Abstract - Ultrasonic testing is being used increasingly across many industries and engineers are turning to modular instrumentation as a solution for these complex and dynamic challenges. The most common categories of automated ultrasonic tests are flaw detection and evaluation, dimensional measurements, and material characterization. These techniques can be applied to a diverse set of applications such as oil pipeline inspection to detect or prevent leaks, the identification of abnormalities in military/aerospace aircrafts that could result in failures, and for diagnosis and therapy research in the biomedical field.

Most ultrasonic test systems consist of a stimulus created by a source capable of producing high voltage electrical signals which are then converted to ultrasonic energy waves by a transformer and propagated through the material or unit under test. The reflected energy wave or response is converted with a transducer to an electrical signal. The electrical signal is then digitized by an instrument so that it can be processed, analyzed, and displayed within a computing environment. Most traditional ultrasonic test systems use a pulser-receiver instrument to generate the stimulus and to acquire the response. Recently, engineers have begun replacing the traditional Pulser/Receiver instrumentation with modular instruments which provide a more flexible and cost effective solution. For instance, an arbitrary waveform generator paired with an amplifier can provide the stimulus to the unit under test. In addition to the common sinusoidal and pulsed waveforms, the user can design and generate any shape of ultrasonic waveform such as multitone, chirp, or enveloped signals. By producing these custom signals, many different types of transducers can be used, resulting in a better characterization of certain materials. The receiver can be replaced with a modular digital oscilloscope which can acquire the reflected signal at greater sampling rates and with more precision. This enables the acquisition of more detailed information about the unit or material under test. The computer contained within the modular system then allows for the instant display, analysis, and storage of data.

This paper will provide a history and the basics of ultrasonic tests and then outline the benefits of a modular approach to solving these problems.

ULTRASONIC STIMULUS & RESPONSE TESTS

Brief History of Ultrasonic Tests

Many of the concepts and techniques of low-frequency ultrasonic tests can be traced back to the development of SONAR (Sound Navigation and Ranging). In 1826, Jean-Daniel Colladon, a Swiss physicist, set up the first known demonstration of the speed of sound through water by using an underwater bell [1]. Through the mid-1800s physicists continued to work towards understanding the fundamental physics of sound waves including transmissions, propagation, and refraction.
The basis of high-frequency ultrasonic tests began with a discovery by an Italian biologist named Lazzaro Spallanzani who showed the ability of bats to navigate through the dark using high frequency inaudible sound [1]. In 1876, Gabriel Galton, an English scientist, generated inaudible high frequency sound waves using the Galton whistle. Perhaps the most important discovery to ultrasonic stimulus and response tests was made by Pierre and Jacques Curie of France in 1880 when they observed a piezoelectric effect in certain crystals. They showed that an electrical potential was generated within a quartz crystal when faced with a mechanical pressure. This enabled the generation and reception of ultrasound waves. This concept was used by French physicist, Paul Langevin, to develop a high-frequency ultrasonic echo-sounding device called a hydrophone in the early 1900s. It consisted of quartz crystals glued between two steel plates with a resonant frequency of 150 kHz. This device was used extensively in naval sonar applications for many years to come.

Another important development to ultrasonic tests came in 1928 when a Soviet scientist, Sergei Sokolov, showed that flaws in metal could be detected by monitoring ultrasonic energy transmitted across the metal [1]. This idea was used by several people to create reflective metal flaw detecting devices during the 1940s. Around this same time, Japanese researchers were exploring the medical diagnostic capabilities of ultrasound for detecting gallstones, breast masses, and tumors. They were also the first to apply Doppler ultrasound which detects the speed of internal moving objects such as blood.

In the 1950s and 1960s, nondestructive testing utilizing ultrasonics emerged and was driven by all of the preceding advances. Nondestructive tests were used primarily for defect detection allowing the replacement of components before failure. Through the 1970s, technology improved to the point that even smaller flaws and cracks could be detected which necessitated more quantitative information about when components would fail.

