

Ultrasound Measurements and Non-destructive Testing Educational Laboratory

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Abstract

The primary goal of this laboratory is to introduce students to the fundamentals of ultrasound measurements and to demonstrate the basic principles of ultrasound non-destructive testing technique. This laboratory presents the engineering principles of ultrasound measurements to the students by combining hands-on laboratory experience with just-in-time lectures. Specifically, the laboratory work consists of eight 3-hour sessions, where the students learn the engineering and physical principles behind the measurements of sound velocity in water and other materials, attenuation of ultrasound waves at different frequencies, directivity patterns of circular transducers with various resonance frequencies, and dimensions of the inhomogeneities in various materials. The work in the laboratory enhances the fundamentals taught in the classroom sessions. Another goal of this laboratory is to improve the students' data gathering and communication skills. Therefore, a concise written report clearly describing all conclusions and comments is required within seven days after completion of the lab, upon which the students become familiar with basic acoustical instrumentation, have hands-on experience with ultrasonic and electronic equipment, and are able to demonstrate the basic principles of ultrasound imaging. In addition, the students are able to determine the frequency of the imaging pulse, pulse duration, pulse repetition frequency, cross section of the ultrasound beam, the axial distance between the transmitter and receiver/reflector, and the thickness of the material.

Introduction

A new educational laboratory for ultrasound measurements (UM) and nondestructive testing (NDT) has been developed to serve primarily students pursuing a B.S. degree in applied engineering technology. The state of the art facility has also been designed to serve working

individuals interested in improving their skills in UM and/or NDT, as well as those seeking knowledge for professional advancement.

The primary goal of this laboratory is to introduce students to the fundamentals of ultrasound measurements and to demonstrate the basic principles of ultrasound nondestructive testing techniques. The laboratory presents the engineering principles of ultrasound measurements by combining hands-on laboratory experience with just-in-time lectures. Specifically, the laboratory work consists of eight 3-hour sessions (within the framework of Drexel's quarter system), where the students learn the engineering and physical principles behind the measurements of sound velocity in water and other materials, attenuation of ultrasound waves at different frequencies, directivity patterns of circular transducers with various resonance frequencies, and dimensions of inhomogeneities in various materials. In addition, students are able to determine the frequency of the imaging pulse, pulse duration, pulse repetition frequency, cross section of the ultrasound beam, the axial distance between the transmitter and receiver/reflector, and the thickness of the material.

The work in the laboratory enhances the fundamentals taught in the classroom sessions. An important objective of this laboratory is to improve the students' knowledge on data gathering, the identification of sources leading to erroneous measurements, and proficiency in communication skills. To this end, a concise written report clearly describing procedures and results is required within seven days after completion of the lab. Students work individually and in teams on projects drawn from several areas of technological interest.

Upon completion of this laboratory/course students become familiar with basic acoustical instrumentation, have hands-on experience with ultrasonic and electronic equipment, and are able to demonstrate the basic principles of ultrasound imaging.

The rest of the paper describes the specific laboratories, instrumentation, and procedures associated with the measurements of sound velocity in water and other materials, directivity pattern, and attenuation coefficient in Plexiglas.

Measurements of the sound velocity in water

Most applications for underwater acoustics, nondestructive testing of materials, and biomedical ultrasound rely on accurate measurements of the sound velocity in water¹ and other materials. The basic principle of sound velocity determination is to measure the time between transmitted and received ultrasound signals (the time-of-flight). In these experiments, the measurement of the transducer displacement is more convenient and accurate than the measurement of the transmitter/receiver or transducer/reflector distance. Such a technique allows one to eliminate additional artifacts caused by the time delays from the transducers and attached electronics. The schematic diagram of the experimental set-up is shown in Fig.1.

