PRACTICAL ULTRASONIC NDTE OF MATERIALS

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TABLE OF CONTENTS

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Sound has been playing an important role in the Nondestructive Testing and Evaluation (NDTE) of materials since the dawn of civilization. Several thousand years ago--in Egypt, China, Greece, and India--the quality of materials such as pottery, bricks, and metal objects, was determined simply by "listening to these materials." Materials would be tapped by fingers or lightly hammered; the sound thus produced would provide clues about the material quality. For example, a "healthy" sound was indicative of "good" quality, while the "dull" sound intonated "bad" quality. Such practices of NDTE are not uncommon even today--they are part of the common sense approach.

For well over a century, seismologists have been evaluating the structure and composition of the earth by using sound waves produced by earthquakes or by artificially created micro-seisms in the crust of the earth. Exploration geophysicists also use such information for detection of ores and oil deposits in the earth.

Sound waves indeed are capable of providing useful information about the media through which they travel. Ultrasound is an extension of audible sound and differs from it only in magnitude, not in principle. While audible sound--less than 20,000Hz--can aid in the detection of relatively large discontinuities in very large materials structures. It cannot be applied to the detection of very small defects in smaller materials. A vast majority of industrial materials used in structural applications such as in the nuclear, aerospace/aircraft, bridges, railroad, petro-chemical, mining, and other industries, may possess defects far beyond the resolving power of audible sound. In order to characterize these materials by nondestructive methods, we must increase the frequency of sound waves--generally into several MHz. By doing so, the wavelength of sound in a given material is shortened, thus facilitating the detection of smaller sub-surface defects. This sets the course for the generation, detection, and interpretation of ultrasound for the purposes of nondestructive testing and evaluation of materials. In this article we will discuss the principles of ultrasound, methods of its generation and detection, and its subsequent interaction with materials. Applications of ultrasound will also be discussed along with the need for further research and development into ultrasound--material interaction phenomenon.

1. ELEMENTARY PRINCIPLES OF ULTRASOUND

Sound consists of a mechanical vibration of the molecules, atoms of a gas, liquid, or a solid material about the equilibrium positions of these particles. When a sound wave strikes a material, its particles are set into motion. If a particle is displaced from its equilibrium position by applied stress, such as by the pressure of a sound wave, internal forces in the particle tend to restore the system to its original equilibrium position. Since a material is composed of infinite particles mechanically coupled to each other, when one particle is displaced from its equilibrium position, it exerts pressure upon the next one. Therefore, displacement at one point induces displacement at the neighboring points. Because of the elastic nature of solid materials, the displacement of vibrating particles is not unidirectional. Each displaced particle bounces back to its original equilibrium position, thus causing a stress-strain wave in the material through which sound propagates. At ultrasonic frequencies, the actual displacement in solids is, of course, very small.

1.1 Types of ultrasonic waves: Depending upon the mode of particle vibration relative to the direction of wave propagation, ultrasonic waves can be classified into the following categories:

1.1.1 Longitudinal waves: When the direction of particle displacement is the same as the direction of wave propagation, the waves so produced are called longitudinal waves. These are characterized by alternate rarefraction and compression of the particles along the direction of propagation, Fig. 1. The most common example of longitudinal waves is speech. Other commonly used terms for this wave type are primary and compressional. For example, the velocity of longitudinal in steel is 580,000cm/s; for water it is 150,000cm/s; and for air it is 33,000cm/s. This wave type is most commonly used in NDTE.

1.1.2 Shear waves: When the direction of particle displacement is perpendicular to the direction of wave propagation, the waves so produced are known as shear waves. For this type of a wave to be propagated, it is necessary for each particle to exhibit a force of attraction to its neighbor so that as one particle moves back-and-forth, it pulls its neighbor with it. This type of particle motion is best illustrated by the vibration of a string, Fig. 2. Another frequently used name for this wave type is the transverse wave. The velocity of shear waves in steel is 312,000cm/s.

