An Introduction to Ultrasonic Testing and Evaluation of Solid Media

Tan Kha Sheng
Department of Physics

Introduction
Non-destructive testing includes all physical testing (NDT) and evaluation (NDE) techniques for the detection of defects and characterization of a material or components without damaging or changing it in any way. One of the more widely used non-destructive testing (NDT) techniques is ultrasound[1]. It is used in defect detection and characterization in composite materials[2]. Ultrasonic waves are usually generated and received by a vibrating source called a probe in NDT jargon. Changes in the material properties such as voids, microcracking, fibre orientation, etc., will manifest themselves as changes in the attenuation, velocity and spectral response of the wave mode traveling in the composite materials.

During the last world war, inroads have been made in the detection of enemy positions using sonar techniques. The technology of sonar is then utilized in the non-destructive testing of materials. According to Krautkramer et. al.[2], individuals such as Sokolov[3] Muhlhauser[4], Trost[5] and Pohlman[6] investigated various through transmission continuous wave techniques in the 1930's. Detection depended on a gross flaw obstructing the transmission of sound through the test piece from one transducer to another.

In the early 1940's, Firestone[7] developed an instrument that utilized pulsed ultrasonic waves to determine the depth and relative extent of flaws, using the pulse echo technique. This became the most widely used method for non-destructive testing. At the present moment, the advancement of ultrasonics have gone up to the GHz frequency as used in acoustic microscopy[8]. The used of acoustic microscopy to study microstructure in material is superior than ordinary optical microscope and can complement other techniques like the scanning electron and atomic force microscopes. One advantage of this acoustic microscopy is probably its ability to scan subsurface layer in the range of a few μm deep depending on the frequency used and the materials studied.

2. Plane Ultrasonic Waves Propagation in Solid Media
Sound is produced by a vibrating body and is itself a mechanical vibration of particles about their equilibrium position. The actual particles do not travel through the material away from the sound source. It is the energy, produced from the source, which causes the particles to vibrate and the energy moves progressively through the medium. The audible range of frequency of vibration is from about 20 Hz to approximately 20 KHz. The frequencies above 20 KHz are usually referred to as ultrasonics. These frequencies cannot be detected by the human ear but they can be transformed electronically and observed through a visual display system. Therefore, the velocity and modes of plane ultrasound waves that propagate through a solid medium depends very much on the elastic constants of the medium concerned. A lot of the current theory of wave propagation in elastic solids is due to E.B. Christoffel[9]. The Christoffel’s equation shows that the velocities of propagation of longitudinal and shear waves in different directions are related to different dynamic elastic constants of the material in which the waves propagate. This also means that the dynamic elastic constants can be determined by measuring the velocities of ultrasound in certain chosen directions[10].
2.1 Isotropic medium

For an infinite isotropic medium, there are only two modes (or types) of waves. These are pure longitudinal and shear modes. A pure longitudinal mode has particle motion parallel to the direction of propagation. These are characterized by the alternate rarefaction and compression of the particles along the direction of propagation as shown in fig. 1.1. The propagation of this mode of sound waves is caused by the elastic bond between the particles, wherein each particle, as it moves from its equilibrium position, pushes or pulls the adjacent particles, which in turn transmit their energy on to the next adjacent particles and so on. This mode of transmission is commonly used in ultrasonic testing and this wave mode can propagate in solids, liquids and gases.

A pure shear mode has particle motion perpendicular to the direction of propagation. The particle motion shears, or cuts across the direction of propagation at a right (90°) angle as shown fig. 1.2. For this wave to travel through a material, it is necessary that each particle exhibits sufficient attraction on the adjacent particles so that, as one particle moves, it pulls its neighbour with it. In this type of energy propagation, there is an inherent lag of phase in time such that a shear wave propagates at less than, approximately half, the velocity of a longitudinal wave in the same material. Therefore for the same frequency, shear waves have shorter wavelength than longitudinal waves. These waves exist, for all practical purposes, only in solids and some very viscous liquids because liquids and gases cannot support shear stresses.