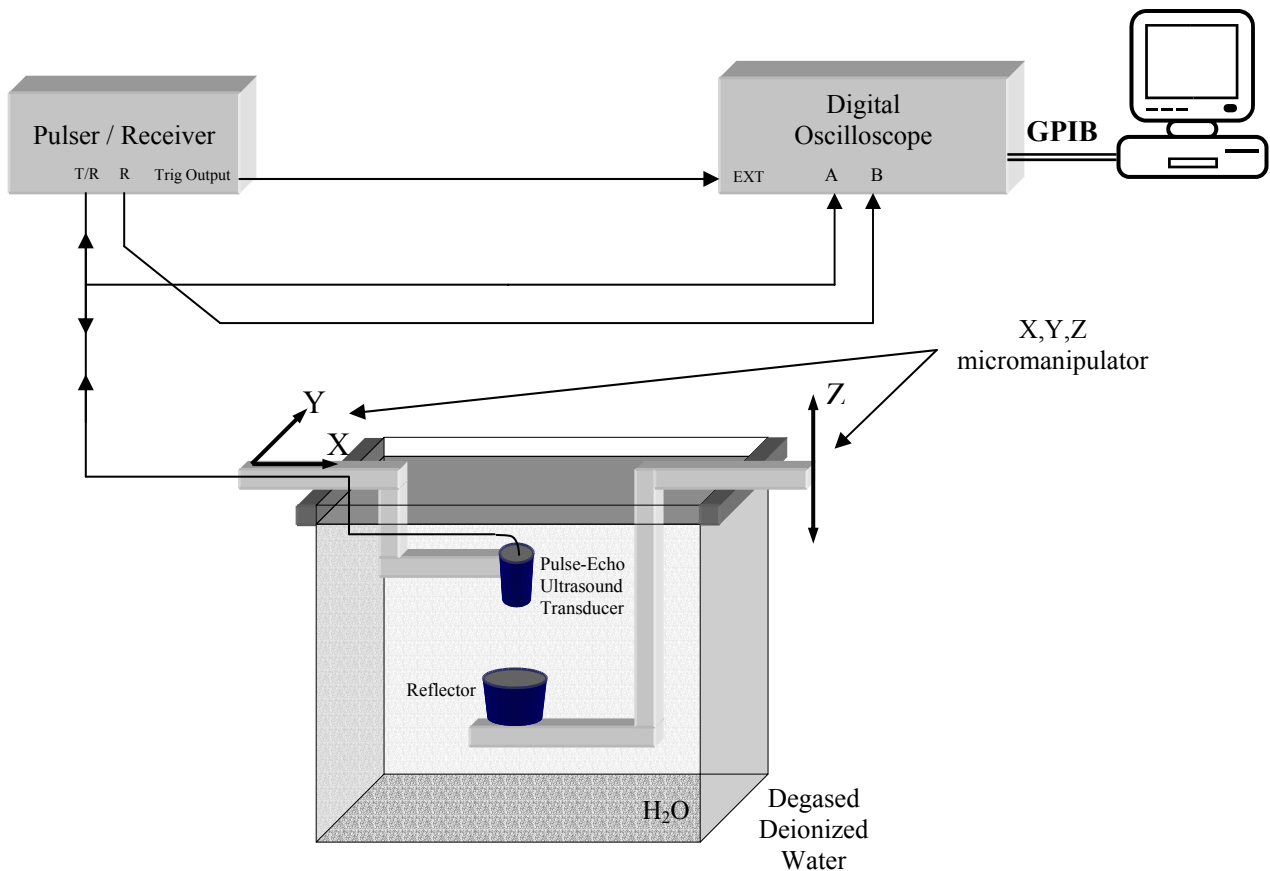


Figure 1. Measurement of the sound velocity in water

During this laboratory, the two sets of measurements are carried out:

1. Using one transducer, which is used as transmitter/receiver, and the reflector.
2. Using two transducers, where one of them is used as a transmitter, and the other one is used as a receiver (In this experiment, the reflector is replaced with the second transducer).

For the experiments, three sets of transducers with resonance frequencies of 2.25 MHz, 3.5 MHz, and 5 MHz are used. The diameters of all transducers are 12.7 mm.

Equipment used:

- DAEDAL XYZ Θ Scanning System (800 mm x 900 mm x 350 mm Travel).
- Pulser/Receiver: Panametrics Pulser/Receiver 5073 PR.
- Oscilloscope: Tektronics TDS220 Digital with the GPIB board.
- Pentium 4 PC.

The placement of the transducers is controlled by the LabView 6 virtual instrument (VI) (Fig.2). The precision of the stepper motors of the Scanning System is 10^{-4} mm per step, which allows the displacement of the transducers from one position to another very accurately. Initially, transducers are installed at 400-mm distance between each other and are perfectly aligned. Then, one of the transducers or the reflector is moved by 50 mm increments to three different positions.