For the transmission of shear waves, there must exist attractive forces between the molecules or particles. In most low viscosity liquids and gases, these forces of attraction are so small that shear waves cannot be transmitted through them. Shear waves are widely used in the detection of weld defects as well as for those defects whose orientation is angular relative to the test surface.

1.1.3 Surface waves: If we attempt to generate a longitudinal wave on the surface of a solid material bounded by air by pulling its "skin" back-and forth, the shear forces generated perpendicular to the surface will not be balanced out. This is because the waves are travelling along the discontinuity bounded on one side by the

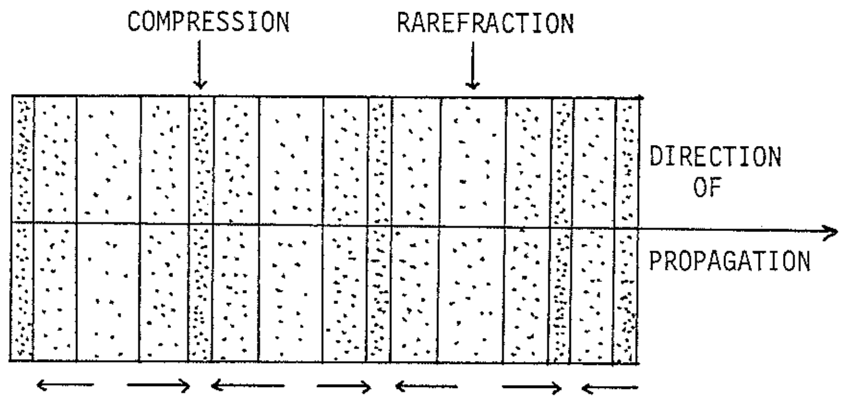

Fig. 1. Longitudinal wave propagation consisting of alternate compression and rarefraction of particles along the direction of wave propagation.

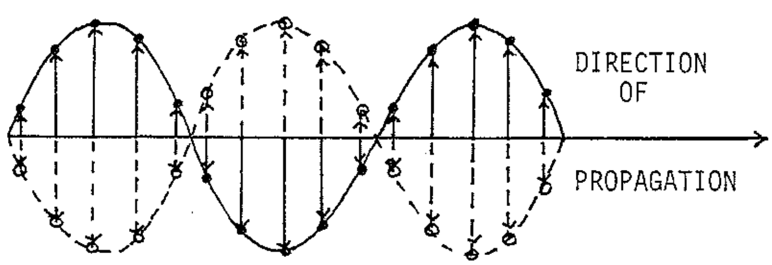

Fig. 2. Shear wave propagation consisting of particle motion perpendicular to the direction of wave propagation. As the particles move back-and-forth they pull their neighbors along with them. "String" vibration.

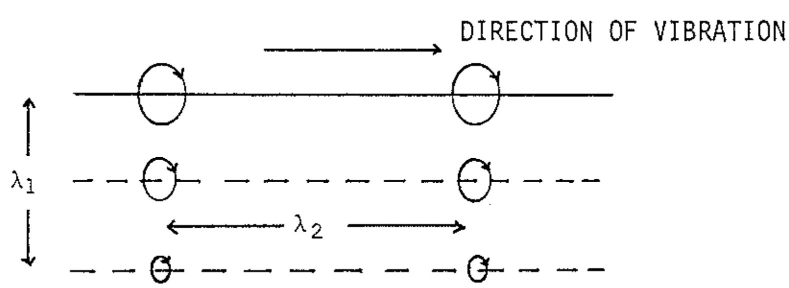

Fig. 3. Surface or Rayleigh wave propagation showing the shear wave propagation perpendicular to the direction of wave propagation and longitudinal waves on the surface. λ_1 is the wavelength of longitudinal waves, and λ_2 is the wavelength of surface waves.

elastic forces of the solid, and on the other by virtually non-existent forces between the gas molecules. Such waves, known as surface waves, are therefore characterized by complex motion of longitudinal and shear waves. These waves are also known as the Rayleigh waves, Lord Rayleigh having first discovered them in 1885. The particle motion of these waves is shown in Fig. 3. The best illustration of this type would be the ripples or currents on the surface of water. It should be noted that rippling is confined only to the surface, while underneath the ripples the material is relatively calm. The penetration of surface waves in a material is approximately one wavelength of the longitudinal waves in the material. For example, the velocity of surface waves in steel is 300,000cm/s. In NDTE, surface waves are used for the detection of surface defects in parts having limited or difficult access.

