Applying Ultrasonic Technology

Designers of ultrasonic systems have their choice of frequency, housing design, and mounting options when utilizing Airmar Airducer® Ultrasonic Sensors. Balancing the trade-offs between sensor performance, acoustic beam characteristics, and incorporated electronics is a critical step in the system design process. The transducer’s performance can be affected by the propagating media, the environmental conditions, and the electronics themselves. Several parameters need to be considered when selecting a transducer appropriate to the application. The purpose of this overview is to outline key factors to be considered.

Maximum Sensing Range

Several factors have an effect upon the maximum sensing range of a transducer. Ranges listed for Airmar Airducer Ultrasonic Sensors are derived from measurements in tone-burst pulse-echo mode and are listed under “Specifications.” When designing an ultrasonic system, several factors should be considered beyond the transducer itself. These factors include atmospheric conditions, drive and receive electronics, and signal processing. Some of these factors are discussed below.

Temperature And Humidity

Changes in temperature cause a change in sound speed of air as well as the materials of any ultrasonic transducer. Airmar transducers are optimized and specified for operation at 22°C. Operation at significantly higher or lower temperatures results in “detuning” of the acoustic matching layer of the transducer and shifting of the resonant frequency resulting in degraded performance. Resonant frequency shifts approximately -0.8% per 10°C (0.8% per -10°C). The reduced sensitivity is tolerable for most applications, but for applications with a wide temperature range, correction may be necessary.

The characteristics of air are dramatically changed by environmental conditions. Shown in Figure 1, signal attenuation is a function of temperature, humidity, frequency, and air pressure. The speed of sound is mainly a function of temperature, shown in Figure 2. Humidity plays a minor role in sound speed, accounting for less than 0.6% change in speed for the temperature range shown. Airmar offers optional internal thermistors for speed of sound compensation. External temperature sensors can be used for a more accurate calibration over a longer range.

Air Currents and Atmospheric Influences

Maximum measurement ranges are affected by air turbulence, which may deflect or deteriorate sound waves and reduce echo signal. Air currents tend to carry sound downwind; large currents can deflect sound enough to miss the intended target. Large sudden temperature differentials will reflect sound.

Light snow or rain in the sound path will attenuate the sound waves thereby reducing range. Lower frequency transducers emit a longer wavelength and the degrading effect of snow and rain is not as significant as it is for high frequencies.

Airducer Ultrasonic Sensors are not damaged by wetting or by brief immersion in water. Liquid on the transducer’s active surface temporarily degrades performance by detuning the matching layer. When the sensor is operating, water on the transducer face is typically vaporized. Standing water on the face of a sensor will impair its ability to function correctly.

Interference (Electrical and Acoustical)

Airducer Ultrasonic Sensors are susceptible to RFI and EMI. AR series Airducers include standard internal shielding. Additional shielding may be required in certain environments and is optional on all AR series transducers. Shielded cabling options are also available.

High-pressure air nozzles, such as blow off guns, create large amounts of ultrasonic noise. This noise can be very wide band and difficult to filter out. Installations near air nozzles should be avoided.

Transducers mounted to vibrating equipment can receive mechanically coupled interference. If the transducer will be subject to vibration, a very compliant mounting material should be considered to minimize vibration transmission to the transducer.
Target Strength
Hard, smooth, and flat targets mounted orthogonally to the transmitted beam return the strongest signals and hence will be detectable at longer ranges. Examples of these mediums are liquid, glass, or metal. If the beam is not orthogonal, it will be reflected off at the angle of incidence and not be received by the transducer. For example, the signal for a transducer with a 10° beam angle will be degraded by 3 dB if the target is misaligned by 2.5°.

If a surface is rough and irregular, the signal returned is varied in amplitude due to the scattering of sound. This type of target has the disadvantage that the return signal is smaller, but has the advantage that the target's alignment is less critical. Further, different materials have widely different abilities to reflect sound. For example, surfaces such as fabric and foam have the lowest reflectivity resulting in low amplitude echoes thereby significantly reducing the effective range of the transducer.

Beam Angle
A transducer transmits energy in a beam pattern. Most of the energy is concentrated in the main lobe which defines the beam width. Energy outside the main lobe is concentrated in sidelobes. Sidelobes can disguise the true location of targets by generating phantom echoes. No transducer is ever completely free of sidelobes but at Airmar, we strive to design transducers with low sidelobes. Most Airducer Ultrasonic Sensors are designed with side lobe levels at least 17 dB below the main lobe.

Beam width is specified at the –3 dB level of the beam pattern at the full angle. The beam angle of each particular model is noted in the specifications in our catalog. Wide beam angles reduce the sensing range of the transducer and provide less target discrimination when compared to narrow beam models. Wide beams spread acoustic energy over a greater volume and hence less acoustic energy is reflected from potential targets than from a narrower, more concentrated beam. When compared to wide beams, narrow beam angles tend to have greater variations in echo amplitude with irregular surfaces such as a wavy fluid target.