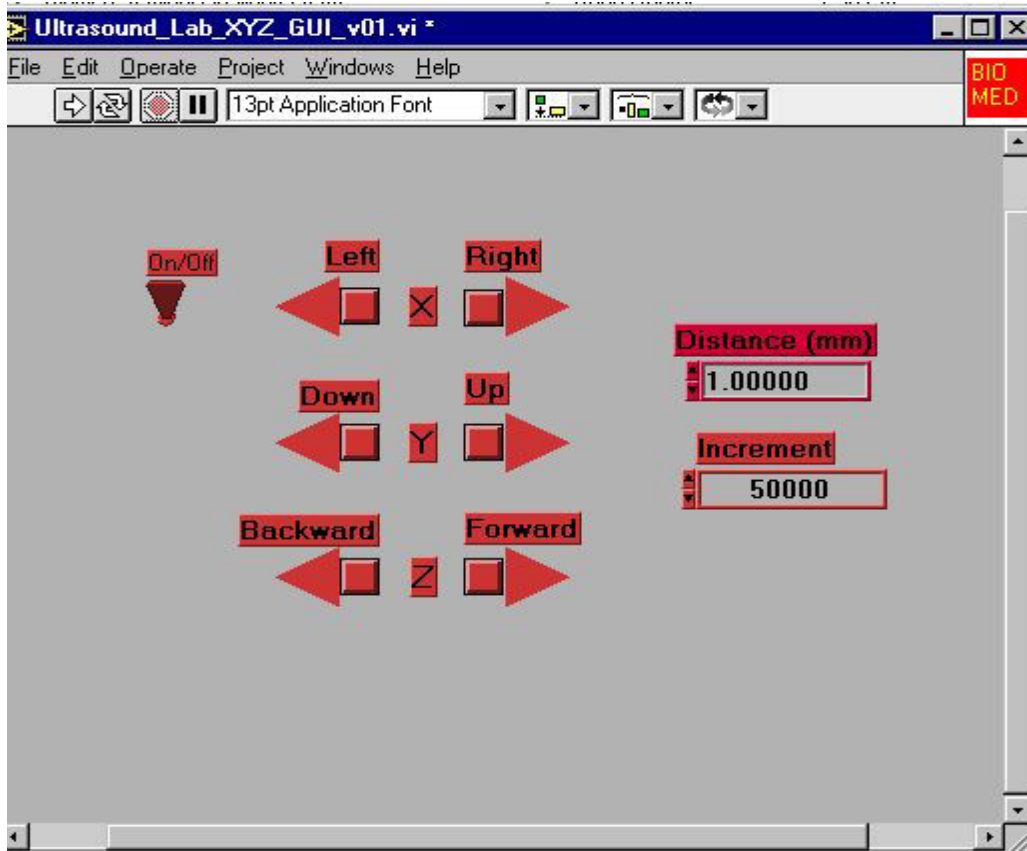


Figure 2. LabView 6 controller

The results obtained for these positions are later averaged. The external triggering of the oscilloscope is activated by the transmitted pulse of the pulser/receiver, which also sends the electrical energy to the piezoelectric transducer. The transducer transmits the ultrasonic wave and receives the echoes. The received ultrasonic signal is then converted to an electrical signal by the pulser/receiver, is amplified, and finally transferred to the oscilloscope. By measuring the time interval between two consecutive pulses on the screen of the oscilloscope and knowing the displacement of one of the transducers, one can estimate the speed of sound in water, as $c = x/\Delta t$, where x is the displacement of the transducer and Δt is the time interval between two consecutive received pulses. If one of the transducers is replaced with the reflector, then the sound speed can be calculated as $c = 2x/\Delta t$, since the ultrasound wave propagates in both directions - from the transducer, which acts as a transmitter, to the reflector and then back to the transducer, which acts as a receiver. Collected data is then transferred to the computer under control of LabView VI and saved as a text file for future processing using Microsoft Excel. The example of the stored and retrieved data of the received ultrasonic signal is presented in Fig. 3.