Another type of surface wave, known as Lamb waves, has also been identified. These waves occur in relatively thin bars and plates. A complex vibration occurs in the entire material thickness, depending upon plate thickness, wavelength of acoustic waves, and the type of solid.

1.2 Propagation of ultrasound in materials: When ultrasound is introduced from its source--to be discussed later--into a material, a variety of phenomena takes place. The principles of these are well-known in optics. Depending upon the direction of wave propagation relative to the material surface, these phenomena are described as follows:

1.2.1 Zero degree incidence of ultrasound: When the angle of incidence of an ultrasonic wave is zero or when it is perpendicular to the surface of the material, a part of ultrasonic energy is transmitted into the material, while the other is reflected from the material surface. The amount of transmission and reflection of ultrasonic energy is defined by the acoustic densities of the medium from which the wave is originating and the medium into which it is propagating. Acoustic density is popularly known as the acoustic impedance, i.e.,

$$Z = \rho \cdot v$$

where, Z = acoustic impedance
ρ = density of medium
v = velocity of sound in the medium.

Consider the propagation of ultrasound from medium 1 of acoustic impedance Z_1 into another medium 2 of acoustic impedance Z_2, Fig. 4. The amount of transmission and reflection at the interface of these media are defined by their respective co-efficients:

$$\text{Transmission co-efficients, } T = \frac{4Z_2Z_1}{(Z_2 + Z_1)^2}$$

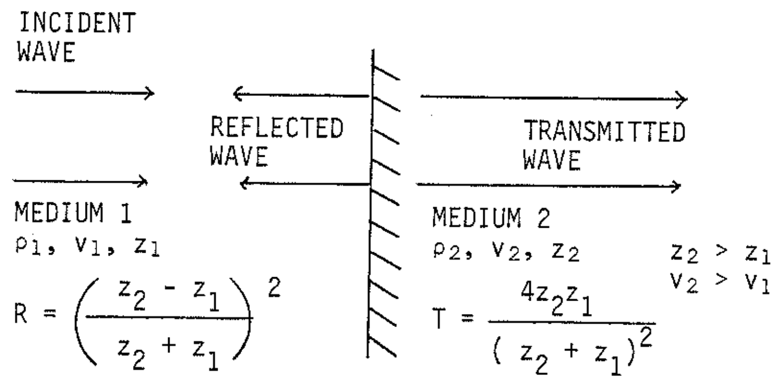

Fig. 4. Zero degree incidence of a plane wave from a medium of low acoustic impedance, z_1 into a medium of high acoustic impedance, z_2.

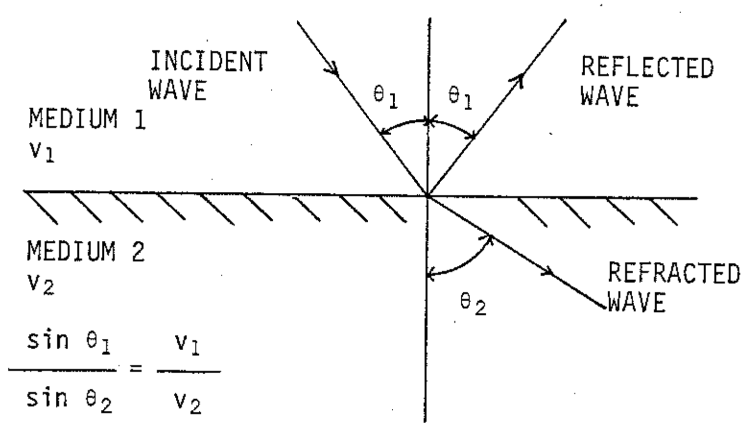

Fig. 5. Oblique incidence of a plane wave from a medium of low velocity, v_1 into a medium of high velocity, v_2.

