Choosing an Ultrasonic Sensor for Proximity or Distance Measurement

Part 1: Acoustic Considerations

The first step toward identifying the right proximity sensor for your application is to understand the fundamental ultrasonic properties of the transmission medium and the way they influence the measurement and system operation.

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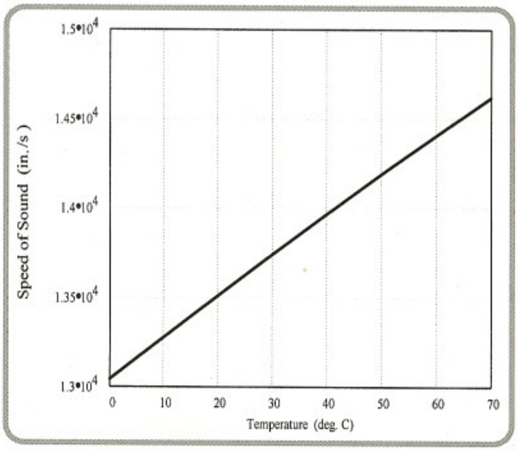

Figure 1. *The speed of sound is plotted as a function of the temperature. At room temperature, sound travels at ~13,500 ips.*

Ultrasonic sensors are commonly used for a wide variety of noncontact presence, proximity, or distance measuring applications. These devices typically transmit a short burst of ultrasonic sound toward a target, which reflects the sound back to the sensor. The system then measures the time for the echo to return to the sensor and computes the distance to the target using the speed of sound in the medium [1,2,3].

The wide variety of sensors currently on the market differ from one another in their mounting configurations, environmental sealing, and electronic features. Acoustically, they operate at different frequencies and have different radiation patterns. It is usually not difficult to select a sensor that best meets the environmental and mechanical requirements for a particular application, or to evaluate the electronic features available with different models. Still, many users may not be aware of the acoustic subtleties that can have major effects on ultrasonic sensor operation and the measurements being made with them.

The overall intent of this article is to help the user select an ultrasonic sensor with the best acoustical properties, such as frequency and beam pattern, for a particular application, and how to obtain an optimum measurement from the sensor. The first step in this process is to gain a better understanding of how variations in the acoustical parameters of both the environment and the target affect the operation of the sensor. Specifically, the following variables will be discussed:

- Variation in the speed of sound as a function of both temperature and the composition of the transmission medium, usually air, and how these variations affect sensor measurement accuracy and resolution
- Variation in the wavelength of sound as a function of both sound speed and frequency, and how this affects the resolution, accuracy, minimum target size, and the minimum and maximum target distances of an ultrasonic sensor
- Variation in the attenuation of sound as a function of both frequency and humidity, and how this affects the maximum target distance for an ultrasonic sensor in air
- Variation of the amplitude of background noise as a function of frequency, and how this affects the maximum target distance and minimum target size for an ultrasonic sensor
- Variation in the sound radiation pattern (beam angle) of both the ultrasonic transducer and the complete sensor system, and how this affects the maximum target distance and helps eliminate extraneous targets
- Variation in the amplitude of the return echo as a function of the target distance, geometry, surface, and size, and how this affects the maximum target distance attainable with an ultrasonic sensor

Fundamental Ultrasonic Properties

Ultrasonic sound is a vibration at a frequency above the range of human hearing, usually >20 kHz. The microphones and loudspeakers used to receive and transmit the ultrasonic sound are called transducers. Most ultrasonic sensors use a single transducer to both transmit the sound pulse and receive the reflected echo, typically operating at frequencies between 40 kHz and 250 kHz. A variety of different types of transducers are used in these systems [4]. The following sections provide an overview of how the sound pulse is affected by some of the fundamental ultrasonic properties of the medium in which the sound travels.

Speed of Sound in Air As a Function of Temperature

In an echo ranging system, the elapsed time between the emission of the ultrasonic pulse and its return to the receiver is measured. The range distance to the target is then computed using the speed of sound in the transmission medium, which is usually air. The accuracy of the target distance measurement is directly proportional to the accuracy of the speed of sound used in the calculation. The actual speed of sound is a function of both the composition and temperature of the medium through which the sound travels (see Figure 1). The speed of sound in air varies as a function of temperature by the relationship [5]:

$$c(T) = 13{,}044\sqrt{1 + \frac{T}{273}} \quad (1)$$

where:

$c(T)$= speed of sound in air as a function of temperature in inches per second

T = temperature of the air in °C

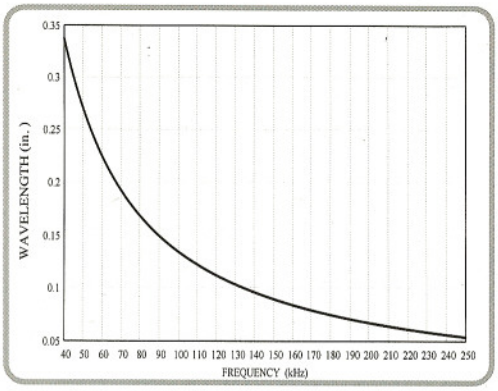

Figure 2. *The wavelength of sound in air at room temperature is plotted as a function of frequency.*

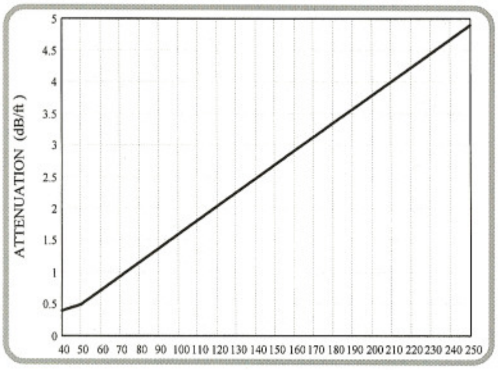

Figure 3. *The maximum attenuation of sound in air at room temperature can be plotted as a function of frequency over all humidities for frequencies between 40 kHz and 250 kHz.*