Over the past few decades, the widespread adoption of PCs and improved instrumentation and waveform analysis techniques has resulted in the adoption of ultrasonic testing in many different industries. The understanding of how waves move through different mediums has also increased significantly, allowing for improved and more accurate characterization of materials.

**Ultrasonic Test Concepts**

Ultrasonic testing is based on acoustics which is how a material’s atoms react to a sound wave. For instance, sound waves can propagate through a solid in four main ways, depending on how the atoms oscillate [2]. These four types of propagation—also called modes—are as longitudinal waves, shear waves, surface waves, and plate waves. Longitudinal, in which particles move in parallel with the sound wave, and shear, in which particles move perpendicular to the sound wave, are the two modes that are most often used in ultrasonic testing. Surface waves in which particles follow an elliptical pattern stay along the surface and are sometimes used to detect exterior defects. Plate waves are complex but are also mostly elliptical and move through the entire thickness of a material. Longitudinal waves are also effective in liquids and gases, since sound moves through these particles using compression and expansion movements parallel to the sound wave. Shear waves are not propagated well through non-solid materials and are relatively weak compared to longitudinal waves.

The speed that sound travels through a material is dependant on the material’s density and elasticity and can be found using the equation:

$$V = \sqrt{\frac{C}{p}}$$

in which $V$ is the speed of sound in a material, $C$ is the elastic constant, and $p$ is the material’s density. The elastic constant is not the same for all directions in most materials, meaning that longitudinal and shear waves will move at different speeds through the material. For instance, longitudinal waves move through aluminum at 0.632 cm/μsec, while shear waves move through aluminum at 0.313 cm/μsec. These known speed constants can be used within ultrasonic tests to determine through which materials a wave has moved. As a sound wave moves through a material, the amplitude of the wave is also attenuated by a predictable amount based on the material’s properties. The amount of attenuation of a sound wave can also be used within ultrasonic testing.
Another important property of a material is its acoustic impedance. It can be used to figure how much sound will be transmitted and reflected at the boundary between two materials and is important in the design of ultrasonic transducers. Acoustic impedance \( Z \) is found using the equation:

\[
Z = \sqrt{pV}
\]

in which \( p \) is the material’s density and \( V \) is its acoustic velocity \([2]\). When ultrasonic waves encounter a boundary between two materials, a greater difference in acoustic impedance will result in more reflection. The equation used to determine what fraction of a wave is reflected when moving from one material to another (\( R \)) is given by the equation:

\[
R = \left( \frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2
\]

in which \( Z_2 \) and \( Z_1 \) are the acoustic impedances of two materials \([2]\). For instance, in Figure 1, a transducer generates a signal in water and the wave then encounters steel. The acoustic impedance of water is 1.483 and steel is 46.43. When applying the above equation, the proportion of the signal that will be reflected is 0.88 or 88% meaning that only 12% will be transmitted into the steel. When that transmitted signal reaches the other side of the steel object, the wave tries to enter back into the water, but 88% of that signal is also reflected back into the steel. Therefore, only 1.4% of the signal will move directly through the steel. Eventually more of the sound will reach the water as it bounces within the steel material. This behavior can be used in ultrasonic testing to characterize the material because not only can you measure the initial reflected signal, but also the secondary reflected waves.

Another important principle of ultrasonic waves is that when they move between materials with different acoustic impedances at an angle, both reflection and refraction occurs. Refraction is the bending of waves due to the different velocities that the wave moves in each material. This is the same effect that occurs when light enters water from air, causing objects to appear in different locations than where they actually are. The figure shows a waveform moving from one material into another material with a higher acoustic impedance. Because one side of the wave enters the material before the other side, the two sides of the wave move at different speeds, causing the wave to change direction. Figure 2 shows an example of sound wave being refracted.

The angle of refraction can be determined using Snell’s Law which gives the equation:
\[
\frac{\sin \theta_1}{V_{L1}} = \frac{\sin \theta_2}{V_{L2}}
\]

in which \( \theta_1 \) is the angle of the incident wave, \( \theta_2 \) is the angle of the refracted wave, and \( V_{L1} \) and \( V_{L2} \) are the longitudinal wave velocities in the two materials. Figure 3 shows this relationship. A certain amount of the sound wave will also be reflected at the same angle of incidence.

