction of the transducer to maximize the echo amplitude. Adjust the frequency for the best echo considering both amplitude and echo pulse shape. Readjust the aim to obtain maximum echo.
4. Recheck transmit pulse amplitude to ensure that changes in transducer impedance have not changed transmit pulse amplitude.
5. The amplitude of the echo is now measured on the oscilloscope display and recorded.

Using this method, comparison of echo amplitude can be made between two similar transducers.

The frequency at peak echo is neither the frequency of maximum transmit source level nor the frequency of maximum receive sensitivity, but is the best composite transmit/receive frequency and corresponds to the Figure of Merit curve presented for each ceramic in the Technical Data Catalog.

When judging what is “good” vs. not acceptable, the following procedure meets good engineering standards.

1. Select a sample of each type/model of transducer which is to be routinely tested.
2. Record echo strength and carefully note all parameters of the test equipment. Repeat these tests over a period of time to establish a firm benchmark for that transducer.
3. As transducers are compared to the standards, keep a record of the results noting particularly the echo strength of any units that give a better echo than the standard.
4. An acceptable transducer would be one which produces 1/2 or more echo voltage of that measured for your ‘standard’ transducer.

Note:

This is based on -3dB transmit and -3dB receive sensitivity difference. Transducer sensitivity can vary considerably in a normal production run. You may measure a voltage variation between the very best transducer and a passable unit of 3 to 1. Bad transducers are usually those having a voltage of 33% or less (usually much less) than that measured for a known “good” unit. In other words, bad transducers are usually very bad. Be careful with regard to transducer ceramic size. A small diameter ceramic will produce only 10% to 25% of the voltage of a large diameter (2”) ceramic. Make sure you are comparing similar diameters and frequencies.■

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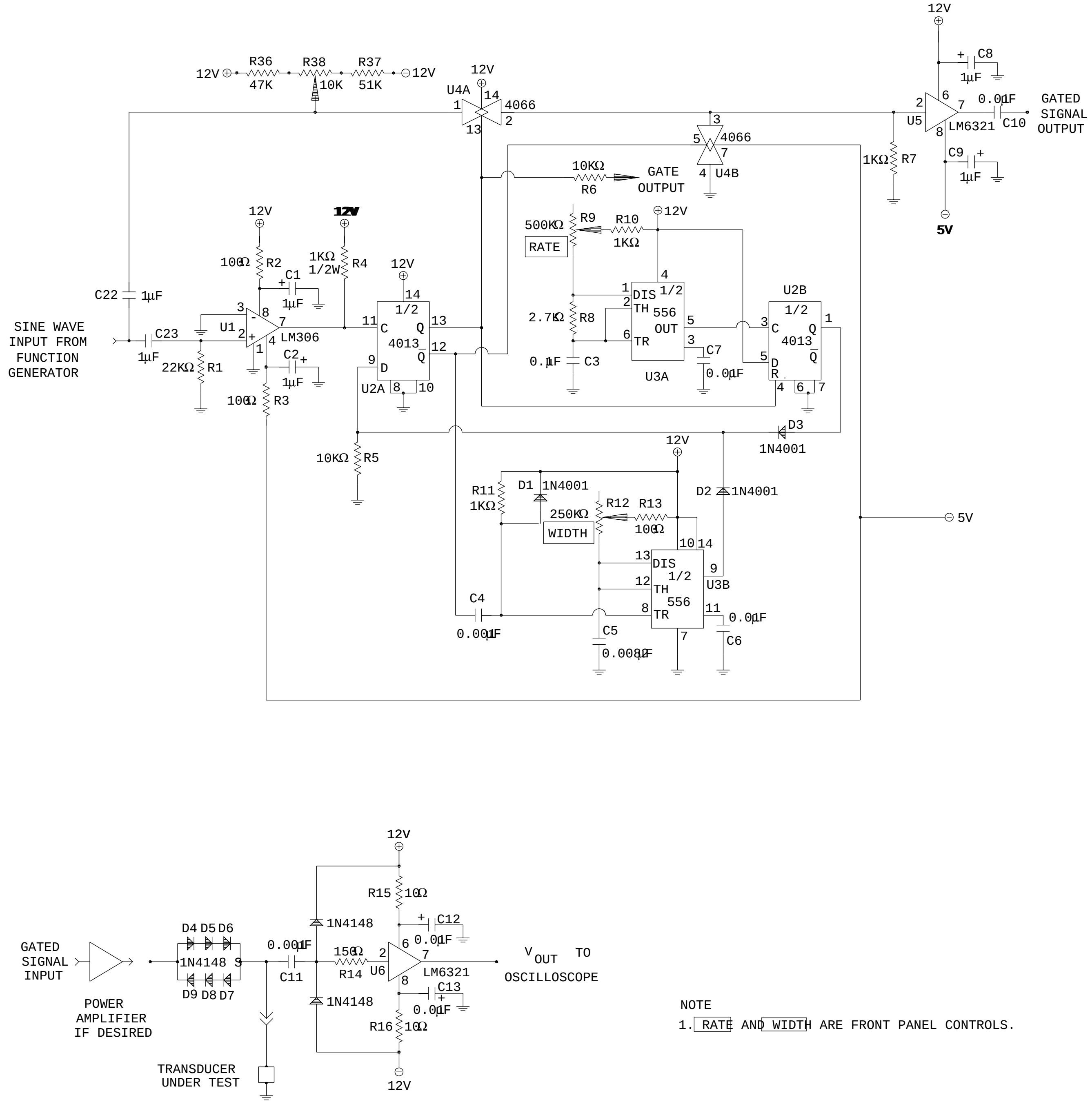
Figure 1