Reflection co-efficient, $R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2$

$T + R = 1$

As a rule of thumb, it is sufficient to know that when ultrasound travels from a medium of lower acoustic impedance into a medium of higher acoustic impedance, $T > R$, and vice versa.

1.2.2 Oblique incidence of ultrasound: When ultrasound hits an interface at an incidence angle other than zero, besides transmission and reflection, it is also refracted and mode converted in a similar manner as does the light wave. Such a situation is illustrated in Fig. 5. Here an incident longitudinal wave from medium 1 at angle θ_1 is reflected at angle θ_1. It is also transmitted at θ_2 by virtue of its refraction in medium 2. Refraction of ultrasound is also defined by the well-known Snell's law of refraction in optics:

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{v_1}{v_2}$$

, where v_1 = velocity of ultrasound in the medium of incidence

v_2 = velocity of ultrasound in the medium of refraction

The law of refraction is the most frequently used relation in NDTE, particularly in the generation and application of shear and surface waves. By angulating longitudinal waves beyond their critical angle, only shear waves will be transmitted into the medium of interest. Similarly, by angulating shear waves beyond their critical angle, only the surface waves will be generated in the medium of interest, i.e., for shear waves to occur:

$$\theta_1' = \sin^{-1} \left(\frac{v_1^1}{v_1^2} \right),$$

θ_1' = the first critical angle of incidence,

v_1^1 = velocity of longitudinal waves in the incident medium,

v_1^2 = velocity of longitudinal waves in the refracted medium.

For example, in order to generate shear waves in steel from a medium such as lucite, the first critical angle of incidence will be 28°. At this angle, the longitudinal waves will be totally reflected from the lucite-steel interface, producing shear waves at the refracted angle of 31°. By varying the angle of incidence from 28° up to the second critical angle, a wide variety of refracted shear wave angles can be produced. This practice is very common in the detection of weld defects as well as those whose orientation is complex in

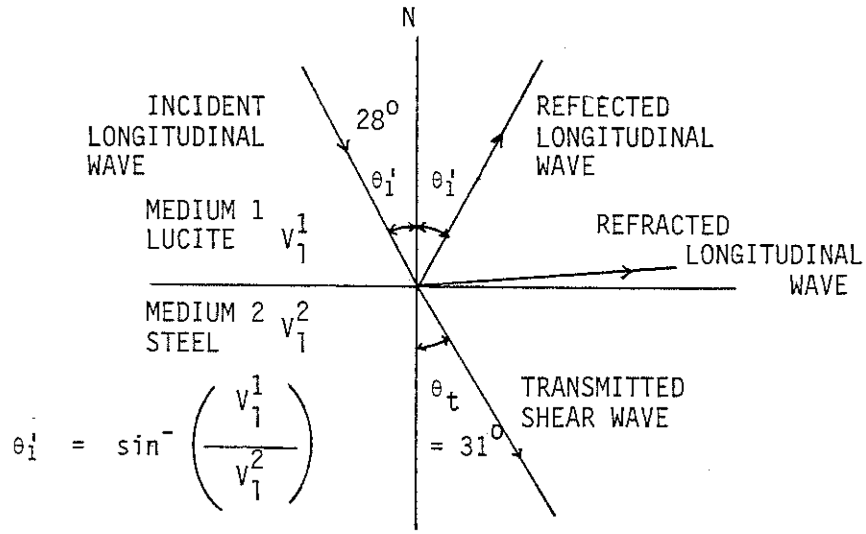

Fig. 6. Generation of shear waves by mode conversion when the incident longitudinal wave is at its first critical angle (θ_1') or more. Longitudinal wave velocity in the medium of incidence, lucite: 279,000cm/s., in the medium of refraction, steel: 585,000cm/s.