![Figure 1.1 Longitudinal waves propagation.](image)

![Figure 1.2 Shear waves propagation.](image)
Both the longitudinal velocity, $c_l$, and the shear velocity, $c_s$, are related to the elastic moduli of the medium in which they propagate and to the given type of dynamic deformations. Table 1.1 shows the various effective moduli[10].

**Table 1.1.** Representation of the effective moduli for longitudinal and shear waves in terms of different elastic constants/moduli. Note: $(C_{11}-C_{12})/2 = C_{44} = G$.

<table>
<thead>
<tr>
<th>Effective stiffness</th>
<th>$C_{11}$, $C_{12}$</th>
<th>$\lambda + 2\mu$</th>
<th>$K + (4/3)\mu$</th>
<th>$\mu(4\mu - E)/3\mu - E$</th>
<th>$E(1-\nu)/(1+\nu)(1-2\nu)$</th>
<th>$3K(1-\nu)$</th>
<th>$3K(1-2\nu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal $c_l^2\rho$</td>
<td>$C_{11}$</td>
<td>$\lambda + 2\mu$</td>
<td>$K + (4/3)\mu$</td>
<td>$\mu(4\mu - E)/3\mu - E$</td>
<td>$E(1-\nu)/(1+\nu)(1-2\nu)$</td>
<td>$3K(1-\nu)$</td>
<td>$3K(1-2\nu)$</td>
</tr>
<tr>
<td>Shear $c_s^2\rho$</td>
<td>$(C_{11} - C_{12})/2$</td>
<td>$\mu$</td>
<td>$\mu$</td>
<td>$\mu$</td>
<td>$E/(2(1+\nu))$</td>
<td>$3K(1-2\nu)$</td>
<td>$2(1+\nu)$</td>
</tr>
</tbody>
</table>

The ratio of the shear velocity, $c_s$, to the longitudinal velocity, $c_l$, is given by $c_s/c_l = (1-2\nu)/(2-2\nu)^{1/2}$ where $\nu$ is the Poisson’s ratio. The maximum value, $\nu = 0.5$ corresponds to a perfectly elastic or plastic medium, e.g., a liquid for which $c_s = 0$. The minimum value, $\nu = 0$ corresponds to the maximum ratio of the velocities $c_s/c_l = 1/\sqrt{2}$. Therefore, for any medium, $c_s \geq 1.41 c_l$. For most linear elastic media, $\nu$ ordinarily lies between 0.25 to 0.35. Measurement of the shear and longitudinal velocities, thus provides a means of calculating the various elastic constants. The elastic constants measured ultrasonically are adiabatic or dynamic elastic moduli. This is so, since the propagation of ultrasound of very small amplitude can be considered as nearly adiabatic. The static mechanical measurements of elastic constants give isothermal or static values. In general, at temperatures at or below room temperature, the differences between isothermal and adiabatic elastic constants are modest[11]. Isotropic materials have only two independent elastic constants to be measured. There are no preferred crystalline directions. In a low loss medium, the group and phase velocities are equal and independent of frequencies.

### 2.2 Reflection and refraction of plane waves

It has been observed that unlike light, a sound wave of one type, such as longitudinal, will not only be refracted and reflected at the interface between the two media, but depending on the angle of incidence, be transformed partially or completely into waves of another type such as shear and surface waves. This phenomena is known as mode conversion. In which case, since these waves have different velocities in the same material, they will refract at different angles according to Snell’s law. Fig. 1.3 shows this phenomenon in a case in which a signal is partially transformed as well as refracted at a perspex-steel interface.

In addition to the above types of waves, surface or Rayleigh waves will also be generated if the angle of incidence is increased past the angle of incidence where the refraction angle for shear waves is just greater than 90°. Surface or Rayleigh waves travel over the surface of the material penetrating only to a depth of approximately one wavelength. The energy at one wavelength deep is 1/25th of the surface energy. In Rayleigh waves, the oscillation path of the particles is elliptical in the plane of wave travel as shown in fig. 1.4. Rayleigh wave is always slower, by about 90%, than the free transverse wave.
Figure 1.3 Mode conversion of an incident longitudinal waves at perspex/steel interface (not to scale).

It is also possible to create different types of waves in a material by mode conversion due to the geometry of the material, e.g., Lamb waves along plate or sheet. This will be considered later.