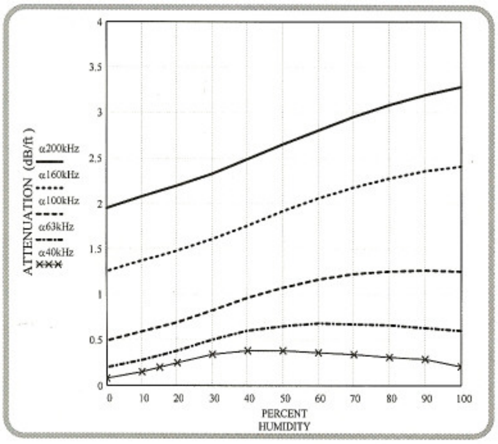

Figure 4. *This family of curves shows the variations in the attenuation of sound in air at room temperature as a function of humidity for frequencies between 40 kHz and 200 kHz.*

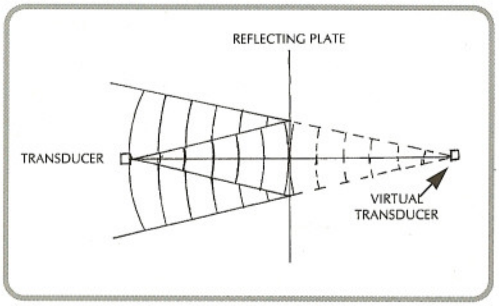

Figure 5. *A sound beam reflected from a flat surface is equivalent to the sound as generated from a virtual transducer at an equal range behind the reflecting plate.*

The speed of sound in different gaseous media is a function of the bulk modulus of the gas, and is affected by both the chemical composition and temperature. Table 1 gives the speed of sound for various gases at 0°C [6].

Wavelength of Sound As a Function of Sound Speed and Frequency

The wavelength of sound changes as a function of both the speed of sound and the frequency, as shown by the expression:

$$\lambda = c/f \qquad (2)$$

where:

λ = wavelength
c = speed of sound
f = frequency

Figure 2 is a plot of the wavelength of sound as a function of frequency at room temperature in air.

Attenuation of Sound As a Function of Frequency and Humidity

As the sound travels, the amplitude of the sound pressure is reduced due to friction losses in the transmission medium. Knowing the value of this absorption loss, or attenuation, is crucial in determining the maximum range of a sensor. The attenuation of sound in air increases with the frequency, and at any given frequency the attenuation varies as a function of humidity. The value of humidity that produces the maximum attenuation is not the same for all frequencies [7]. Above 125 kHz, for example, the maximum attenuation occurs at 100% RH; at 40 kHz, maximum attenuation occurs at 50% RH.

Since an ultrasonic sensor usually is required to operate at all possible humidities, target range calculations should use the largest value of attenuation. A good estimate for the maximum attenuation in air at room temperature over all humidities for frequencies up to 50 kHz is given by:

$$\alpha(f) = 0.01\,f \qquad (3a)$$

where:

$\alpha(f)$ = maximum attenuation in dB/ft
f = frequency of sound in kHz

Between 50 kHz and 300 kHz, the maximum attenuation over all humidities is:

$$\alpha(f) = 0.022\,f - 0.6 \qquad (3b)$$

Figure 3 and Figure 4 illustrate the attenuation of sound as a function of frequency and humidity.

Background Noise

The level of background ultrasonic noise diminishes as the frequency increases. The reason is that less noise at the higher frequencies is produced in the environment, and the noise that is produced is greatly attenuated as it travels through the air.

Effects of Frequency, Distance, and the Transmission Medium on the Magnitude of Sound Pressure

In an ultrasonic sensor, the transducer produces a short pulse of sound. The magnitude of the sound pressure generated will vary from one type of sensor to another. In acoustics, sound pressures are typically expressed in decibels because of their large dynamic ranges. Sound pressure is usually measured in micropascals (μPa) at a reference distance, R_0, from the sensor, usually 12 in. (30 cm). The sound pressure level (SPL) at R_0 is then converted to dB referenced to (//) 1μPa as follows:

$$\mathrm{SPL}(R_0) = 20\log(p) \qquad (4)$$

where:

$\mathrm{SPL}(R_0)$= sound pressure level at distance R_0 in dB//1μPa
p= sound pressure at distance R_0 in μPa

As the sound travels through the medium, the magnitude of the sound pressure is reduced due to both absorp-

TABLE 1

Speed of Sound for Various Gases

Gas	Speed, in./s at 10°C
Air	13,044
Ammonia	16,332
Argon	11,886
Carbon Dioxide	10,152 (low frequency) 10,572 (high frequency)
Carbon Disulfide	7,272
Carbon Monoxide	13,272
Chlorine	8,088
Ethylene	12,360
Helium	38,184
Hydrogen	49,980
Illuminating Gas	19,308
Methane	17,004
Neon	17,124
Nitric Oxide	12,792
Nitrogen	13,152
Nitrous Oxide	10,308
Oxygen	12,492
Steam (100°C)	15,876

tion (attenuation) and spreading loss caused by the expanding surface of the radiating beam as the sound pulse travels from the transducer. The SPL at a distance R from the transducer is given by:

$$\mathrm{SPL}(R) = \mathrm{SPL}(R_0) - 20 \log (R/R_0) - \alpha (f) R \qquad (5)$$

where:

$\mathrm{SPL}(R)$ = sound pressure level at distance R in dB//1μPa

$\mathrm{SPL}(R_0)$ = sound pressure level at distance R_0 in dB//1μPa

$\alpha(f)$ = attenuation coefficient in dB/unit distance at frequency f

Relative Echo Levels From a Flat Surface for Different Ultrasonic Frequencies

If the sound pulse is reflected from a large flat surface, then the entire beam is reflected (see Figure 5). This total beam reflection is equivalent to a virtual source at twice the distance. Therefore, the spreading loss for the sound reflected from a large flat surface is equal to 20 log (2R), and the absorption loss is equal to $2\alpha R$. For this to hold, it is important that the reflecting surface be both larger than the entire sound beam to ensure total reflection, and perpendicular to the sound beam.