Another important point is that different types of modes will have different angles of refraction. For instance, longitudinal waves move through materials faster than shear waves, so the refraction would be less in shear waves. Another complication is that different modes may change from one type to another when moving between different materials at different angles. For instance, when a longitudinal wave enters a material, a certain amount of energy may be transferred to start a shear wave. Many of these properties must be considered when developing ultrasonic tests.

Transducers

Transducers are essential to ultrasonic testing because they convert electrical pulses to mechanical vibrations and vice versa. Most transducers today consist of a polarized piezoelectric ceramic in which some part of each molecule is positively charged, and some part is negatively charged. When an electric field or voltage is applied, the polarized molecules align themselves with the electric field, thus causing the piezoelectric material to change shape. Applying an alternating voltage (AC), causes the material to oscillate at high frequencies, producing sound waves. Piezoelectrics also change shape when a mechanical sound wave impacts them, which induces a voltage. This is the reason that some ultrasonic transducers can be used to both generate and receive waves.

The wavelength of the oscillation of a piezoelectric is twice its thickness. Therefore, piezoelectric crystals are cut to \( \frac{1}{2} \) of the thickness of the desired wavelength [2]. This means that the thinner that the material is cut, the higher the frequency that is generated. Figure 4 shows a cut away of a typical piezoelectric transducer. The piezoelectric ceramic material is the active element. To optimize the energy produced, transducers usually also have a matching layer that is made of a material with an impedance closer to that of the material for which it will be used—such as steel or water. This matching layer is cut at \( \frac{1}{4} \) of the desired wavelength so that the portion of the wave that is reflected is in phase with the original wave. A backing material is also used to provide damping to the oscillations of the piezoelectric. If the backing material has an acoustic impedance similar to that of the active material, the damping will be greater and only a narrow bandwidth of waves can be generated, resulting in higher sensitivity. As the impedance mismatch between the backing and active element grows, the damping decreases which results in a better material penetration, but lower sensitivity.
sensitivity. Some transducers are now available beyond 150 MHz which improves resolution greatly. All of these factors must be considered when selecting an ultrasonic transducer depending on what materials are being analyzed and what characteristics need to be found.

There are two classifications of transducers: contact and immersion. Contact transducers are placed directly on the surface of the material to be analyzed. Because the acoustic impedance of air is so much different than solids, a coupling material must be used between the transducer and the material. Otherwise, the air would reflect nearly all of the induced waves. This couplant displaces the air and makes the wave conveyance more efficient. It usually consists of a thin film of oil, glycerin, or water. There are several different types of contact transducers. Dual element transducers have two separate crystals; one for transmitting and one for receiving. Delay line transducers introduce a delay between when the sound wave is generated and received with a single crystal. Angle beam transducers are available with either fixed or adjustable angles, allowing them to generate refracted shear waves into materials. Normal incidence shear wave transducers are able to induce shear waves without being set at an angle. Paint brush transducers are long and narrow which allow them to characterize a large section of material. Immersion transducers do not contact the material to be analyzed. Both the transducer and material are immersed in liquid apart from each other, essentially using the liquid as a couplant. Immersion transducers generally use a lens to focus the waves efficiently into the water.

Although not as common as piezoelectric transducers, Electromagnetic Acoustic Transducers (EMATs) are also available. Instead of mechanical energy, EMATs use electromagnetic energy to generate and receive ultrasonic waves. They consist of an electromagnet or permanent magnet and a coil of wires. When brought close to a conductor, EMATs induce ultrasonic energy in the material. The advantages of EMATs are that they don't have to be in contact with the material and no couplant is necessary. They also improve the capability of generating certain types of waves, such as shear waves. The disadvantages are that EMATs generate much lower ultrasonic energy than piezoelectrics, so they are more susceptible to noise. Also, higher frequencies (above 1 MHz) cannot be applied. Finally, although they do not have to be in contact with the object being tested, they still need to be placed in a very close proximity (~1 mm) [5].