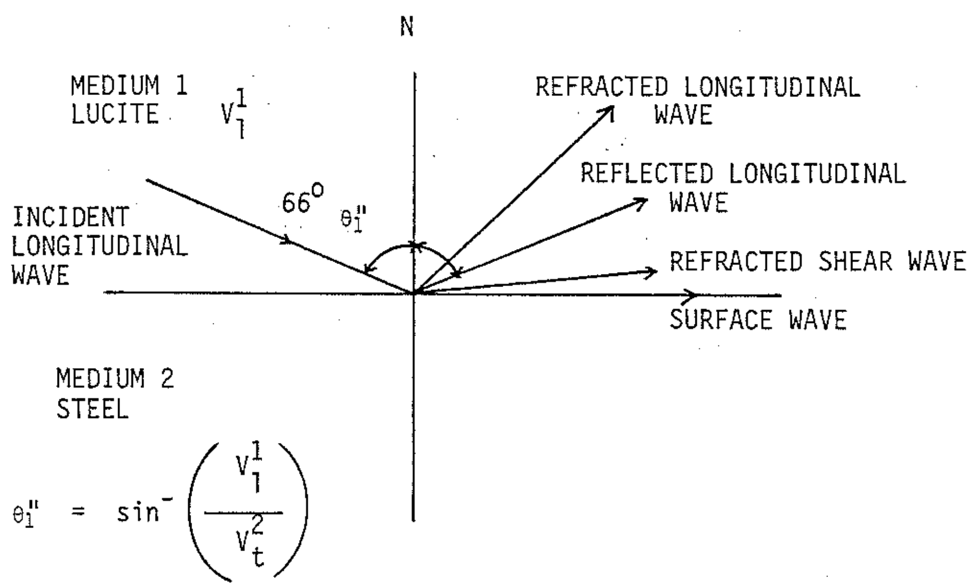

Fig. 7. Generation of surface waves by mode conversion when the incident longitudinal wave is at its second critical angle (θ_1'') or more. Velocity of shear waves in the medium of refraction, steel: 304,000cm/s.

relation to the test material surface. An example of this exercise is shown in Fig. 6.

Similarly, for surface waves to occur,

$$\theta_1'' = \sin^{-1}\left(\frac{v_l^1}{v_t^2}\right),$$

θ_1'' = the second critical angle of incidence,

v_l^1 = velocity of longitudinal waves in the incident medium,

v_t^2 = velocity of transverse waves in the refracted medium.

For example, in order for surface waves to occur in steel from a medium such as lucite, the second critical angle of incidence will be 66°. At this angle both longitudinal and shear waves will be nearly totally reflected at the lucite-steel interface, yielding the complex motion of surface waves in steel. An example of this is illustrated in Fig. 7. In these calculations the velocities are:

v_l^1 = longitudinal wave velocity in lucite = 279,000cm/s.

v_l^2 = longitudinal wave velocity in steel = 585,000cm/s.

v_t^2 = transverse wave velocity in steel = 304,800cm/s.

The phenomenon of conversion of longitudinal waves into shear waves is called mode conversion. Mode conversion in direct contact ultrasonic testing is done through the utilization of refracting wedges constructed from materials having sound velocity lower than that in the refracted medium. Commonly used materials are plastics. In immersion testing mode conversion is accomplished simply by angulating the transducer at the desired angle.

In principle, for mode conversion to occur, it is not necessary for longitudinal ultrasonic waves to have oblique incidence. Because ultrasound is diffracted at some point during its propagation in a medium, some amount of mode conversion will occur. Also, if the reflecting target in the medium is at some angle relative to the incident wave, mode conversion of longitudinal waves will occur. This phenomenon is less pronounced in low impedance materials such as plastics.