Equation (5) can be used to compute the relative effect of varying the sound frequency on echoes produced from a flat reflector at different distances from the sensor. In Figure 6, it is assumed that each sensor produced the same SPL at a range of 1 ft. Therefore, the variations in EL are only a function of the varying attenuations due to the different frequencies of sound. The maximum attenuation for all humidities was used for the value of α for each frequency.

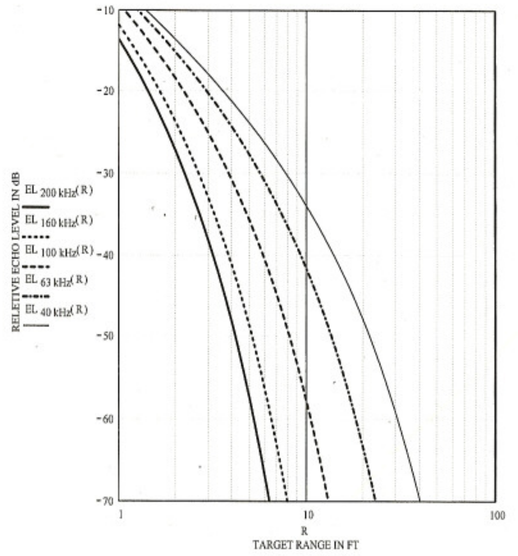

Figure 6. *The relative echo levels from a flat reflecting target at varying distances are plotted against range for different frequencies.*

Summary

Part 1 of this article has provided an overview of the some of the fundamental acoustical parameters that affect the operation of an ultrasonic sensor. Part 2 will address the use of these acoustical data to optimize the selection of an ultrasonic sensor for a particular measurement. ■

Part 2: Optimizing Sensor Selection

Part 1 of this article, which appeared in the February issue of *Sensors,* was an overview of some of the fundamental acoustical parameters that affect the performance of an ultrasonic sensor. In Part 2 we address radiation patterns and echo variation from targets other than flat surfaces, and the way these parameters can be used to help optimize the selection and operation of ultrasonic sensors for different applications. The figures, equations, and references are numbered sequentially from Part 1.

Radiation Patterns of Transducers and Ultrasonic Sensors

Transducer Beam Patterns. The acoustic radiation pattern, or beam pattern, is the relative sensitivity of a transducer as a function of spatial angle. This pattern is determined by factors such as the frequency of operation and the size, shape, and acoustic phase characteristics of the vibrating surface. The beam patterns of transducers are reciprocal, which means that the beam will be the same whether the transducer is used as a transmitter or as a receiver. It is important to note that the system beam pattern of an ultrasonic sensor is not the same as the beam pattern of its transducer, as will be explained later.

Transducers can be designed to radiate sound in many different types of pattern, from omnidirectional to very narrow beams. For a transducer with a circular radiating surface vibrating in phase, as is most commonly used in ultrasonic sensor applications, the narrowness of the beam pattern is a function of the ratio of the diameter of the radiating surface to the wavelength of sound at the operating frequency, D/λ [8]. The larger the diameter of the transducer as compared to a wavelength of sound, the narrower the sound beam. For example, if the diameter is twice the wavelength, the total beam angle will be ~30°, but if the diameter or frequency is increased so that the ratio becomes 10, the total beam angle will be reduced to ~6°.

For most ultrasonic sensor applications, it is desirable to have a relatively narrow beam pattern to avoid unwanted reflections. The diameter of the transducers is therefore usually large compared to a wavelength.

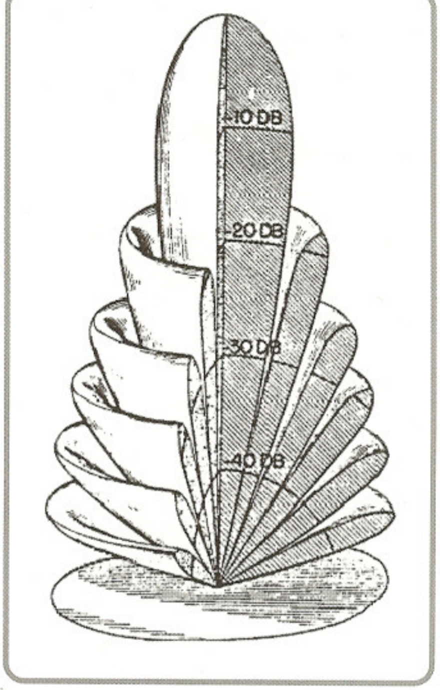

Figure 7. *A transducer with a circular radiating surface whose diameter is large in comparison to a wavelength produces a narrow, conical beam pattern with multiple secondary lobes.*

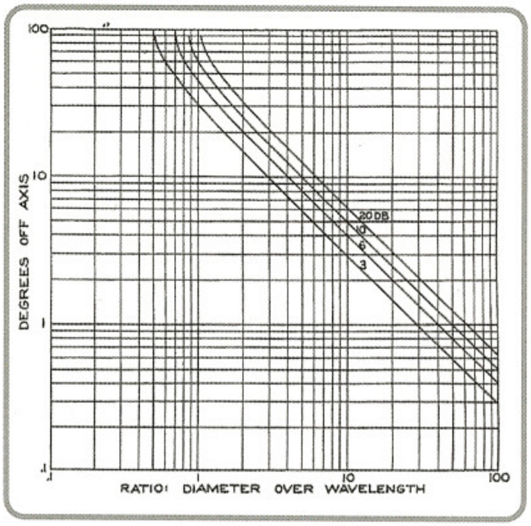

Figure 8. *Chart No. 67 from* Acoustic Design Charts *shows the directional radiation characteristic of circular pistons mounted in an infinite baffle as a function of D/λ.*

