

Angular Dependence of Target Strength for Simple Geometric Shapes

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Abstract. Understanding the active sonar equation is a fundamental skill for a course in Underwater Acoustics and Sonar such as that taught at the United States Naval Academy. Students must develop an intuitive understanding of each term in both the noise limited and reverberation limited cases. In this tabletop demonstration, the angular dependence of the Target Strength term is explored using commercially available 25 and 40 kHz airborne piezoelectric transducer/receiver pairs. By rotating standard target shapes (e.g. rectangular plates, circular plates, finite cylinders, ellipsoids), reflected intensity is measured as a function of angle of rotation. The measured data is compared with that predicted by standard theoretical models. While the same measurements could be made in a tank using submerged transducers, the airborne transducers offer the advantage of lower cost and simplicity of apparatus. Additionally, unwanted modal interference from sound reflection off tank surfaces is reduced in the airborne measurement. By direct observation, future sonar operators and designers are able to study target strength in order to understand how to position their sensors to optimize their own active sonar performance while positioning their own ships to minimize detection by opposition active sonar.

Keywords: underwater acoustics, active sonar, target strength, scattering, ultrasonic

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INTRODUCTION

Undergraduate acoustics courses risk becoming mathematics seminars without linking the science to the required mathematics. Demonstrations and hands on laboratory experiments are critical to student visualization and conceptual understanding of physical phenomena. This is not a new idea in physics pedagogy. Physics and acoustics have a rich tradition of exceptional demonstrations that so captivate students, many university Physics Departments have held showings of their best demonstrations at times when they can be viewed by the general public. It goes without saying that laboratory experiments are a necessary component of teaching physics.

In the field of underwater acoustics and sonar, a focus of classroom instruction necessarily involves the passive and active sonar equations. The active sonar equation attempts to predict the ability of a system to detect a signal emitted by a sonar and reflected off a target. The noise limited, active sonar equation can be written [1]

$$L_{S/N} = (SL - 2TL + TS) - (NL - DI) \geq DT. \quad (1)$$

This equation states that if a target is to be detected using active sonar, the signal to noise level, $L_{S/N}$ (in dB) received by the sonar system must be greater than some empirically determined detection threshold (DT). When calculating the signal to noise level, the term in parenthesis on the left is called the echo level and is made up of the source level (SL), round trip transmission loss (TL) and target strength (TS). The term in parenthesis on the right is the noise level in the direction of the target and is made up of the isotropic noise level (NL) and the directivity index (DI). Students often believe, and perhaps we encourage through our development of problems, that every term in this equation is a constant. To be fair, some terms like the isotropic noise level (NL) and sonar array directivity index (DI) might be nearly constant for a particular sonar system operating at a particular frequency for a period of time. Others like the transmission loss (TL) are necessarily variable with some parameters, in this case distance

from the sonar system to the target and the active frequency. In the case of the target strength (TS), the term changes with several factors, including the relative aspect angle the target presents to the sonar system.

Target strength is defined to be logarithmically related to the ratio of the sound intensity scattered from a target to a range of 1 m, I_r , and the incident intensity, I_i .

$$TS = 10 \log \left[\frac{I_r}{I_i} \right] = 20 \log \left[\frac{P_r}{P_i} \right]. \quad (2)$$

In this demonstration we will be studying the target strength for a square plate, a circular plate or a right circular cylinder. The ratio of the scattered to incident intensity for each case is the Fourier transform of the scattering aperture and is given in standard texts [2] as equation (3), (4) or (5) respectively.

$$\frac{I_r}{I_i} = I_o \left(\frac{\sin \beta}{\beta} \right)^2 \cos^2 \theta, \quad \beta = \frac{ka \sin \theta}{2}, \quad \text{side length} = a, \quad (3)$$

$$\frac{I_r}{I_i} = I_o \left(\frac{J_1(\beta)}{\beta} \right)^2 \cos^2 \theta, \quad \beta = ka \sin \theta, \quad \text{plate radius} = a \quad (4)$$

$$\frac{I_r}{I_i} = I_o \left(\frac{\sin \beta}{\beta} \right)^2 \cos^2 \theta, \quad \beta = \frac{kL \sin \theta}{2}, \quad \text{cylinder length} = L \quad (5)$$

In each case, k is the wavenumber and the aspect angle θ is referenced to the object's normal.