1.3 Source of ultrasound: The most commonly used source of ultrasound is the piezoelectric transducer. It is a device that converts electrical energy into mechanical energy--ultrasonic--and vice versa. When a transducer containing an active piezoelectric element is excited or pulsed by electrical voltage, at each pulsation the transducer vibrates at its frequency. The frequency of vibration is determined by the characteristics of the piezoelectric element. A typical set-up for ultrasonic NDTE, including the system for frequency domain analysis, is shown in Fig. 8. Here a pulser sends electrical energy bursts into the transducer, causing the transducer to oscillate at its resonant frequency. These oscillations are transmitted into the test material by physically coupling the transducer to it. Ultrasound travels into the material until it encounters a discontinuity or some other similar sharp phase change in the material. At such points a portion of ultrasonic energy will be reflected by the discontinuities along with a reference reflection, generally the bottom surface of the material. All these reflections are amplified and displayed on the oscilloscope screen. Such displays are known as real time rf traces.

Piezoelectric materials are characterized by the absence of the center of symmetry in the crystallographic structures. There is a large number of naturally occurring piezoelectric materials; however, only very few are of practical importance in NDTE transducers. Advances in crystal chemistry and materials synthesis have generated an extremely large number of piezoelectric materials as a choice. A few of these materials, commonly used in NDTE transducers, are listed below along with their general uses:

PIEZOELECTRIC MATERIALS	TYPICAL NDTE APPLICATIONS
Lead titanate-lead zirconate PZT: Pb (Ti, Zr)O_3.	High sensitivity, deeper materials penetration, attenuative media, etc. Usable frequencies: generally below 10MHz.
Lead meta-niobate, high Q_m $PbNb_2O_6$ PMN.	Moderate sensitivity, general purpose NDTE. Usable frequencies: generally below 25MHz.
Lead meta-niobate, low Q_m	Low sensitivity, high resolution. Usable frequencies: generally below 10MHz.
Thin film transducers: ZnO, CdS, AlN, etc.	Ultra high frequencies, above 100MHz.
Lithium niobate, $LiNbO_3$	Very high frequencies, generally up to 100MHz and shear wave devices.

By far the most common piezoelectric materials used in NDTE are based upon perovskite structure $BaTiO_3$, such as PZTs and PMNs. They occupy a significant position among the ferroelectric and high capacitance materials. Ilmenite, $FeTiO_3$, and structured materials such as $LiNbO_3$, have proven to be among the highest temperature ferroelectrics known.