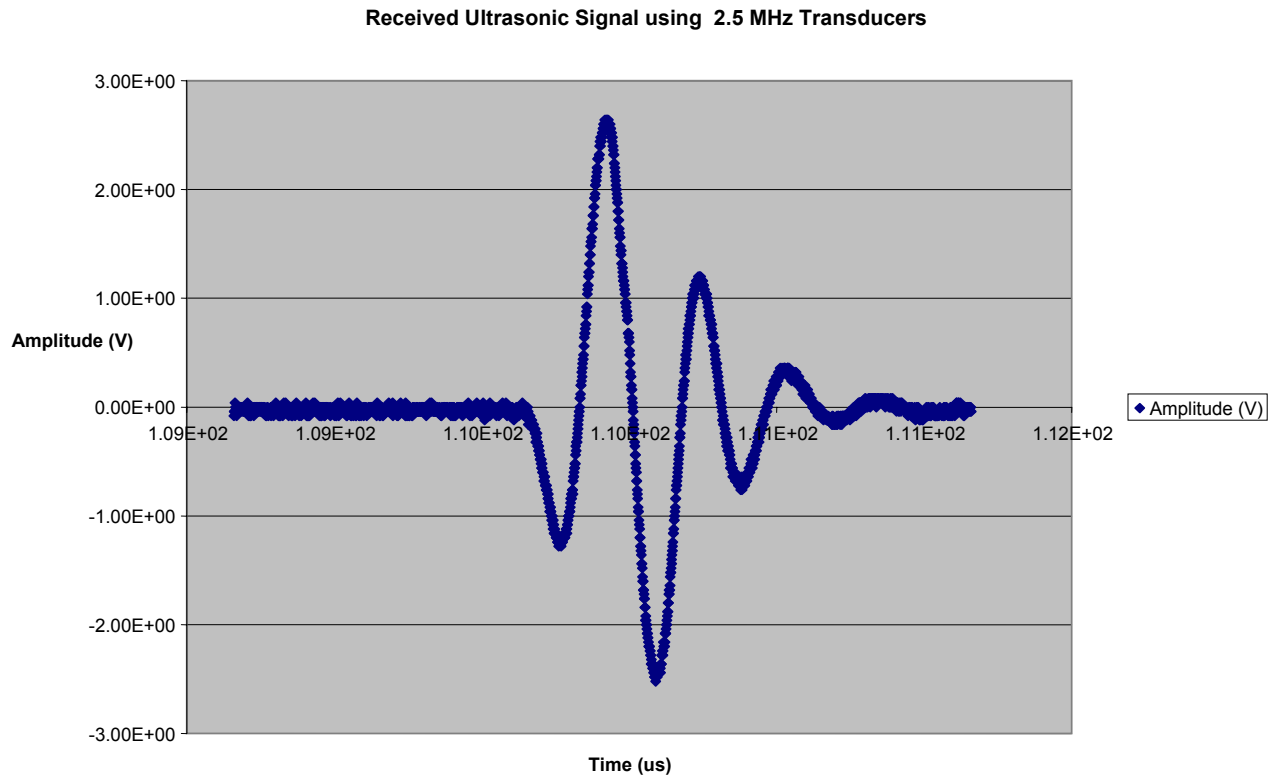


Figure 3. Received ultrasonic signal

The experiments are repeated with the three sets of transducers using both methods, and the results are presented in the report.

Measurements of the sound velocity in other materials

The propagation velocity of traveling waves are characteristics of the media in which they travel and are generally not dependent upon the other wave characteristics such as frequency, period, and amplitude. Three pairs of transducers are used in this laboratory session to confirm these statements. The Plexiglas plate and three various rubber plates are used for determining the sound velocity in these materials using the through-transmission configuration. The experimental set-up is shown in Fig. 4. The distance between transducers is larger than the thickness of the sample material, allowing a free alignment and positioning of the sample along the ultrasonic beam. The measurement system consists of a pair of coaxial transducers of similar frequency characteristics, here denoted as a transmitter and a receiver (hydrophone), and a sample material placed between them. The whole system is immersed in a water tank. Two methods for measurements of the sound velocity in the samples are used.