Figure 7 is a 3D representation of the beam pattern produced by a transducer with a diameter that is large compared to a wavelength. As can be seen, the beam is narrow and conical and has a number of secondary lobes separated by nulls. Each of these secondary lobes is sequentially lower in amplitude than the previous one. (Even though the beam is called conical, it does not have straight sides and a flat top as the word might imply.) The beam angle is usually defined as the measurement of the total angle where the sound pressure level of the main beam has been reduced by 3 dB on both sides of the on-axis peak. However, the transducer still has sensitivity at greater angles, both in the main beam and in the secondary lobes [9]. Figure 8 is a family of curves reproduced from *Acoustic Design Charts* for transducers with circular radiating pistons mounted in an infinite baffle. The curves show the degrees off axis for the beam angle to be reduced from the on-axis amplitude by 3 dB, 6 dB, 10 dB, and 20 dB as a function of D/λ [10]. Note that the angles on these curves are half of the total beam angle.

When describing transducer beam patterns, 2D plots are most commonly used. These show the relative sensitivity of the transducer vs. angle θ in a single plane cut through the 3D beam pattern. For a symmetrical conical pattern such as that shown in Figure 7, a simple 2D plot will describe the entire 3D pattern. Figure 9 shows a 2D polar plot from –90° to +90° of the beam of a circular radiating piston mounted in an infinite baffle with a diameter equal to two wavelengths of sound. As can be seen, the pattern is smooth as a function of angle, and the –3 dB points are at +15° and –15° off axis, producing a total beam angle of 30°. However, the total angle of the major radiating lobe between the first two nulls is ~70°, and the side lobes peak at approximately +55° and –55°. When using an ultrasonic sensor, it is important to be aware that nearby unwanted targets that are beyond the beam angle can inadvertently be detected because the transducers are still sensitive at angles greater than the beam angle. Some transducers used in sensing applications are specially designed to minimize or eliminate the secondary lobes to avoid detecting unwanted targets.

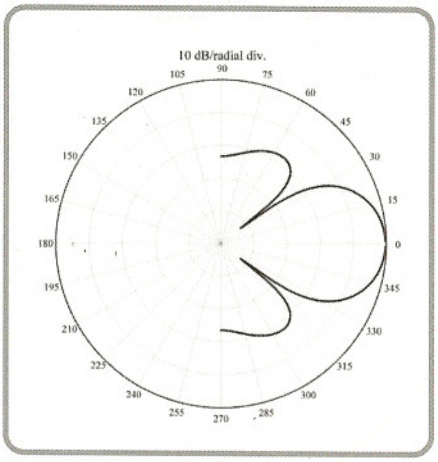

Figure 9. *This 2D polar plot represents the beam pattern of a transducer with a circular disc radiator mounted in an infinite baffle, where D/λ = 2.*

System Beam Patterns. In an echo ranging system, the transmitting transducer sends out sound at reduced amplitudes at different angles, as described by the beam pattern of the transmitting transducer. The receiving transducer has less sensitivity to echoes received at angles off axis, as described by the beam pattern of the receiving transducer. The system beam pattern is the sum in decibels of the transmitter's and the receiver's beam patterns.

The solid curve of Figure 10 is a plot of the beam pattern of Figure 9 on rectilinear coordinates for angles from 0° to 30° off axis. This beam pattern is the same for the transducer whether it is transmitting or receiving. The dashed curve shows the system beam pattern for a sensor using this same transducer to both transmit and receive. As can be seen, the system beam pattern for the ultrasonic sensor is narrower than the pattern of the transducer alone.

A target located on the acoustic axis (θ = 0°) will produce an echo that is not reduced in amplitude due to the transmitting beam pattern, and the voltage the echo will cause the receiving transducer to produce will not be diminished due to its beam pattern. If a target is 15° off axis, however, the sound pulse from the transmitter will be reduced by 3 dB due to the beam pattern, which will cause the magnitude of the resulting echo to be reduced by 3 dB. When the echo reaches the receiver, the resulting voltage produced will be reduced by another 3 dB from the voltage that the same magnitude of echo would have produced if it had been received on the acoustic axis of the transducer. Therefore, the 3 dB reduction in echo level plus the 3 dB reduction in receive sensitivity result in a total reduction of 6 dB in the voltage produced by a target 15° off axis as compared to the same target located directly on the acoustic axis.

The magnitude of the voltage in the system produced by a target echo as a function of angle will therefore be reduced by twice the number of decibels as indicated by the beam pattern of the transducer

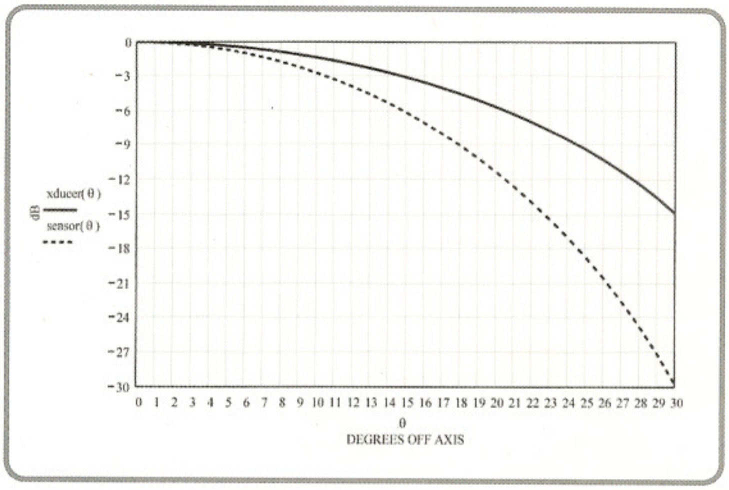

Figure 10. *The transducer beam pattern of Figure 9 is plotted on rectilinear coordinates as the solid curve, and the system beam pattern for a sensor using the transducer to both transmit and receive is plotted as the dashed curve.*