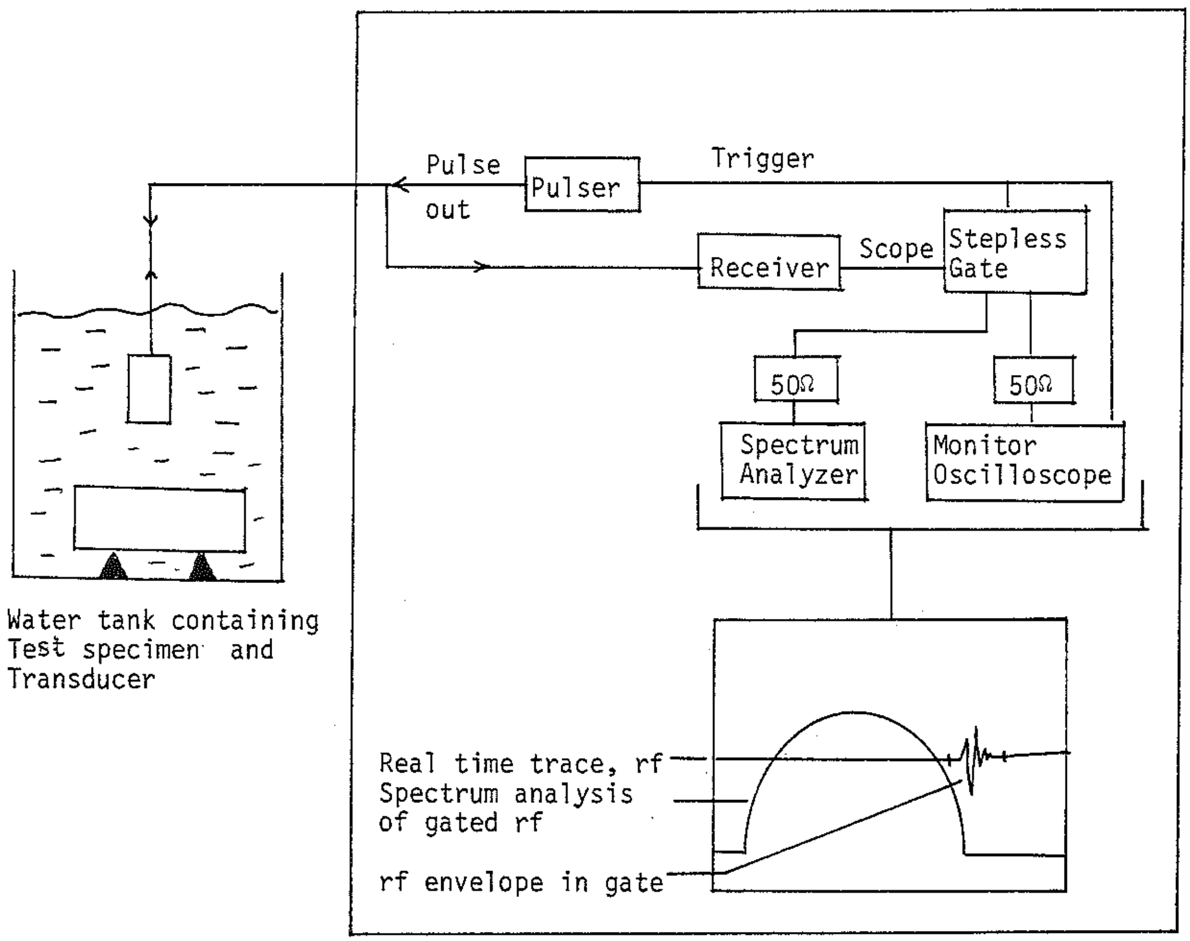

Fig. 8. A typical lay out for pulsed ultrasonic realtime and frequency domain analysis used in NDTE.

All the above-mentioned piezoelectric materials are capable of producing longitudinal and shear waves in a wide range of frequencies. However, since PZTs and PMNs are polycrystalline ceramics, it is generally difficult to polarize them to yield shear waves; thus, they are widely used as longitudinal wave devices. The following steps describe the methods of generating longitudinal, shear, and surface wave transducers.

1.3.1 Longitudinal wave transducers: Polarized PZTs and PMNs when cut in the form of plates or discs can be made to vibrate in thickness or compressional mode to yield longitudinal waves. Similarly, $LiNbO_3$--a single crystal--when cut along its Y-axis produces longitudinal waves.

1.3.2 Shear wave transducers: Shear waves can be produced by angulating the incident longitudinal waves beyond their first critical angle, section 1.2.2. This is accomplished by mounting a longitudinal wave transducer on an appropriately constructed shear wave refracting wedge.

For the generation of pure zero-degree incident shear wave transducers, single crystals such as quartz or lithium niobate are used. X-cut plates of these materials yield nearly pure shear waves.

1.3.3 Surface wave transducers: Surface waves can be generated by angulating longitudinal waves at their second critical angle, section 1.2.2. By doing so, both longitudinal and shear wave components are nearly totally reflected from the refracting wedge and test material interface.

Surface waves can also be produced by angulating a pure shear wave transducer at its first critical angle. However, the surface waves so produced are weaker and also cumbersome to use due to coupling problems.

Another method for the generation of surface waves involves the diffraction phenomenon in ultrasound. If a longitudinal wave transducer was constructed in such a manner that the ratio λ/D is greater than 0.819, it would only produce surface waves in all directions. Here λ is the wavelength of longitudinal waves in the test material and D is the diameter of the transducer. These relationships are derived from the diffraction of ultrasound, i.e.,

$$\psi_1 = \sin^{-1} 1.22\ (\lambda/D)$$

Clearly, when the angle of diffraction is 90^{o}--or more!--only the longitudinal waves are propagated on the material surface. This situation can be described as total diffraction of ultrasonic waves when they strike a material surface.