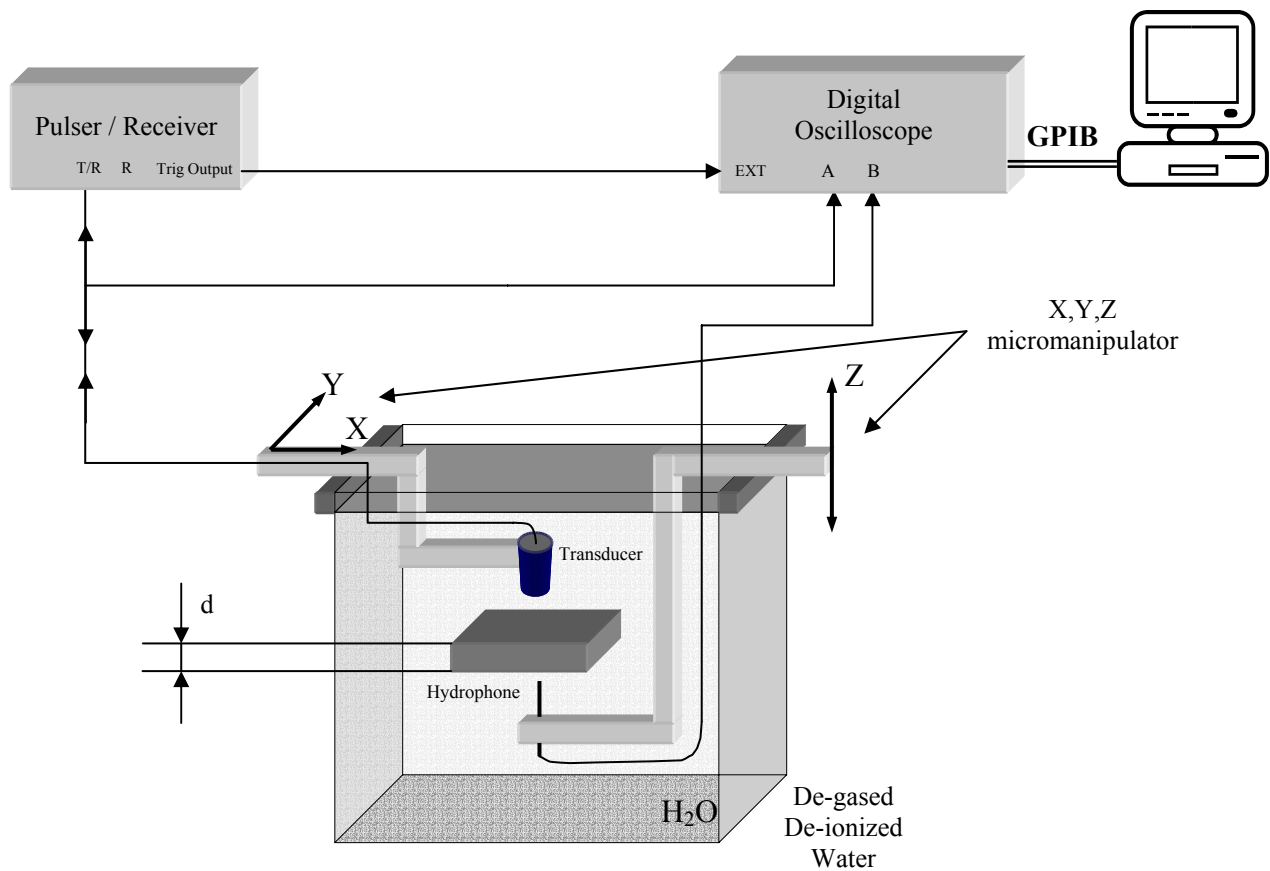


Figure 4. Measurement of the sound velocity in the material

Method # 1. The arrival time of the received signal, τ_1 , is recorded by the oscilloscope without placing the sample material between the transducers. Then, the sample material is placed between the transducers and the arrival time of the received signal, τ_2 , is recorded again. The sound velocity in the sample material can now be easily determined via the following expression:

$$c_m = \frac{d}{\frac{d}{c} - \Delta\tau}, \quad (1)$$

where c is the sound velocity in water (m), which was previously determined, d is the thickness of the sample material (m), and $\Delta\tau = \tau_1 - \tau_2$ (s).