APPARATUS

To measure the angular dependence of target strength it is necessary to rotate the test object (square plate, circular plate, and cylinder) in the transmitting beam of an airborne ultrasonic piezoelectric transducer (shown below) and measure the backscattered ultrasonic radiation on a receiving airborne ultrasonic transducer in the far field as shown in Figure 1.

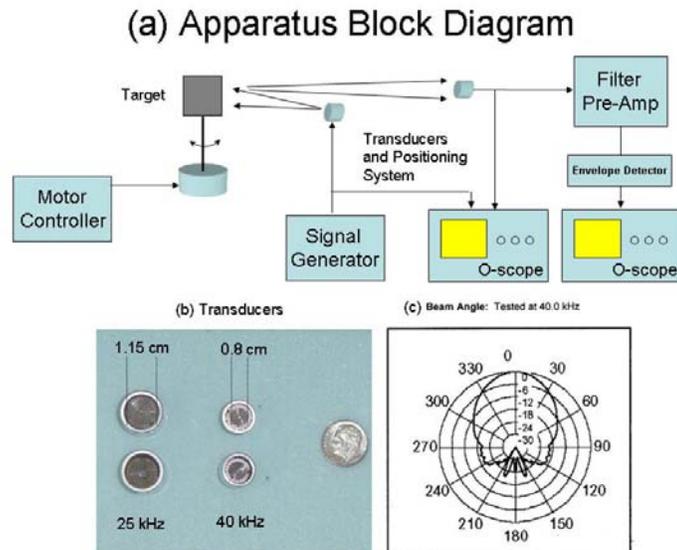


FIGURE 1. (a) Apparatus block diagram showing the signal processing. (b) Relative size of the ultrasonic transducers. (c) Manufacturer supplied angular sensitivity.

While any rotating table can be used, it is necessary to know and be able to control the rotation speed. In this demonstration we use a system manufactured by Velmex, Inc., a supplier of rotational and translational positioning systems. The table was turned with a period of 72 sec. Ultrasonic transducers at 25 and 40 kHz are readily available from many sources and are very inexpensive. The digital oscilloscopes, signal generators (Wavetek model 29), and filter pre-amplifiers (SRS 560) are typical of those found in undergraduate physics laboratories. The filter preamplifier was set to band pass filter receiving transducer output from 10 kHz to 100 kHz with a gain of 20 so as to supply a sufficient input voltage to the envelope detector.

As the target is rotated, it is necessary to determine the maximum amplitude of the scattered ultrasonic wave. To make this measurement, an envelope detector was used to display only the waveform envelope. Some oscilloscopes have an envelope detector function built in. The circuit below in Figure 2 completely filters out the high frequency carrier, leaving only the slowly varying amplitude of the positive envelope.

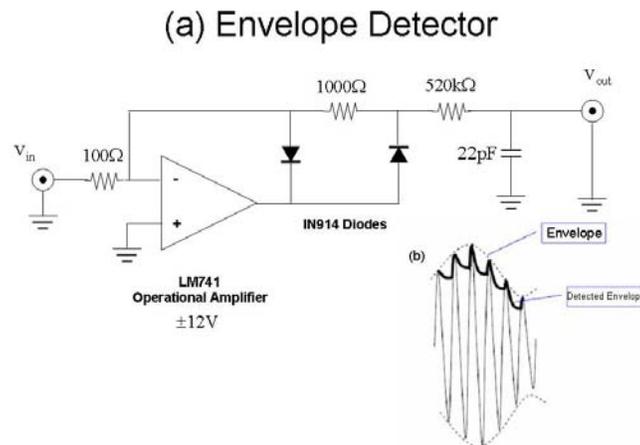


FIGURE 2. (a) Envelope detection circuit used in this demonstration. Note that the signal is amplified by this circuit. (b) This graphic depicts how a low pass filter removes the carrier and the rectifier only passes the positive the envelope.