Figure 1.4 Surface or Rayleigh waves propagation showing elliptical oscillations. $\Lambda$ is the wavelength of surface waves.

2.3 Diffraction

In reflection and refraction, the ultrasonic waves are assumed to travel only in a straight path. However, an important property of waves is their ability to bend around obstacles which are comparable in size to their wavelengths. This wave diffraction would occur, for example, if the wave impinges upon a small inclusion or pore in a material. A portion of the energy would bend around the defect and normal reflection would be reduced.
The diffraction effects of a sound field can be deduced according to Huyghens' principle. If the source of sound from a vibrating probe is considered as a simple piston source, the variation in acoustic pressure, $P(x)$, along the beam axis at a distance $x$ is given by [2]:

$$P(x) = 2P_0 \sin \left( \frac{\pi}{\Lambda} \left( \frac{D^2}{4} + x^2 \right)^{\frac{1}{2}} \right)$$

where $P_0$ is the initial acoustic pressure and $D$ is the diameter of the probe. Here the pressure oscillates between zero and $2P_0$ due to the sine function. Along the axis of the beam, the last maximum is located at a distance $x = N$ from the source, where:

$$N = \frac{D^2 - \Lambda^2}{4\Lambda}$$

which is usually taken as approximately equal to:

$$N = \frac{D^2}{4\Lambda}$$

Distance $N$ is known as the near-field length or the Fresnel zone and the ultrasonic field beyond $N$ is called the far field or the Fraunhofer zone. Based on a plane, uniformly-emitting, ultrasonic source, the profile of an ultrasonic beam shape is as shown in fig. 1.5 according to equation (1.1) for a 10 mm diameter probe vibrating at 4 MHz in water.

![Figure 1.5](image)

**Figure 1.5** Sound pressure, $P(r)/P_0$, along the axis, $r$ of a probe

Equation (1.1) considers the use of a single frequency continuous wave. Broadband ultrasonic pulses are usually used in ultrasonic non-destructive testing and evaluation. The length of the near field then depends on the pulse length of the ultrasound. The near field is reduced as the pulse length reduces [2].
From diffraction theory for a circular disc the divergence of the beam or beam spread from colinearity, measured as angle $\theta$, can be given by [2]:

$$\sin \theta = 1.22 \frac{\Lambda}{D}$$  \hspace{1cm} (1.4).

As seen from Fig. 1.5, beyond the interference field or near field is an interference-free far field. The beam intensity in the far field follows the inverse square law, neglecting absorption and scattering effects. From equation (1.4), the beam spread angle is dependent upon the transducer diameter and wavelength. As the wavelength decreases the beam spread angle decreases. As the transducer diameter increases, the beam spread angle decreases. This is also true for broadband pulses, where in addition to a reduced interference pattern in the near field along the axis for very short pulses, the maxima and minima off the axis, i.e., the side lobes, in the directivity diagrams also disappear [2]. Fig. 1.6 shows the polar directivity patterns for various $D/\Lambda$. For $D >> \Lambda$, the beam is more collimated, i.e., increase in directivity in the far field, but with a longer near field. In general, for $\Lambda >> D$, the transducer would act as a point source in which case, there will be a hemispherical wavefront. There is then, a loss of directivity of the beam.

$D$ = Diameter of transducer  
$\Lambda$ = Wavelength  
$\theta$ = Angle of reflection of main loop
2.4 Attenuation

In practice, energy losses occur whenever an ultrasonic wave passes through a material. The causes of this attenuation are scattering and absorption.

The scattering is due to the fact that the material is not homogenous. In frequency dispersion, the amount of scattering depends on the frequency, hence the wavelength, of the wave relative to the inhomogeneity. This dispersion can affect the amplitude (geometric dispersion) and velocity (velocity dispersion) of the ultrasonic wave. The inhomogeneities can be anything that will present a boundary between two materials of different acoustic impedances such as inclusions, pores, grain boundaries and foreign inclusions. Each entity in the agglomeration has a different acoustic impedance and consequently, produces scattering of waves. The attenuation in geometric dispersion depends on the scattering domain size of the particle, $s$ and the wavelength, $\lambda$ of the wave. Table 1.2 shows the various scattering regime depending on $s$ and $\lambda$. For particle sizes of 1/000th to 1/100th of the wavelength, scatter is negligible for all practical purposes. It is also possible to encounter scattering in a material of just one crystal type if the crystals exhibit velocities of different values when measured along different axes. A material of this type is said to be anisotropic.