Method #2. The arrival time of the received signal, τ_1 , is recorded by the oscilloscope without placing the sample material between the transducers. Then, the sample material is placed between the transducers and the receiver is moved back from the transmitter by the distance, which is equal to the thickness of the sample material. The arrival time of the received signal, τ_2 , is recorded again, and the sound velocity is determined by the following expression:

$$c_m = \frac{d}{\Delta\tau}, \quad (2)$$

where $\Delta\tau = \tau_2 - \tau_1$.

It is worth mentioning that Method #2 does not require the knowledge of the sound velocity in water, since the water path for both measurements remains the same and is eliminated in the calculations. The procedures described for both methods are repeated for three types of rubber plates with different thickness. In the final report, students should clearly state the advantages and disadvantages of both methods and compare the results obtained by both methods. The described above technique can be also used for measuring the thickness of the sample materials, as well as the dimensions of inhomogeneities in the sample materials.

Directivity Pattern Measurements

The directivity pattern is an important far-field characteristic of a transducer. The directivity pattern is a dimensionless and relative parameter. The mathematical expression for the normalized directivity pattern of the plane circular piston is²:

$$p(\theta) = \frac{2J_1(ka \sin \theta)}{ka \sin \theta}, \quad (3)$$

where $k = 2\pi f/c$ is the wave number, J_1 is the first order Bessel function, a is the radius of the transducer, and c is the sound velocity in water. The geometry used in deriving the far-field radiation characteristics of a circular plane piston is presented in Figure 5.

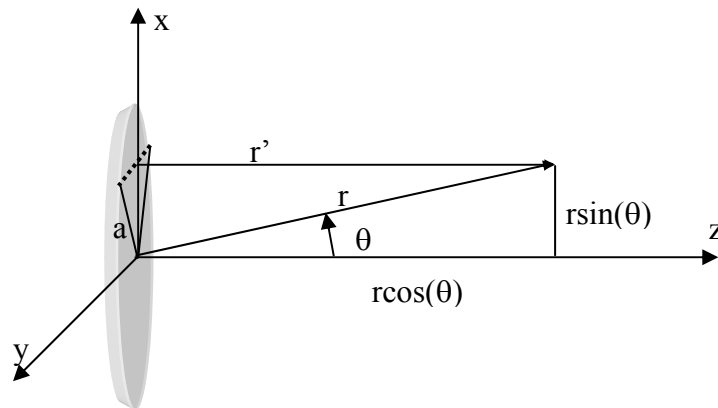


Figure 5. Far-field pressure distribution of the circular plane piston

In this laboratory session, the directivity pattern is determined analytically and measured experimentally. During the experiment, a projector and a hydrophone are separated by the minimum acceptable distance, x , to minimize interference from reflections. The standard criteria for uniform circular pistons are

$$x \geq \frac{\pi a^2}{\lambda}, \quad (4)$$

where $\lambda = c/f$ is the wavelength, and f is the resonance frequency of the transducer.

The experimental set-up for measuring the directivity pattern is similar to that of the one presented in Fig. 4, with the sample material between the transducers removed. Initially, both transducers are aligned in x , y , and θ directions. The alignment is based on the recording of the maximum amplitude of the received signal. Directivity pattern measurements are carried out with the hydrophone (receiver) fixed and the transmitter rotated using LabView 6 from 0° to 15° in 0.1° increments. For each angle, the peak-to-peak voltage of the received signal is recorded, and the data are saved in the computer as text files. Three pairs of transducers, 12.7 mm in diameter, having resonance frequencies of 2.25 MHz, 3.5 MHz, and 5 MHz are used in these experiments. Results of the computed and experimentally obtained directivity pattern for the 2.25 MHz-resonance frequency transducers is presented in Fig. 6.