The voltage envelope is directly proportional to the pressure signal detected by the receiving transducer and is displayed on an oscilloscope as a function of time. A slow sweep speed (e.g. 4 sec/div) allows 40 sec of data to be captured by the oscilloscope. The rotary table must turn through the desired angles in this time. The envelope signal is then transferred from the oscilloscope to a PC where time is converted to angle using the table rotational speed and the envelope signal is scaled and normalized. In the following examples, the data was transferred from a Tektronix TDS 3012 oscilloscope to a laptop computer using a serial to USB cable. Transfer time for 10000 data points is about a minute. Utility software supplied by Tektronix allows data to be easily transferred from the oscilloscope into Microsoft Excel.

Alignment of the transmitting and receiving transducers is important to provide adequate signal to noise ratio. To gain control over transducer alignment, standard optical system jack stands and rotational stages were used.

RESULTS

The square and circular flat plates shown in Figures 3 and 4 were the easiest to align and resulted in data that agreed reasonably well with theoretical predictions out to about 50 degrees from the normal to the plate. Noise is always a problem. Additional filters and amplification would be needed to obtain better results. Data was obtained at both 25 and 40 kHz to study the effect of frequency on the location of nulls and maxima.

The 40 kHz case was simpler since the far field limit was closer to the rotating object and alignment was easier. In the case of the square plate shown in Figure 3, not only are the nulls and maxima of the data occurring at the angles predicted by equation (3), the relative amplitude of the secondary maxima are also as predicted.

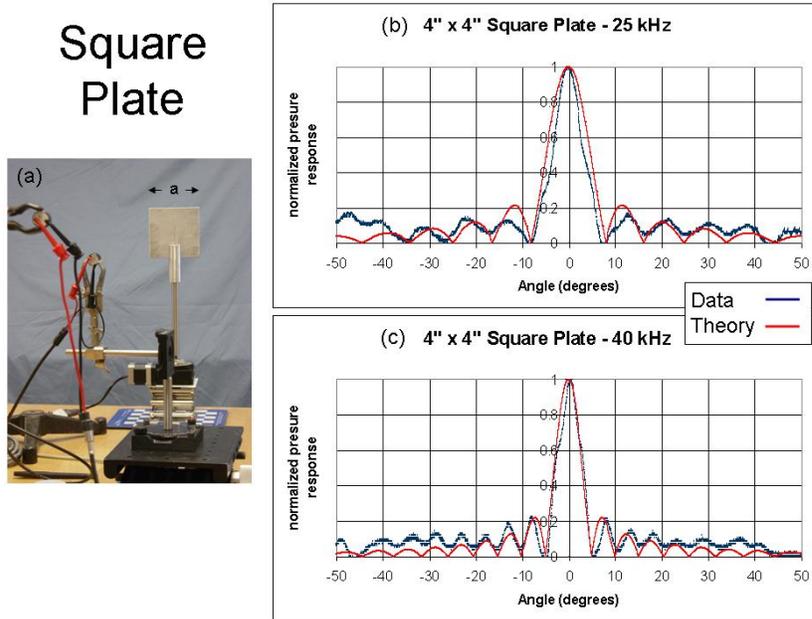


FIGURE 3. (a) Photograph of the apparatus showing the square plate and the transmitting and receiving ultrasonic transducers. (b) Data and predicted results at 25 kHz within 50 deg of the normal. (c) Data and predicted results at 40 kHz within 50 deg of the normal.

The circular plate results shown in Figure 4 demonstrate agreement with the theoretical location of nulls and maxima predicted by equation (4). Relative amplitude of the sidelobes is not consistent with predicted due to noise.