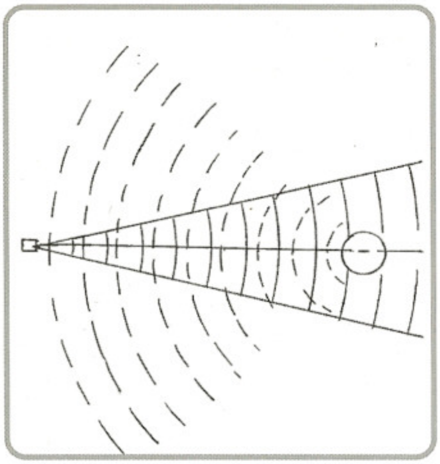

Figure 11. *A small sphere used as a target partially reflects the beam and reradiates an echo.*

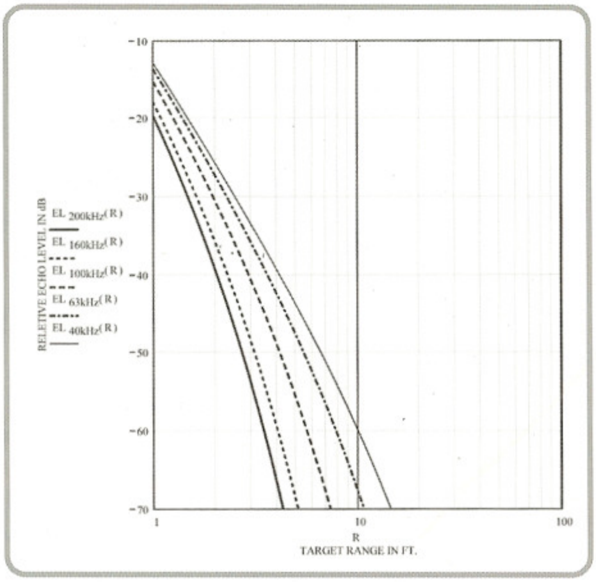

Figure 12. *The relative echo levels from a 6-in.-radius sphere at varying distances are plotted against range for different frequencies.*

alone, if the same transducer is used to both transmit and receive. Since this difference can obviously have a significant effect on ultrasonic sensor operation, system beam patterns, not transducer beam patterns, should be used when evaluating a sensor application.

Targets' Effect on Echoes

The relative echo levels from large flat surfaces where the reflector is larger than the entire incident sound beam was discussed in Part 1 of this article. This type of reflection is typical for an ultrasonic sensor used in applications such as liquid level control. For other types or sizes of targets, though, the echo levels are affected differently. Figure 11 illustrates the behavior of a small sphere as a target. As can be seen, the sphere intercepts only a portion of the sound beam and then reradiates the sound pulse. During this process, the sound pressure is reduced by spreading loss, 20 log (R/R_0), as it travels from the sensor to the target. When the sound reradiates from the target, the sound pressure is again reduced by spreading loss as it travels back toward the sensor. In the case of a reradiating target, the total spreading loss will therefore be 40 log (R/R_0), which is the sum of the spreading loss for the sound traveling to the target plus the spreading loss of the reradiated sound returning to the sensor.

The measure of the reflectivity of a target is called Target Strength (TS) [11]. It is defined as 10 × the logarithm to the base 10 of the intensity of the sound returned by a target at a reference distance from its "acoustic center," divided by the incident intensity of the transmitted sound pulse. The TSs of simple geometric shapes can be theoretically computed; Table 2 contains the expressions of TS for a few types of target forms. When using this table, all dimensional units must be the same, including the reference range, R_0, the range distance to the target, R, and all dimensions of the targets.

Such idealized computations of TS should be used only as approximations of real targets, since actual targets are usually not simple reflectors but rather are complex with multiple surfaces of reflection. The sound reflecting from each of these multiple surfaces will produce echoes of different amplitudes that will sum together when they return to the sensor. Since the sound pulse is reflected at different times by the various reflecting surfaces as it propagates across the target, the individual echoes will be different in both amplitude and phase. The total received echo will therefore be a complex summation of these multiple pressure waves of different amplitudes and phases.

Any movement of the target, or any variation in the relative velocity of sound due to air turbulence along the various acoustic path lengths from the different reflecting surfaces of the target, will cause a dramatic change in the TS. The result can be large variations in the echo level produced by a target from one pulse to another during ultrasonic sensor operation. The extent of the variations in TS for a specific target in a given environment can be experimentally determined by measuring the changes in the magnitudes of echoes from the target for a series of pulses at all expected variations of target position and over all expected environmental conditions.

For reradiating targets, the echo level as a function of target range is:

$$EL_f(R) = SPL(R_0) - 40\log(R/R_0) - 2\alpha_f R + TS \qquad (6)$$

where:

$EL_f(R)$ = echo level at frequency f

R = range distance to target

$SPL(R_0)$ = sound pressure level of transmitter at reference distance R_0

α_f = attenuation coefficient of sound at frequency f

TS = target strength

Equation (6) can be used to compute the relative effect that varying the sound frequency will have on echoes produced from reradiating targets at different distances

TABLE 2

Theoretical Target Strengths for Simple Forms

R_0=reference range; $k=2\pi/\lambda$; R=range to target
(all dimensions, including R and R_0, must be in same units)