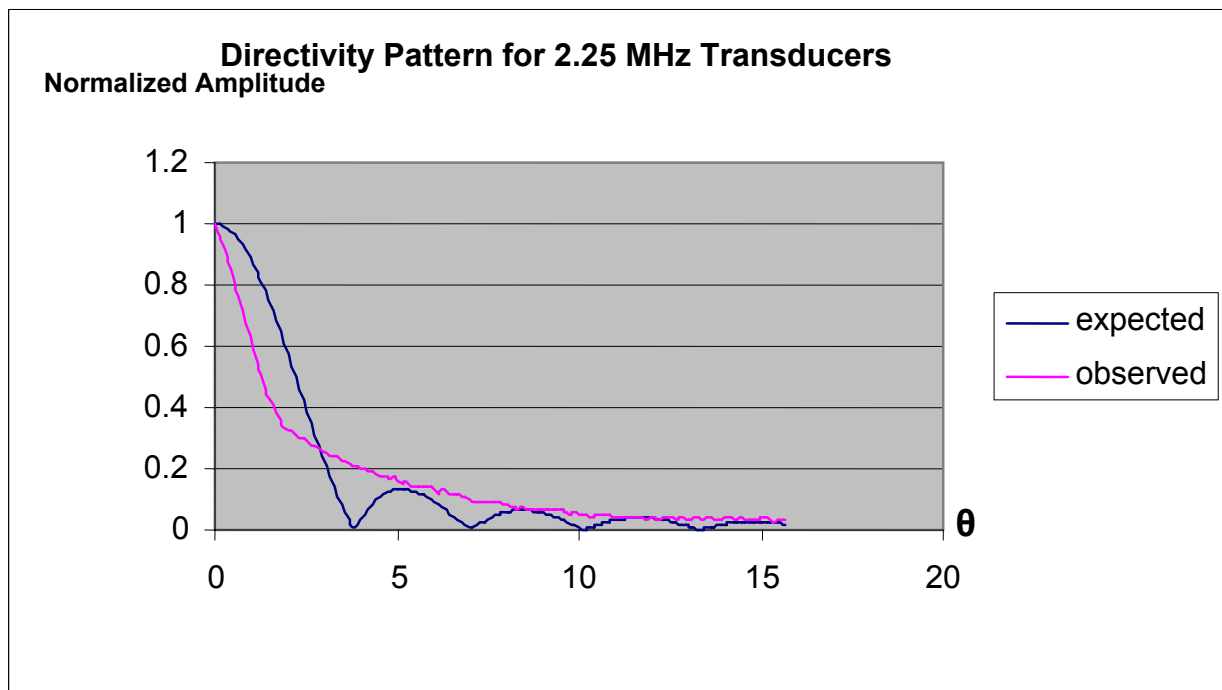


Figure 6. Theoretical and experimental directivity patterns of the 2.25 MHz piezoelectric transducer

Measurements of the attenuation coefficient of the ultrasonic waves in Plexiglas

The attenuation of a wave is determined by scattering and absorption, which are properties of the medium through which the wave passes. Since the scattering and absorption are frequency dependent, attenuation can be used in the quality control of the materials, as well as in medical diagnostics. In this laboratory session, the immersion technique is used for the measurements of the attenuation coefficient in Plexiglas. Three Plexiglas plates, which have the same mechanical and physical properties and thickness of $x_1 = 0.58$ cm, $x_2 = 1.19$ cm, and $x_3 = 1.69$ cm, respectively, are used in the experiments. The experimental set-up is presented in Figure 4. As can be seen, the Plexiglas plate is placed in the path of a propagating ultrasonic wave, which is partially reflected by changes in the acoustic impedance along its path. At least two samples of the Plexiglas are required for the experiment, since the reflection coefficient of the Plexiglas is not known and should be eliminated from the evaluation of the attenuation coefficient. Both transducers having the same resonance frequency are preliminary aligned in x , y , and θ directions. The alignment is verified by the maximum peak-to-peak received signal.

The following procedure is used for the measurements of the attenuation coefficient:

1. The Plexiglas plate of the thickness x_1 is placed between the transducers (Figure 7).

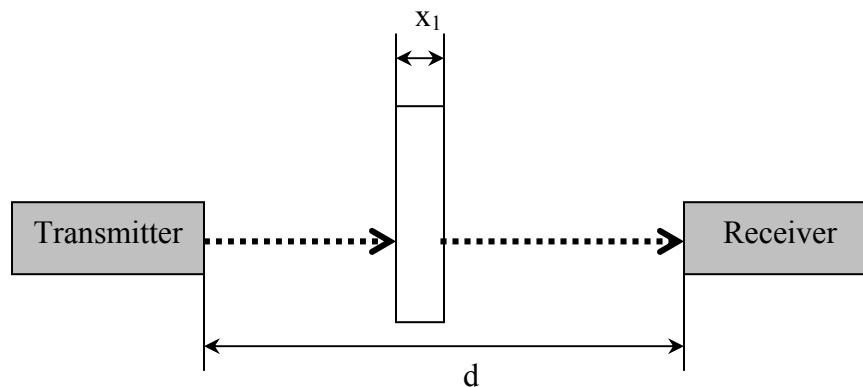


Figure 7. Schematic diagram of the attenuation coefficient measurement

The peak-to-peak voltage of the received signal is recorded by the oscilloscope and saved in the computer.