<table>
<thead>
<tr>
<th>$\lambda, s$</th>
<th>$\lambda/s$</th>
<th>Scattering type</th>
<th>Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda &gt; s$</td>
<td>$&gt; 1$</td>
<td>Rayleigh</td>
<td>$\alpha \sim s^2f^4$</td>
</tr>
<tr>
<td>$\lambda &gt; s$</td>
<td>$= 1$</td>
<td>Stochastic</td>
<td>$\alpha \sim sf^2$</td>
</tr>
<tr>
<td>$\lambda &lt; s$</td>
<td>$&lt; 1$</td>
<td>Diffusive</td>
<td>$\alpha \sim 1/s$</td>
</tr>
</tbody>
</table>

A second cause for attenuation is absorption. This is the result of the conversion of a portion of the sound energy into heat. In any material not at absolute zero, the particles are in random motion as a result of thermal agitation. As sound wave propagates through this material, energy is transmitted to the particles. These particles collide with other particles, causing them to oscillate. This activity persists after the sound wave has passed on, so the energy of the passing wave has been converted to heat in the material[2].

Since the amplitude and intensity of the ultrasonic waves decrease with the distance traveled in the material, the amplitude $A$ after traveling a distance $x$, assuming that the plane waves has no geometrical beam spread, is given by:

$$A = A_o e^{-\alpha x} \quad (1.5)$$

where $A_o$ is the incident amplitude, and $\alpha$ is the attenuation coefficient. As the intensity is proportional to the square of the amplitude, the reduced intensity $I$ is given by:

$$I = I_o e^{-2\alpha x} \quad (1.6)$$

where $I_o$ is the incident intensity. A convenient way to measure amplitude is in terms of $n$ decibels (dB) which is defined as:
\[ n = 20 \log \left( \frac{A1}{A2} \right) \text{dB} \quad (1.7) \]

where \( A1 \) and \( A2 \) are the amplitudes of two successive echoes on the CRT screen. An amplitude ratio between two echo signals of amplitude 2:1 will correspond approximately to 6 dB. Attenuation is usually defined as dB/mm at certain ultrasonic frequencies[2].

2.5 Waves in plate materials

When ultrasonic waves travel along a relatively thin solid material, whose thickness is slightly less than one wavelength, a complex vibration occurs throughout the material thickness. Unlike the other waves, their velocities through the material are dependent not only on the type of material, but on the material thickness, the frequency of the sound wave and its mode. These are Lamb waves named after Prof. H. Lamb who analyzed the mode of vibrations in plate material[12].

Lamb waves are elastic displacements propagating in a solid plate (layer) with free boundaries. The displacements occur both in the direction of wave propagation and perpendicularly to the plane of the plate[13]. There are two fundamental modes of Lamb waves; they are the symmetrical mode, \( S_0 \), where the vibration on the surface is symmetrical relative to the mid-plane of the plate (fig. 1.7a) and the anti-symmetrical mode, \( A_0 \), where the vibration on the surface is anti-symmetrical relative to the mid-plane of the plate (Fig. 1.7b).

(a) Symmetrical.
The phase velocity, \( c \), is the fundamental characteristic of a Lamb wave. Fig. 1.8 shows the dispersion curve for a carbon fibre composite laminate plate. This is a unidirectional laminate plate with the waves travelling parallel to the fibre direction. From fig. 1.8 it can be shown that as the frequency \( f \) varies from zero to infinity, the phase velocities of the \( S_0 \) and \( A_0 \) waves vary from some finite values to \( c_\infty \), the velocity of Rayleigh waves. The phase velocities of other non-zero modes vary from infinity, at the instant the wave sets in, to \( c \to c_\infty \) as \( f \to \infty \).

Figure 1.7 (a) Symmetrical, \( S_0 \) and (b) anti-symmetrical, \( A_0 \) wave modes.