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CIRCUIT INTERFACES TO HALL-EFFECT SPEED SENSORS

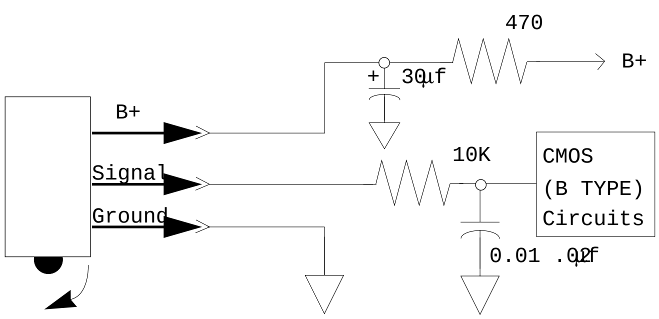
Interfacing to CMOS Logic

When interfacing a Hall-effect sensor to a CMOS input, two filters are recommended, one in the line supplying power to the transducer, the other in the signal line from the Hall-effect circuit.

The supply line filter is recommended mostly as a matter of good engineering practice, being comprised of a series resistor of 470 to 1000 ohms and a capacitor of 0.1 µf to 33 µf. This prevents noise pickup in the speed sensor cable from entering the electronic circuitry of the knotmeter as well as protecting the circuitry from short circuits in the external wiring.

The signal line filter helps prevent noise picked up on the cable from being counted as a pulse from the transducer. A series resistor of 10K ohms and a 0.01 µf or 0.02 µf capacitor should be adequate.

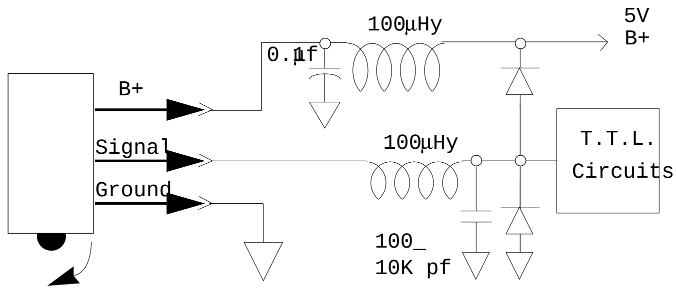
Further, it is recommended that the first electronic circuit encountered by the signal be arranged as a buffer or squaring circuit so that any rounding of the input signal caused by the cable, input filter, etc., is removed and further signal processing circuits are driven by a full CMOS signal.



Interfacing to TTL Logic Systems

When interfacing a Hall-effect sensor to a TTL input, the power filter should be an L-C type to prevent dropping the supply voltage below the 5 volt TTL level. Current limiting in case of a short circuit in the external wiring will have to be accomplished by the 5 volt regulator.

The input filter should, for the same reasons, be an L-C type. In addition, diodes should be used between the signal input and ground and signal input and the 5 volt bus so that any noise pulses cannot drive the signal line above 5 volts or below ground.



Two-Wire Systems

For retrofitting to certain systems, a two-wire system is available which operates through a coaxial cable. Typically, the Hall device operates at 5 volts and the output pulse amplitude is from 5.6 to 12VDC.

"Bullet Proof" Models

If the ultimate in impulse protection is a requirement, Airmar can provide designs which use proven types of circuit protection. Note that these protection circuits will not fit into the S21 and S63 "Snap-In" assemblies.

Calibration

The need for instrument calibration is attributed to the variations in the speed of water past the speed sensor caused by the flow characteristics of the hull design.

Consideration should also be given to whether the knotmeter is to be calibrated at the factory in statute miles per hour, or nautical miles per hour. Statute miles are in common use on inland charts in the United States; nautical miles are prevalent on ocean charts worldwide. A statute mile is 5,280 feet, a nautical mile is approximately 6,076 feet (note that there is also an "Admiralty" mile of 6,070 feet).

The traditional methods of calibrating knotmeters by traversing a known distance in both directions, recording the elapsed time, calculating speed in each direction and averaging should be used with Airmar speed sensors. While Airmar speed sensors have good linearity, maximum accuracy will be obtained if the calibration run is performed at the most used vessel cruising speed.

Instruments with greatest customer acceptance are those with adjustable speed calibration accessed via a display menu. Some models have an adjustment located on the back panel or via an access hole in the back panel. This allows the end user to calibrate the instrument and minimizes complaints concerning accuracy.

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Typically, the calibration range on most instruments is wide enough to accommodate the changeover from nautical to statute miles, and vice versa.

Pulse Rates

The nominal rates listed in Airmar literature are for the standard paddlewheel magnetization. Electronic dividers can be built into most models of the speed sensors to provide lower pulse rates to assist in matching the requirements of existing equipment. Divide-by-2, divide-by-4 and divide-by-100 circuits have been most popular, but others are available. By using a divide-by-100 circuit it is possible to provide approximately 200 pulses per nautical mile for use with most types of ARPA and satellite navigation systems. ■

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