Common Measurement Techniques

The pulse-echo ultrasonic measurement technique is the most prevalent in test. In this setup, the same transducer is used to introduce the sound wave into the unit under test and then receive the waves that bounce off of the material and return to the transducer (echoes) [2].

One of the simplest tests that uses this technique is measuring the thickness of a material. In this test, an ultrasonic pulse generated by the transducer, is introduced into the material, and the wave then bounced off of the opposite side and returns to the transducer. By detecting the amount of time that has elapsed from when the signal is generated to when the echo is received, the thickness of the material can very easily be calculated. The simple equation:

$$d = \frac{vt}{2}$$

in which $d$ is the thickness of the material, $v$ is the velocity of the sound waves in that particular material, and $t$ is the amount of time that elapsed between generating and receiving the wave. The value must be divided by two to account for the down and back journey. This same method can be used to find the location of cracks, holes, and other discontinuities within a material. In some cases, the thickness of a material is known, but the material's properties are not well defined. The velocity can then be used to define properties such as elasticity, texture, and density. In these situations, the amount of attenuation or loss in amplitude of a signal as it passes through the material can also reveal different characteristics.

Pulse-echo systems can make use of transducers that introduce waves normal to the surface of the material, or angled transducers which can introduce refracted waves which can be used to avoid obstructions. The pulse-echo technique is the method used for applications such as ultrasonic flow meters, medical ultrasound machines, and sonar. For instance, ultrasonic flow meters reflect off of bubbles or suspended particles within a liquid as it flows. By monitoring a particular bubble over a period of time, the
velocity at which the liquid is moving can be determined.

A second, less common ultrasonic measurement technique is through-transmission. With this method, a second transducer is placed at another location on the material. Instead of acquiring the reflected waveform, the waveform that has passed through the material is acquired. Many of the same measurements such as thickness, discontinuities, and material type can be found using the through-transmission technique. An advantage of this method is that the sound waves only have to pass through the material a single time, so this is helpful for heavily attenuating materials. The disadvantages are that you need an additional transducer, you need access to the other side of the material, and the transducers must be lined up precisely.

A third ultrasonic technique is called spread spectrum. While pulse-echo and through-transmission techniques generate and acquire a single pulse, spread spectrum uses continuous signals. This technique generates a modulated waveform or signature that is then often acquired at many different points along the structure using multiple transducers [2]. Figure 5 shows an example of a modulated signal.

![Figure 5. Graph of a Signature Wave for Spread Spectrum Ultrasonic Tests [2]](image)

If the signature signal is not demodulated correctly, then the waveform has encountered a flaw somewhere in its path. Using multiple transducers, this flaw can be triangulated. One common application for this technique is monitoring large structures such as bridges where multiple transducers can be permanently affixed. Over time, fractures within the bridge can be detected if the signature wave is not correctly received at all points along the structure.

**ULTRASONIC STIMULUS & RESPONSE TEST METHODS**

**Traditional Test Equipment Approach**

The traditional approach to general purpose ultrasonic testing usually includes a pulser-receiver instrument, transducers and either a computer or oscilloscope.

The pulser portion of the pulser-receiver instrument provides the high-voltage pulses required by ultrasonic transducers. When applied, these electric pulses are then converted into short ultrasonic pulses by the transducer. Some of the parameters of the pulser that can be controlled are the pulse length, pulse amplitude and pulse repetition rate. Most pulser circuits supply 100 V to 800 V to a transducer.

The receiver portion of the pulser-receiver instrument amplifies the small electric signal generated by the transducer. The receiver also provides signal conditioning such as filtering to shape and smooth signals. Once the receiver has conditioned the signal, it is usually passed to a digital oscilloscope for display and analysis. For automated test systems, the pulser-receiver and oscilloscope are controlled by a computer via a standard bus such as Serial, GPIB, or USB. This allows the user to develop and run a test program that configures the instruments’ settings, triggers the generation and acquisition of the ultrasonic wave, and then displays and analyzes the waveforms in either the oscilloscope or within the computer program itself. Figure 6 shows a graph of the relationship between the different components in a traditional ultrasonic test.