Form	t (TS = 10 log t)	Definitions	Direction of Incidence	Conditions
Sphere	$a^2/4$	a = radius of sphere	any	ka>1 R>a
Cylinder, Infinitely Long	aR/2	a = radius of cylinder	normal to axis of cylinder	ka>1 R>a
Cylinder, Finite Length	$aL^2/2\lambda$	L = length a = radius	normal to axis of cylinder	ka>1 $R>L^2/\lambda$
Smooth Convex Object	$S/16\pi$	S = total surface area of object	average over all directions	All dimensions >λ
Ellipsoid	$(bc/2a)^2$	a,b,c = semimajor axes of ellipsoid	normal to major axis	ka,kb,kc>1 R>a,b,c

from the sensor. For example, it is assumed that the same sound pressure level is produced by the sensor at all frequencies, and that the same target is placed in line with the acoustic axis of the transducer. For illustration, the target is assumed to be a sphere with a radius equal to 6 in. ($^1/_2$ ft). From Table 2, this will result in a TS equal to –12 dB. Figure 12 shows plots of the relative $EL_f(R)$ from a reflecting sphere with a 6 in. radius at different distances from sensors operating at different frequencies.

Comparing Figure 12 to Figure 6 in Part 1 shows that there is a considerable reduction in level when an echo from a large flat reflector is compared to an echo from a 6-in.-radius sphere at the same range and frequency. This shows that the maximum range of a sensor can be greatly reduced by different targets.

TABLE 3 **Ranges for the Relative Echo Levels from Flat and Spherical Targets to Reach – 60 dB//1µPa for Different Frequencies**

(From Figures 6 and 12)

	Target Range for EL – 60dB//1µPa		
Frequency	Target Large Flat Reflector	Target 6 in. Radius Sphere	Decrease in Target Range for Spherical Target
200 kHz	5.2 ft	3.5 ft	1.7 ft (33%)
160 kHz	6.5 ft	4.0 ft	2.5 ft (38%)
100 kHz	10.5 ft	5.6 ft	4.9 ft (47%)
63 kHz	18.2 ft	7.8 ft	10.4 ft (57%)
40 kHz	30.2 ft	10.0 ft	20.2 ft (67%)

Selecting and Using Ultrasonic Sensors

When selecting an ultrasonic sensor for a particular application, it is important to consider how the echo will be affected by the acoustical fundamentals. There is a wide variety of sensors available that operate at different frequencies and have different beam angles. In addition, systems can have different electronics options such as temperature sensing and signal averaging. The proper choice of sensor parameters will help optimize the system performance.

Variations in Frequency of Sensors. In general, the lower the frequency of the sensor, the longer the range of detection, while a higher frequency sensor will have greater measurement resolution and less susceptibility to background noise. The background noise produced under most conditions is lower in amplitude at higher frequencies, and will attenuate more at higher frequencies as it travels toward the sensor. Because most sensors produce relatively narrow beam angles, the physical size of the transducer in the sensors will typically become larger as the frequency decreases.

Absolute Accuracy, Relative Accuracy, and Resolution. The concepts of absolute accuracy, relative accuracy, and resolution are different in ultrasonic sensors. *Absolute accuracy* is the uncertainty error in the exact distance measurement from the face of the ultrasonic sensor to the target. *Relative accuracy* is the uncertainty error in the change in distance measurement when the target moves relative to the sensor. *Resolution* is the minimum change in distance that can be measured by the sensor when the target moves relative to it. These measurements are affected by factors such as the wavelength of the sound, the Q of the transducer, the reflecting characteristics of the target, the operation of the target detection electronics in the sensor, and the uncertainty in the assumed value of the speed of sound.

Uncertainty in accurately knowing the exact speed of sound over the entire transmission path is usually the major contribution to inaccuracy in the absolute measurement of the range to the target. Figure 1 in Part 1 shows the speed of sound in air as a function of temperature based on Equation (1). During operation, the ultrasonic sensor measures the time interval from when the sound pulse is transmitted to when the echo is received, Δt, and computes the target range.

In the vicinity of room temperature, a 1°C change in temperature will produce an uncertainty in sound speed of ~23 ips. This causes an uncertainty error in the accuracy of the absolute distance measurement for a 1°C temperature change of:

$$err_{Rin}(R) = 0.0017\,R \qquad (7a)$$
$$err_{Rft}(R) = 0.0204\,R \qquad (7b)$$

where:

$err_{Rin}(R)$ = uncertainty error in target range in inches for a 1°C uncertainty in temperature when target range R is in inches

$err_{Rft}(R)$ = uncertainty error in target range in inches for 1°C uncertainty in temperature when target range R is in feet

Figure 13 plots the uncertainty error in the absolute target range measurement in inches as a function of target range for a 1°C uncertainty in temperature, as computed by Equations (7a) and (7b). The solid curve shows the measurement error if the target range R is in feet; the dashed curve is for target range in inches.

Uncertainties in the average value of the speed of sound along the acoustic path can occur for a variety of reasons. A sensor with an internal temperature probe will obviously have less uncertainty in sound speed approximation than a sensor that does not measure the temperature. In some applications, however, the temperature in the transmission medium between sensor and target can be different from the temperature at the sensor, which therefore will cause an error even if a temperature probe is used.