2. The Plexiglas plate x_1 is replaced by the Plexiglas plate x_2 (Figure 8).

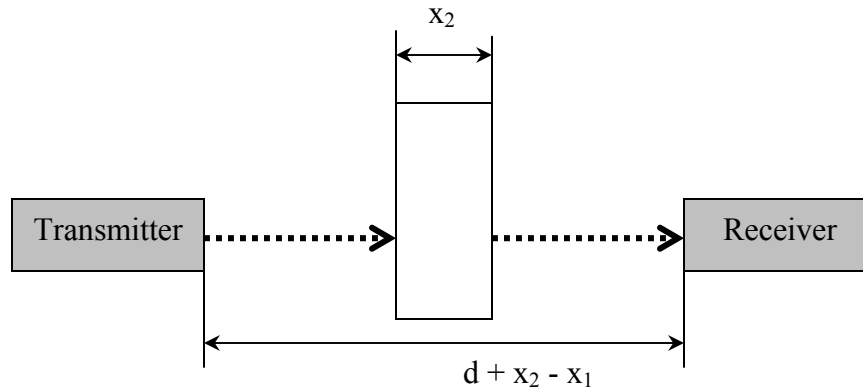


Figure 8. Schematic diagram of the attenuation coefficient measurement

To keep a constant length of the water path and eliminate the changes of attenuation in the water, the distance between the transducers is increased by $x_2 - x_1$. This change could be done by moving either transmitter or receiver away from each other. The time waveform of the received signal is then stored in the computer.

The attenuation coefficient is computed as follows^{3,4}:

$$\alpha_f = \frac{20}{x_2 - x_1} \left(\log_{10} V_{pp_x_2} - \log_{10} V_{pp_x_1} \right) \text{ dB/cm} \quad (5)$$

The procedure is repeated when the Plexiglas plate, x_2 , is replaced by the plate the plate, x_3 . Then, the distance between the transducers is increased by $x_3 - x_1$. The time waveform of the received signal is again stored in the computer and the attenuation coefficient is computed as:

$$\alpha_f = \frac{20}{x_3 - x_1} \left(\log_{10} V_{pp_x_3} - \log_{10} V_{pp_x_1} \right) \text{ dB/cm} \quad (6)$$

The average attenuation coefficient is computed at the operating frequency. Measurements are repeated with two other sets of transducers. The attenuation coefficients, in dB/cm/MHz, are computed by the following expression [3, 4]:

$$\alpha_{\text{dB/cm/MHz}} = \frac{\alpha_{f_1} - \alpha_{f_2}}{f_1 - f_2} \quad (7)$$

The results obtained in this laboratory session are presented in the report and discussed during the final presentation.

Conclusion

A unique laboratory experience for students enrolled in Drexel's Applied Engineering Technology program is presented. The article provides a description of a set of experiments in ultrasound and non-destructive testing as well as the protocol of operation. The experiments include measurements of several acoustic parameters, such as sound velocity, attenuation coefficient, and the directivity pattern of the transducers used in the ultrasound measurements and non-destructive testing. The experiments are part of a laboratory course that spans over a period of eight weeks within the framework of a quarter system. Students are organized in groups of two to three, providing a unique opportunity of involvement in each of the experiments and familiarity with equipment and set ups. By the end of the term, students become proficient and knowledgeable in topics that include electronic and ultrasound instrumentation, measurement procedures, data collection, interpretation of results and identification of possible sources of errors. In addition, the course stresses on verbal and written communication skills since each experiment must be presented by each group in the form of a report following best practices utilized in professional settings. This unique laboratory experience, in terms of operation and content, is aligned with the general philosophy and mission of the applied engineering technology program.

References

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