![Figure 6. Traditional Approach to Ultrasonic Tests [Pics courtesy of Panametrics-NDT and Agilent]](image)

Occasionally, tone burst generators have been used as an alternative to the system outlined above. Tone burst generators are very specialized instruments designed for high power ultrasonic applications and contain the pulser-receiver,
signal conditioning, and analysis all built within a single box. These instruments are most often used in materials science research and very advanced non-destructive test applications where higher power is necessary to study highly attenuative materials or work with less efficient transducers such as EMATs.

### Modular Instrument Test Approach

The requirements of ultrasonic test systems have become increasingly complex and dynamic, pushing many scientists and engineers to implement more novel approaches to solve problems. Many tests now require the use of multiple types of transducers or to excite a transducer in multiple ways to get different material properties. For instance, many general-purpose contact transducers are highly damped, so they must be excited by a wideband, spike-like pulse that is provided by many pulser-receiver units. However, the lightly damped transducers used in high power generation require a narrowband tone-burst excitation. This would require two separate generator units. To solve this problem, many test engineers have replaced pulsers with an arbitrary waveform generator (AWG). AWGs allow users to design and generate almost any waveform in addition to the standard sine and square wave pulses. This allows AWGs to accommodate any type of transducer and excite them in different ways. One limitation of an AWG is that it does not always supply a high enough voltage to excite most transducers, so they must be paired with an amplifier or transformer. AWGs can also be used to generate the modulated continuous waveforms used in spread spectrum tests. Creating these custom signature waveforms is impossible with most pulser-receiver instruments. Finally, the specifications of modern AWGs allow users to create very precise waveforms with varying frequencies and amplitudes.

As an example, the ZTEC Instruments ZT530 series of modular arbitrary waveform generators provides 16-bit resolution and update rates up to 400 MS/s. Not only can you create custom arbitrary waveforms with the ZT530 for applications like spread spectrum, but you can also select common shapes such as sine, square, and triangle at frequencies from 2 mHz to 75 MHz for almost all types of transducers. The on-board gain selections allow ranges from 10 mVpp to 20 Vpp, which utilize the 16 bits of resolution in both small and large signals.

The receiver portion of a pulser-receiver instrument can also often be replaced by modern digital signal oscilloscopes (DSOs). For instance, ZTEC Instruments offers several different series of modular digital signal oscilloscopes that are used within ultrasonic applications. The two most prevalent are the ZT4610 series which has 8 bits of resolution and 4 GS/sec sampling rates, and the ZT410 series which has 16 bits of resolution with 400 MS/sec sampling rates. Although the 4 GS/sec sampling rate may seem like overkill for analyzing sound waves—typically in the kHz range—this fast sampling rate allows users to pinpoint the time when pulses occur down to the sub-nanosecond level. This precise timing is imperative for many ultrasonic applications in which the time from when the stimulus signal is generated to when the response signal is received must be very accurate. On the other end of the spectrum, the ZT410’s high bit resolution—still at relatively high sampling rates—provides a more accurate depiction of the acquired pulse. This is especially important for vertical measurements such as amplitude. DSOs can also be paired with an external amplifier, but ZTEC DSOs have ranges under 100 mV, so amplification of the received ultrasonic waveform is not often necessary. Additionally, like most oscilloscopes, ZTEC DSOs have built-in filtering, smoothing, and other signal conditioning necessary for ultrasonic waveforms. The averaging feature can also be used to acquire multiple waves over time and reduce noise and further improve the accuracy of the measurements. Finally, the built-in measurements such as phase, amplitude, time of maximum, and pulse-width provide the necessary measurements to characterize the ultrasonic waveform.