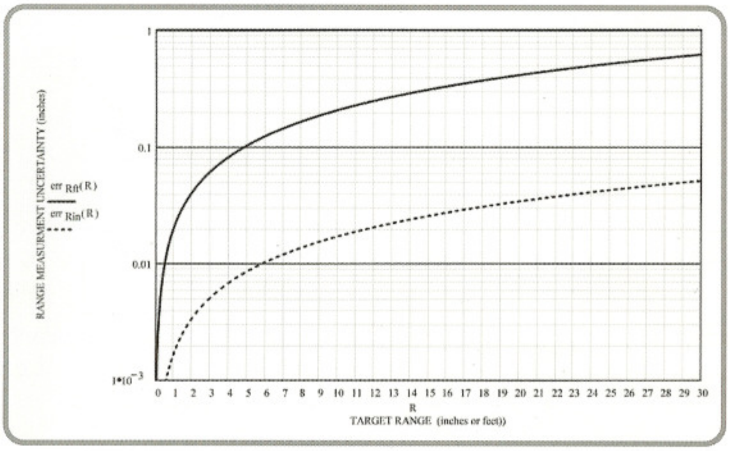

Figure 13. *The uncertainty errors in inches are plotted for different absolute range measurements for a 1°C uncertainty in temperature. The solid curve is used if range R is in feet; the dashed curve is used if R is in inches.*

If there is air turbulence along the path from the sensor to the target, then the average speed of sound will randomly change, causing the target range computed by the sensor to randomly vary from pulse to pulse. Similar variations in the arrival time of a target echo will appear if the target surface is moving, such as when a liquid surface contains waves. For these applications, measurement accuracy will increase if the sensor is capable of averaging a number of measurements before providing a target range output.

The uncertainty in sound speed over the acoustic path has much less effect on the sensor's relative accuracy when a change in target range is being measured. For this situation, equation (7a) becomes:

$$\mathrm{err}_{Rin}(\Delta R) = 0.0017\ \Delta R \qquad (8)$$

where:

$\mathrm{err}_{Rin}(\Delta R)$ = uncertainty error in relative change in target range in inches for a 1°C uncertainty in temperature when target range changes by ΔR inches

If the temperature is unknown by 5°C, and a target at a range of 100 in. moves 0.500 in. toward the sensor, the error in the absolute target range measurement of 100 in. will be 0.85%, or 0.85 in. However, the error in the relative distance measurement of 0.500 in. will be only 0.004 in.

The resolution of a range measurement made with an ultrasonic sensor is influenced by many factors. Since the sensor is measuring the arrival time of an acoustic pulse, the higher the ultrasonic frequency the greater the resolution because both the wavelength and period of the echo signal are smaller at higher frequencies. The accuracy of the time-measuring circuits in the sensor also affects the resolution, as will the averaging capabilities of a sensor if there is turbulence along the sound path. The best way to measure the true resolution of an ultrasonic sensor for a particular application is to place a target at a fixed distance and obtain a stable range measurement. Then slowly move the target forward or backward until the sensor indicates a measurable change in target range. Accurately measure the distance the target moved. This change in distance is the resolution of the sensor. Compare the actual distance the target moved to the change in range measured by the sensor. This is the error in the resolution of the device.

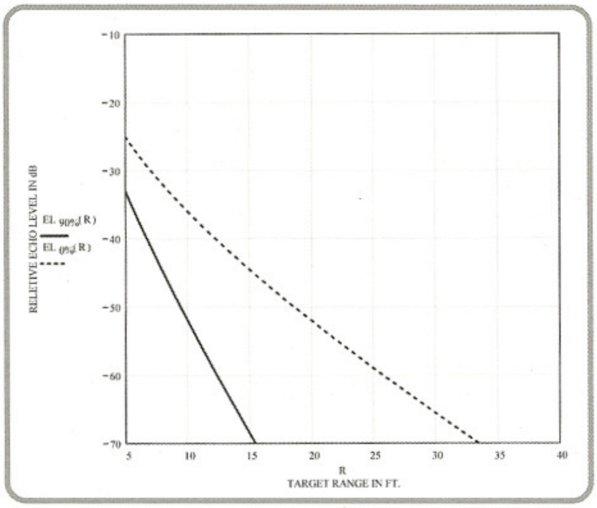

Figure 14. *The relative echo levels of a 100 kHz sound pulse from a flat reflecting target at varying distances are plotted against a range for 0% and 90% RH.*

Target Range Measurement. For each application, it is important to select a sensor that will detect the desired targets when they are located within a specified area in front of the sensor, but ignore all targets outside this area. As previously noted, a lower frequency sensor should be selected for longer ranges of detection and a higher frequency sensor should be used for shorter range, higher resolution measurements. Sensor beam angles should be selected to cover the desired detection geometry, and to reject unwanted targets.

The maximum range at which an ultrasonic sensor can detect a target is affected by attenuation of the sound and the target strength. These effects can be illustrated by using the data in Figure 6 in Part 1 and Figure 12, and setting a minimum echo detection threshold. Table 3 was prepared by arbitrarily choosing for illustration –60 dB//1µPa as the minimum echo level the sensor can detect. It shows that the range at which the echo level reaches –60 dB//1µPa will vary for sensors operating at different frequencies between 40 kHz and 200 kHz for both a large flat target and a 6-in.-radius sphere. These range values are therefore the maximum detection ranges for the sensors and targets used in this illustration.

As can be seen from Table 3, the lower the sound frequency, the longer the detection range. The maximum detection range of a sensor is greatly reduced, however, when the target is spherical rather than a large flat reflector, and the percentage of range reduction is greater for lower frequencies. At 200 kHz, the maximum range between the targets is decreased by 33%, while at 40 kHz the range reduction is 67%.

Humidity can also have a significant effect on the target range. The curves of Figure 6 in Part 1 and Figure 12 use values of attenuation that are greater than the maximum attenuation that would be caused by humidity variations at each frequency. Figure 4 in Part 1 shows that there is a large variation in attenuation at any particular frequency as the humidity varies. For example, at 100 kHz the attenuation varies from 0.5 dB/ft at 0% RH to 1.3 dB/ft at 90% RH. This means that if a target is at a range of 10 ft from the sensor, the echo level will change a total of 16 dB if the humidity changes from 0% to 90%.

Figure 14 shows plots of the relative echo levels from a large flat target that can be obtained with a sensor operating at 100 kHz for humidities of 0% RH and 90% RH. As can be seen, the magnitude of the echoes at each range changes dramatically between the two humidities, so the maximum detectable range of the sensor for a given target will also be greatly affected by humidity. It is therefore possible to successfully install a sensor for a particular application, and at a later date find that it is no longer detecting targets if the humidity changed enough to cause the target echoes to attenuate below the detection threshold of the sensor.