Figure 1.8 Dispersion curves of phase velocity versus frequency-thickness. (Courtesy of Dr. N. Guo, MPE, NTU, Singapore)
3. Methods of generation and reception of ultrasound in materials

All generation and reception of ultrasound involve the use of some kind of transducers. A transducer is any device that is capable of converting energy from one form to another, e.g., mechanical energy to electrical energy and vice versa. The type of transducer commonly used in non-destructive testing is termed the piezoelectric. A piezoelectric crystal converts external mechanical pressure that deforms the crystal, into electrical charges. This phenomenon was discovered by the Curie brothers in 1880. The reverse piezoelectric effect was discovered by Lippman in 1881. The reverse phenomenon involves placing electrical charges on the crystal to produce mechanical deformation, thereby vibrations. The entire action of the transducer therefore, consists of the production of electrical signals when mechanically deformed and vice versa. The combination of these two effects makes possible most ultrasonic systems[2]. Fig. 1.9 shows the transmission of waves from the transducer. The pulsed vibrations that propagate through the material depends on the density and elasticity of the test material. The surface waves are usually produced whenever a transducer is coupled to a solid. However they are usually very weak compared to the main longitudinal or transverse waves. This is particularly so for large D/A ratio. Interference of unwanted surface waves with other waves would occur by the use of; low frequency probes below 1 MHz, very small diameter probes, angle probes of large beam angles and if there is incomplete contact between probe and material surface[2].

![Figure 1.9 Transmission of waves from transducer.](image)

Depending upon the modes of ultrasonic transmission and reception in a test material, the methods used in ultrasonic testing can be broadly classified as follows[2]:

1. Pulse echo method or transit time method. This includes:
   - Transit time method with pulses.
   - Resonance method (transit time method with continuous sound).
   - Phase measurement method (transit time method with continuous sound).
   - Shadow method (through transmission method, intensity method).
2. Acoustic holography.
3. Image methods.
4. Sound emission method.
5. Frequency modulation method.

A detailed description of the above methods can be found in Krautkramer[2]. Among these inspection techniques, both the pulse echo and through transmission methods will be briefly discussed.

3.1 Pulse echo method

In the pulse echo method[14], the transducer emits short pulses of ultrasound and receives the reflections of these pulses from discontinuities in the medium in the intervals between emitting pulses, as shown schematically in fig. 1.10. Since this technique depends on detection of echo-pulses from a
discontinuity, the larger the size of the discontinuity, the more intense will be the signal received. The time interval between transmission of the pulse and reception of the echo is used to indicate the distance of the discontinuity from the probe. By measuring the time between the same phase of two or more individual backwall echoes, the phase velocity of the ultrasound in the material can be calculated if the distance between the echoes are known and vice versa. There are several sophisticated techniques if very accurate absolute time measurement is required. One of the well known method is the pulse echo overlap method[15] which utilized the sweep frequency across the time display. This frequency is varied such that two echoes, overlap with the same phase. The reciprocal of the sweep frequency is the time difference between these two echoes. This method usually requires narrowband pulse. The errors in this technique can be reduced to a few parts in a million[16].

The amplitude of an echo cannot be translated readily into useful information. Factors such as the following have to be taken into account for signal interpretation:

1. The coupling between the probe and the test specimen.
2. The gain of the amplifier.
3. The characteristic of the probe.
4. Attenuation along the path of the sound beam.
5. The reflectivity of the discontinuity, its size, its orientation relative to the ultrasound beam and its distance from the probe.

Detailed information on the above can be referred to in Krautkramer[2].

![Diagram of Pulse Echo Method](image)

**Figure 1.10** Pulse echo method.

### 3.2 Through transmission method

In this method, a transmitter probe is placed in contact with the test-piece surface, through a couplant, and a receiving probe is likewise placed on the opposite side of the material (Fig. 1.11).

If there is no discontinuity within the material, a certain strength of signal will reach the receiver. If a discontinuity is present between the transmitter and receiver, there will be a reduction in
the strength of the received signal because of partial reflection of the pulse by the discontinuity. Thus, the presence of a discontinuity can be assumed.