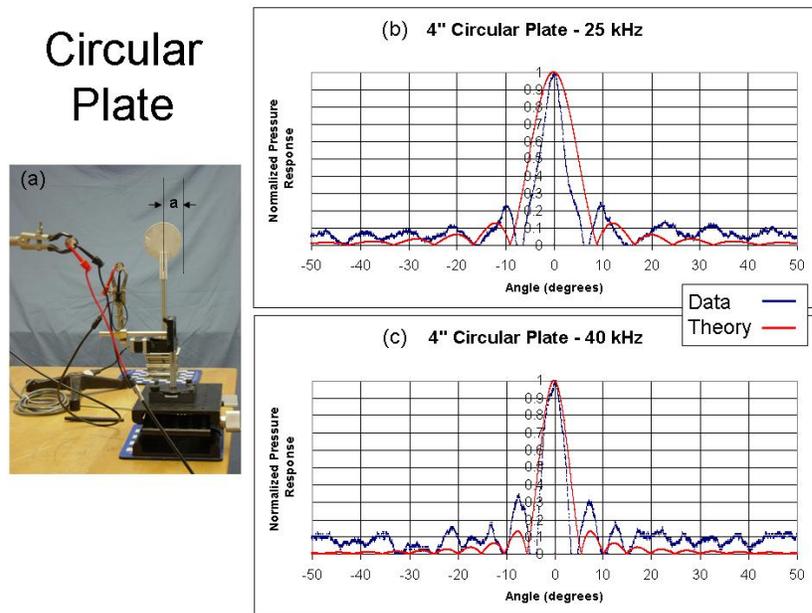


FIGURE 4. (a) Photograph of the apparatus showing the circular plate and the transmitting and receiving ultrasonic transducers. (b) Data and predicted results at 25 kHz within 50 deg of the normal. (c) Data and predicted results at 40 kHz within 50 deg of the normal.

Similar results were obtained for the 10 cm long cylinder when measured within 50 degrees of the normal to the curved side as shown in Figure 5. The backscattered signal is difficult to align with the receiving transducer and

results in a very weak signal relative to the noise, particularly in the 25 kHz case. Still the demonstration clearly shows a central maximum and null angles corresponding to those predicted by equation (5). While the experiment is difficult for undergraduates to perform, scattering from a cylinder is the most practical real world shape to investigate and demonstrates the difficulty of employing active sonar in a noisy environment.

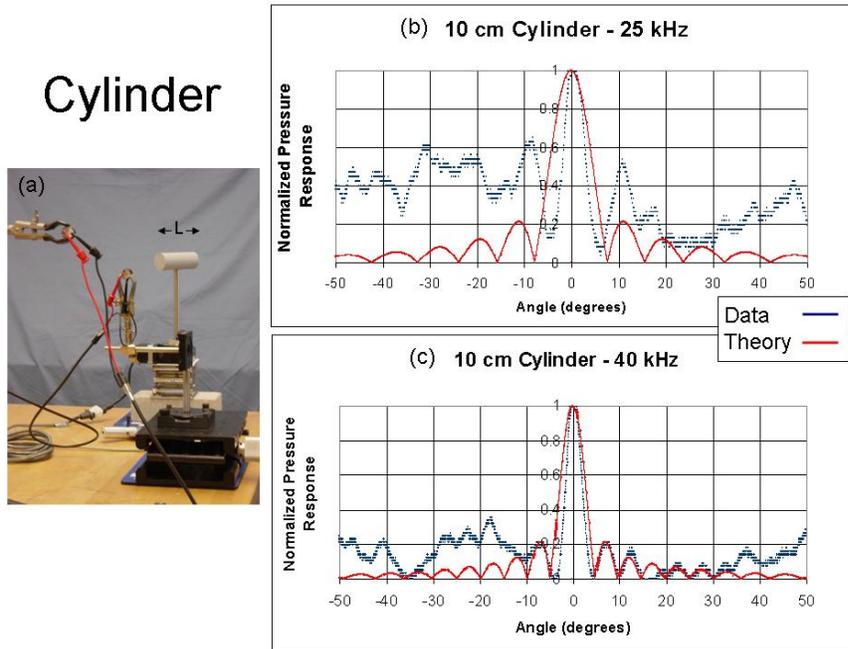


FIGURE 5. (a) Photograph of the apparatus showing the 10 cm long cylinder and the transmitting and receiving ultrasonic transducers. (b) Data and predicted results at 25 kHz within 50 deg of the normal. (c) Data and predicted results at 40 kHz within 50 deg of the normal.