Many ultrasonic test engineers have also adopted a computer based modular test platform. Instrument buses such as VXI, PXI, and LXI provide many benefits to ultrasonic tests. First, modular instruments are very compact so that both the AWG and DSO can be contained within a single chassis, allowing for very powerful systems with a small footprint. This small size also facilitates portable or remote systems which are often needed for ultrasonic applications. The modular nature of these instruments also allows the addition of multiple AWGs and DSOs within a single system for multiple-channel applications. By utilizing the timing and triggering buses within each chassis, the DSO and AWG can be synchronized very tightly together. This is critical
for determining the time elapsed between the generation of the stimulus signal and the acquisition of the response signal. Because the instruments reside directly on the computer's backplane, waveforms and measurements can be quickly transferred into computer memory for further analysis. Finally, modular instruments generally have very easy-to-use drivers which allow them to be quickly integrated together within a software program. Figure 7 shows how a single PXI system with a ZTEC Instruments AWG and DSO could be used to replace a traditional system.

![Modular System Diagram]

The ZTEC ZT530PXI-01 arbitrary waveform generator provides sampling rates up to 400 MS/sec and voltage levels of 20 Vpp. This high voltage range eliminates the need for an amplifier. The ZT530's 4 MSample of onboard memory, were also essential to generating the wideband linear chirps for this test. Another important feature of the ZT530 for this application was interpolation. The signal output by the ZT530 can interpolate by 2x, 4x or 8x, essentially adding that number of points between each point in memory. This interpolation capability can help reduce the step quantization that occurs when digitizing analog signals. Figure 8 shows a 200 kHz signal sampled at 100 MS/sec with no interpolation and 4x interpolation. The 4x interpolation provides a much smoother signal.

![Interpolated Chirp Signal Generated by ZT530 AWG for Ultrasonic Test]

**British Geological Survey Application**

One application where a modular approach to ultrasonic test was implemented was at the Ultrasonics Research Laboratory of the British Geological Survey. Researchers there are studying the extremely sophisticated capabilities of bats and dolphins to use ultrasound for object detection, location, and characterization. Their capabilities in the generation, reception, and processing of acoustic signals go way beyond man's current understanding. Their goal is to better understand these biological systems used by bats and dolphins and then create ultrasonic systems which mimic them.

One study of the phase and magnitude of echo-reflected waves is a key component in understanding the achievements of bats and dolphins [4]. The British Geological Society is working with Alba Ultrasound Ltd. to provide very wideband piezo-composite transducers capable of generating new coded waveform signals. The bandwidths and efficiencies will be further improved when combined with new transducer matching networks provided by Blacknor Technologies. The generation and detection of these coded waveforms requires long memory lengths, high sampling frequencies, and high dynamic ranges offered by ZTEC Instrumentation.

Signal discrimination techniques can be much improved even if the transmitting transducer technology is bandwidth limited. For example, Barker code sequences can be sent to a transmitting transducer, each of which initiates a wave packet mainly containing damped oscillation at the resonant frequency of the transducer [4]. The multiple reflections when returned to this
transducer produce a composite signal that is the result of the convolution of all the echo returns from the various reflectors. Not only is the transmitted signal of long duration, but also the detection of pulse echoes requires a very long acquisition window. The ZTEC ZT410PXi-51 modular oscilloscope with its combined 16-bit resolution, 16MSample memory, and 400 MS/sec sampling rate offers the capability of very high sampling rates of long duration events. This allows time delay measurements with very high resolution during pulse compression. Figure 9 shows the de-convolution of an 11-point Barker code emitted from a piezoelectric transducer from a complicated pulse train comprising multiple echoes acquired with the ZT410. The top graph shows the transducer response to a series of impulses in an 11-point barker code. The middle and lower graphs show the deconvolution of the upper source signal.

![Figure 9. Ultrasonic Pulse Train Acquired by ZT410 DSO [4]](image)

**SUMMARY**

The history of ultrasonic testing is long and varied. As the understanding of the physics behind ultrasonics has improved, so have the testing techniques. Equipment is also an essential part of any ultrasonic test, and with the continued acceptance of modular instrumentation, more complex and dynamic tests are being realized.

**REFERENCES**