Effective Beam Angle. It is important to consider an ultrasonic sensor's effective beam angle, which is the angle around the acoustic axis where a target will be detected. If the target moves closer to the sensor, or if a target with a greater TS is used, then the effective beam angle will increase. At only one range for a particular target will the effective beam angle be equal to the classical beam angle that is obtained from the polar radiation pattern. Therefore, the classical beam angle can be used only as a first order guide in determining whether targets will be detected or ignored by the sensor.

At the maximum detection range, the amplitude of the target echo is just barely large enough to be detected by the sensor electronics when the target is directly in line with the transducer's acoustic axis. Reducing the echo level by rotating the target slightly off the beam's acoustic axis will lower the amplitude of the echo below the sensor's

Is It µbar or µPa?

Because sound pressures vary by more than 10 orders of magnitude, they are expressed by acoustical engineers as logarithmic ratios, called sound pressure levels (SPLs). The SPL in decibels for a sound pressure, p, is calculated as $20 \log(p/p_{ref})$, where p_{ref} is a standard reference sound pressure. Some confusion can occur because several different reference pressures are in use, which results in a given sound pressure's being expressed with several different possible sound pressure levels.

Most of the early work in acoustical engineering was associated with the development of audio equipment, so it was natural to use the threshold of human hearing for the reference pressure. In the cgs system, that sound pressure is 0.0002 dyne/cm^2 (0.0002 µbar), so sound pressure levels were expressed in terms of dB//0.0002 µbar [SPL = 20 log(p/0.0002)dB//0.0002 µbar, where p is in µbar].

During World War II, there were major advances in the development of sonar for detecting submarines. Since the sounds produced by sonar systems are not heard directly by people, sonar engineers began using 1 µbar as a more logical standard reference pressure. Sound pressure levels therefore began to be expressed in terms of dB//1 µbar, [SPL = 20 log(p/1)dB//1µbar, where p is in µbar].

In the early 1970s, the SI system of units was adopted in acoustical engineering and the µPa, which is equal to 10^{-6} N/m^2, became the reference pressure. Sound pressure levels therefore began to be expressed in terms of dB//1 µPa [SPL = 20 log(p/1)dB//1 µPa, where p is in µPa]. This is now the most often used reference pressure for ultrasonic measurements, but it is not unusual to encounter data using any of these three standard reference pressures. To add to the confusion, sometimes the SPL will be improperly stated in terms of dB only, without indicating the reference pressure used to compute the ratio. It is obviously important to know which reference pressure was used whenever an SPL is expressed, and when comparing sensors, all sound pressure levels should be converted to the same reference pressure. It is quite simple to convert sound pressure levels among the three reference pressures by using Table 4. ☐

TABLE 4 **Sound Pressure Level Conversion**

To Convert SPL in:	To SPL in:	
dB//0.0002 µbar	dB//1 µbar	add 74 dB
dB//0.0002 µbar	dB//1 µPa	subtract 26 dB
dB//1 µPa	dB//0.0002 µPa	add 26 dB
dB//1 µPa	dB//1 µbar	add 100 dB
dB//1 µbar	dB//0.0002 µbar	subtract 74 dB
dB//1 µbar	dB//1 µPa	subtract 100 dB

detection threshold. Under these operating conditions, the effective beam angle of the sensor will therefore be essentially 0°.

As a target moves closer to the sensor, the echo level increases dramatically. For a sensor operating at 100 kHz and using a large flat plate as a target, the echo level can increase more than 60 dB as the target moves from a range of 10 ft to a range of $^1/_2$ ft. This means that at a range of $^1/_2$ ft, for any angle off the acoustic axis where the sensor beam pattern has not reduced more than 60 dB, the flat target will produce an echo larger than that from the target on axis at a range of 10 ft. For a sensor with a transducer radiation pattern as shown in Figures 9 and 10, a large flat target at a $^1/_2$ ft range would be detected almost continuously as the sensor is rotated ±90°. Some sensors have variable gain amplifiers that lower the detection levels for close targets, and therefore reduce the tendency to widen the effective beam angle of the sensor.

Summary

This two-part article has provided a brief overview of some of the fundamentals that influence the operation of ultrasonic sensors. As was shown, the maximum detection range of an ultrasonic sensor is typically longer for lower frequencies, while the resolution and accuracy are typically better at higher frequencies. The strength of the target echo, however, is greatly affected by the geometry and reflectivity of the target, thereby affecting the range and resolution of the distance measuring system.

One of the biggest sources of error in an ultrasonic position measurement is the variability of sound speed in the transmission path between the sensor and the target, largely caused by uncertainty in the average temperature along the path. Maximum measurement accuracy is therefore obtained when temperature compensation is used within the sensor. Note that temperature uncertainty affects absolute accuracy substantially more than it does the relative accuracy of an incremental measurement.

It is not unusual for the amplitude of echo levels to change by large amounts from pulse to pulse due to variations in sound speed in the medium, caused by factors such as air turbulence or target movement. Also, long-term changes in humidity can have a significant effect on the strength of an echo from a target.

It is usually desirable to use a sensor with the narrowest possible radiation pattern that can detect the required targets. For a given frequency, the narrower the radiation pattern of the sensor, the longer the maximum range of the sensor and the less susceptibility to unwanted targets at the sides of the sensor. However, a very narrow radiation pattern from a sensor will require more accurate orientation of the sensor's axis with regard to the acoustic beam's perpendicularity to a flat target. In any event, the user must understand the effective beam angle of the sensor when determining which targets will be detected and which will be ignored. This effective beam angle changes with the distance of the target and the strength of the reflection from the target. ■

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