Additionally, scattering data from 360 degrees around the cylinder was obtained at 40 kHz as shown in Figure 6. This data can be explained by considering the cross section of the cylinder as approximating a rectangle when viewed from the side and a circle (radius = 2 cm) when viewed from the end. The scattering data results from a combination of these two features.

Cylinder 360° Pressure Response

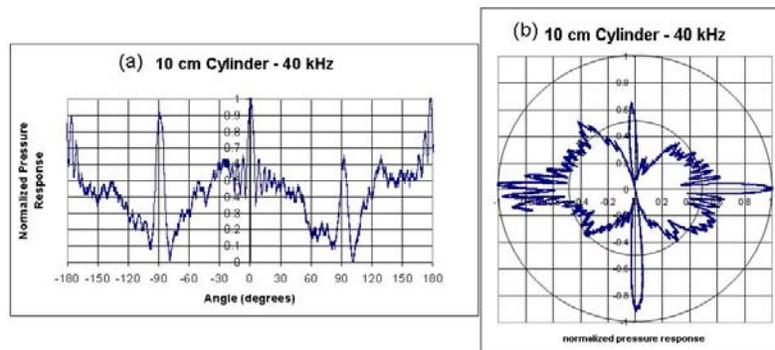


FIGURE 6. Scattering at 40 kHz from a 10 cm long cylinder shown on a (a) Cartesian plot (b) Polar plot.

When a polar plot is constructed, the variation in target strength with aspect angle can be easily visualized. In the case of Figure 6(b), the normal to the cylinder is plotted to the right with the circular end at ± 90 degrees. Notice that on the back side at ± 180 degrees, the envelope signal drifts with noise and there is not perfect amplitude agreement in the overlap. Still there is always repeatable agreement of the angle at which nulls and maxima exist.

Cylinder Target Strength

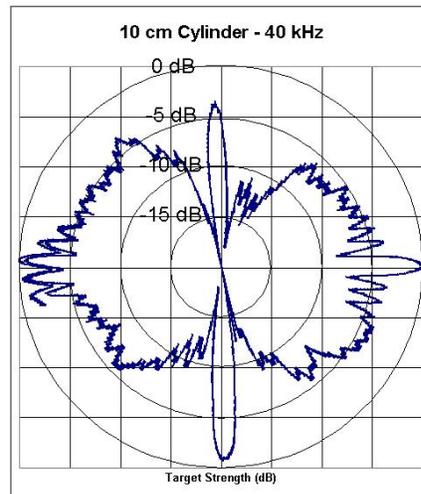


FIGURE 7. Scattering at 40 kHz from a 10 cm long cylinder shown on a logarithmic polar plot.

While it is academically pleasing to match scattering results with the predictions of equations (3), (4), and (5), it is critical to remember that the quantity of interest in underwater acoustics is target strength, defined logarithmically in equation (2). Figure 7 displays the target strength of a 10 cm long cylinder on a polar plot. Most important to educating the future undersea warrior is the unmistakable conclusion that target strength is not constant but varies with aspect angle. Further, positioning a sensor on the beam or directly in front of or behind a cylindrical target increases target strength by as much as 10 dB, thereby improving signal to noise ratio of an active return by the same amount. This could easily be the difference between the ability to detect or miss detecting a hostile target.

ACKNOWLEDGMENTS

Professor Murray Korman designed the envelope detector for a related experiment and provided valuable insight for improving this classroom demonstration.

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