![Figure 1.11 Through transmission method](image)

This method is not suitable for determining the location of discontinuity in materials. Through transmission methods are used for the measurement of sound velocity, attenuation and absorption, and for the characterization of attenuative materials such as composites, lumber, rubbers etc.

3.3 Lamb waves in plate

Lamb waves can be generated using Snell's law. The angle of incidence, \( \theta \), is varied to get the required mode (fig. 1.12). The required mode can be determined from the speed of the wave as determined from the dispersion curve (fig. 1.8). The other way of generating Lamb waves is by inputting the incidence ultrasonic pulse across the whole thickness of the plate. The same probe or another probe can be used to detect the pulse.

![Variable angle probe](image)

Figure 1.12 Schematic diagram for generating Lamb waves in plate.

3.4 Types of display

The information obtained about a specimen during an ultrasonic test can be presented in A, B, or C scan. These will be briefly described below.
3.4.1 A-scan

The ultrasonic A-scan presents a one dimensional data showing the response along the beam path at a specific location of the test object. Such scans can produce detailed information about discontinuities in the scanned material. The depth of discontinuities is indicated by the time of flight as measured from the time base of the cathode ray display. The size of discontinuities can be estimated from the amplitude of the reflected signal but has to be corrected for any attenuation within the material. Fig. 1.10 shows an A-scan display. The linear position of the echo is proportional to the distance of the reflecting surface from the probe, assuming a linear time base. This type of discontinuity can be determined by the analysis of the amplitude and phase information. The A-scan method is the most widely used on standard ultrasonic instruments.

3.4.2 B-scan

With the ultrasonic B-scan, the test object is scanned along one axis to produce a presentation of its cross section. The location along the scanning path is shown on the x axis and the time of flight values are shown along the y axis of the display. This system is shown in Fig. 1.13. When the probe is in position 1 the indication on the screen is shown in the figure with (i) representing the initial signal and (ii) representing the backwall. When the probe is moved to position 2, line (iii) on the display represents the defect. This representation of the test piece cross-section may be recorded on a paper chart, photographed, or viewed on a long persistence screen.

![B-scan diagram](image)

**Figure 1.13 Schematic B-scan presentation.**

3.4.3 C-scan

The ultrasonic C-scan is applied to the test object in a raster pattern and presents a view of the discontinuity’s area as seen from above, i.e., a plane view, see fig. 1.14. Discontinuity location and size data are available from changes in amplitude as a function of position. Where the specimen is defective or the ultrasound is attenuated due to some specimen property, a lower amplitude will be recorded and is usually shown as a lighter trace from the display unit. Modern C-scan system uses
computers to control the transducer position and to acquire, display, document and store the test results. The computer synchronously acquires the digitized position of the transducer and the associated value of a specific ultrasonic parameter. Most computerized C-scan systems acquire only one or two ultrasonic parameters as a function of position. In most cases, the parameter is the time of flight or the amplitude of reflection or transmission within a certain time gate. This parameter is digitized with the aid of an analog to digital converter.

3.5 Immersion testing

All the techniques discussed above can be used in scans known as contact scanning. The inspection probe or probes are held in contact with the surface of the material, through a thin film of liquid couplant. In the system of immersion testing, the component to be inspected is immersed in a tank of water and the test probe is placed above the test piece but below the water surface. Therefore, this technique eliminates or reduces the coupling variation which may be present in contact scanning.

Immersion testing is suited for the examination of processed parts or finished parts in a production plant and the test equipment is usually fully automated. The screen display obtained during an immersion test will show an echo corresponding to the water/specimen interface, a backwall echo from the material and, between these two, extra echo corresponding to any defect which may be present, see fig. 1.15. The distance between the probe and the test material must be set so that repeated echoes from the water/specimen interface do not appear within the length of the time base corresponding to the thickness of the specimen. A time-base delay is usually incorporated into the display so that the first peak visible at the left hand edge of the screen corresponds to the water/specimen interface. The final display can be in any of the scan formats discussed above.

Acknowledgements

I like to thank Dr. B. S. Wong and Mr. K.C. Chan for their contributions to this work.
Figure 1.14 C-scan presentation.
Figure 1.15 Immersion testing: (a) Test piece arrangement; (b) Screen display.

References