Environmental Conditions
AT and AR models can be used in most environments where the sensor will not be in contact with (or in a condensing environment of) corrosive materials. Most chemical vapors do not damage AT or AR series sensors (except ketones). ATK and ARK series sensors are designed for installations in which the sensor may come in contact with a corrosive chemical or with damaging vapors. Custom design models are available for hazardous environment applications.

Minimum Sensing Range
The distance from the active surface of a transducer to the minimum sensing range is often referred to as the Blanking Zone. Within this zone no echo signals can be received. Ideally, this distance would be zero.

The blanking zone is caused by a phenomenon called ringing. Ringing is the continued vibration of the piezoelectric transducer element beyond the electrical excitation pulse. Due to the nature of piezoelectric ceramics and the constraints of transducer design, there will always be some amount of ring time. This time is necessary to dissipate mechanical and electrical energy after excitation ceases.

The extent to which a transducer rings depends on its design. The amount of ring will also vary slightly from transducer to transducer of the same design due to manufacturing tolerances.

The type of electrical pulse used to drive the sensor can have a profound effect on the amount of ring. Airmar's characterizations of ring time are based on a tone burst drive (i.e., typically ten cycles at best operating frequency). A transducer has many modes of vibration, some are strongly coupled to air and some are not. When designing a system, the objective is to drive the transducer at a frequency strongly coupled to air and avoid exciting extraneous resonances. Hence, the use of a tone burst (narrow bandwidth) is beneficial. In contrast, the use of a wide-band transmit scheme can excite undesirable vibration.
modes. For example, “impulse” drive electronics in which a high-voltage, short duration burst of energy is applied to the transducer excites virtually all vibration modes. Modes of vibration other than the desired resonance often dissipate their energy more slowly. When these undesirable frequencies are stimulated, ring time increases.

All air transducers have a secondary resonance adjacent in frequency to the desired resonance. This secondary resonance is a direct result of the use of an acoustic matching layer to better couple the piezoelectric ceramic element to air. Please refer to Figure 6. The secondary resonance is more weakly coupled to air and also exhibits greater ringing than the desired resonance.

Mounting

Since the transducer is an electromechanical device, some vibrational energy is transmitted to the transducer housing. A rigid mount of the transducer can accentuate these vibrations and cause an increase in ring time. A compliant mount typically has the least effect on sensor performance. Transducers should not be forced into a press fit mounting location. If a rigid mount is required on an AT sensor, glue the sensor into a slip fit hole, preferably touching only the front or rear edges of the sensor. Use a soft encapsulant if a sensor is to be mounted in a pocket.

AR sensors should be mounted by the supplied threads on the cap. Mounting the transducer on the outside diameter of the housing could cause an increase in ring time. If additional isolation is necessary, the use of an isolation bushing (as shown) is recommended.
Notes On The Design Of Matching Systems for Piezo Elements

These notes describe a simplified approach to match a piezo 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 ranging instrument, 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 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 value of these components also vary with frequency (See Transducer Impedance).

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.

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).
Find the frequencies at which the response of the tuned circuit is down 3dB from peak response.

\[
Q = \frac{F_h + F_l}{F_h - F_l}
\]

\[
F_l = \text{lower } -3 \text{ dB frequency}
\]

\[
F_h = \text{higher } -3 \text{ dB frequency}
\]

\[
R_p = Q \times C
\]

The Rp of the coil should now be considered to be in parallel with Rp of the transducer.

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

Also, the division of the available output power must be considered. If the two Rp'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 Rp of the coil be as high as possible compared to the Rp of the transducer.

The advantages of this method of matching are:
- Minimum components —minimum cost
- Highest impedance in the connecting cable, hence the lowest I2R losses
- If the cable must be extended, a simple removal of fixed capacity 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 I2R losses, resulting in a net loss of power delivered to the load in the usual case.

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 = 3400pf).

\[
R_p = R_s + \frac{X_p}{R_s} = 151 + \frac{239}{151} = 529.3 \text{ ohms}
\]

\[
X_p = \frac{R_s \times X_s}{X_s} = \frac{151(529.3)}{239} = 334.4 \text{ ohms}
\]

\[
(C_p) = 2483 \text{ pf}
\]

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:

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

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

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 capacity must then be 9204 – 2483 = 6721 pF.

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

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

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

$$T_{pr} = \frac{T_{sec}}{N_p} = \frac{55}{12.1} = 4.55$$

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 the piezo device

Of course the voltage across the load will probably be measured with an oscilloscope and read as peak to peak voltage. Therefore, 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 $Z = \sqrt{R_p^2 + X_L^2}$

2. $I_L = \frac{E}{Z}$  
   $E$ is RMS voltage across the load as previously shown

3. $P = I^2 R_p$

4. The above equations are combined into a single equation

$$P = \frac{R_p E^2}{R_p + X_L^2}$$

**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 capacity 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 just the capacity 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 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.