1.4 Geometrical acoustics: Ultrasonic waves from a transducer into a medium of interest cannot be regarded to have rectilinear propagation. Like all forms of wave motion, elastic waves also exhibit the phenomena of interference and diffraction. Knowledge of these phenomena are of extreme value in understanding and interpreting the nature of ultrasound in a given medium.

1.4.1 Interference of ultrasound: The field occupied by ultrasound is best explained by the methods used in the analysis of light waves, especially the Huygen's principle. According to this principle, wave energy is radiated from a point in all directions. The wave front is spherical in shape and its intensity per unit area decreases as the square of the distance from the source. If two wave fronts are placed next to each other, the wave front will be a combination of two spherical wave fronts, and the resultant wave will no longer be spherical.

A plane transducer can be considered as the large group of point sources close to each other. The resultant wave front from such a source is the composite of various maxima and minima caused by the interference of wave fronts from a large number of point sources. Interference occurs when two or more waves, varying in phase, are superimposed upon each other.

From a practical standpoint, this phenomenon can be best explained by measuring the acoustic pressure of ultrasonic waves at a number of points. Imagine a reflecting target--a small spherical ball--being brought from infinity on the central axis of the transducer. The first maximum of acoustic pressure, denoted by Y_0^+, is followed by the first pressure minimum denoted by Y_1^-. These are successively followed by the second pressure maximum, Y_1^+, the second pressure minimum, Y_2^-, and so on. Such a relationship is shown in Fig. 9.

These points of varying acoustic pressure--intensities--are of extreme significance not only in the transducer designs considerations, but also in the interpretation of reflected ultrasonic signals from within a medium through which ultrasound is propagating. The location of various pressure maxima and minima can also be calculated by the following well-known relationships:

For a square-shaped transducer, the central maxima is given by:

$$Y_m^+ = \frac{D^2 - (2m\lambda)^2}{8m\lambda}, \quad (m = 0, 1, 2, 3, \ldots)$$

For a square-shaped transducer, the central minima is given by:

$$Y_n^- = \frac{D^2 - (n\lambda)^2}{4n\lambda}, \quad (n - 1, 2, 3, \ldots)$$

For a circular-shaped transducer, the central maxima is given by:

$$Y_m^+ = \frac{D^2 - \lambda^2(2m + 1)^2}{4\,\lambda(2m + 1)}, \quad (m = 0, 1, 2, 3, \ldots)$$

For a circular-shaped transducer, the central minima is given by:

$$Y_n^- = \frac{D^2 - \lambda^2 n^2}{8\,n\,\lambda}, \quad (n = 1, 2, 3, \ldots)$$

where, Y^+ = a maximum

Y^- = a minimum

Y_0^+ = the first maximum when approached from infinity

Y_1^- = the first minimum when approached from infinity

Y_n^+ = the nth maximum when approached from infinity

Y_n^- = the nth minimum when approached from infinity

D = distance across the transducer or its diameter

λ = the wavelength of ultrasound in the medium in front of the transducer

m = a maximum pressure point

n = a minimum pressure point.

For the sake of simplicity, the relationships involving the squares of wavelengths can be ignored. This is because the majority of test materials such as metals, ceramics, composites, etc., are characterized by rather short wavelengths at commonly used frequencies. However, if the wavelengths are relatively large, such as for very high velocity materials at lower frequencies, the significance of this term would be obvious.

Upon the calculations or observations of acoustic pressure maxima and minima close to the transducer face, Fig. 9, it is noticed that these points of varying ultrasonic intensities are rather "crowded." Therefore, if observations were made in this region of wave propagation, slight changes in the location of reflectors in the medium would cause significant variations in the amplitude of reflections. Also, situations may exist when a reflector may be located on a minimum, yielding no observable reflected signal. Due to these difficulties, the region very close to the transducer face is called the "zone of confusion" and observations in this region are avoided. Generally, the length of this region is from the transducer face up to the appearance of Y_1^-. According to this author's experience, the best ultrasonic observations are made in

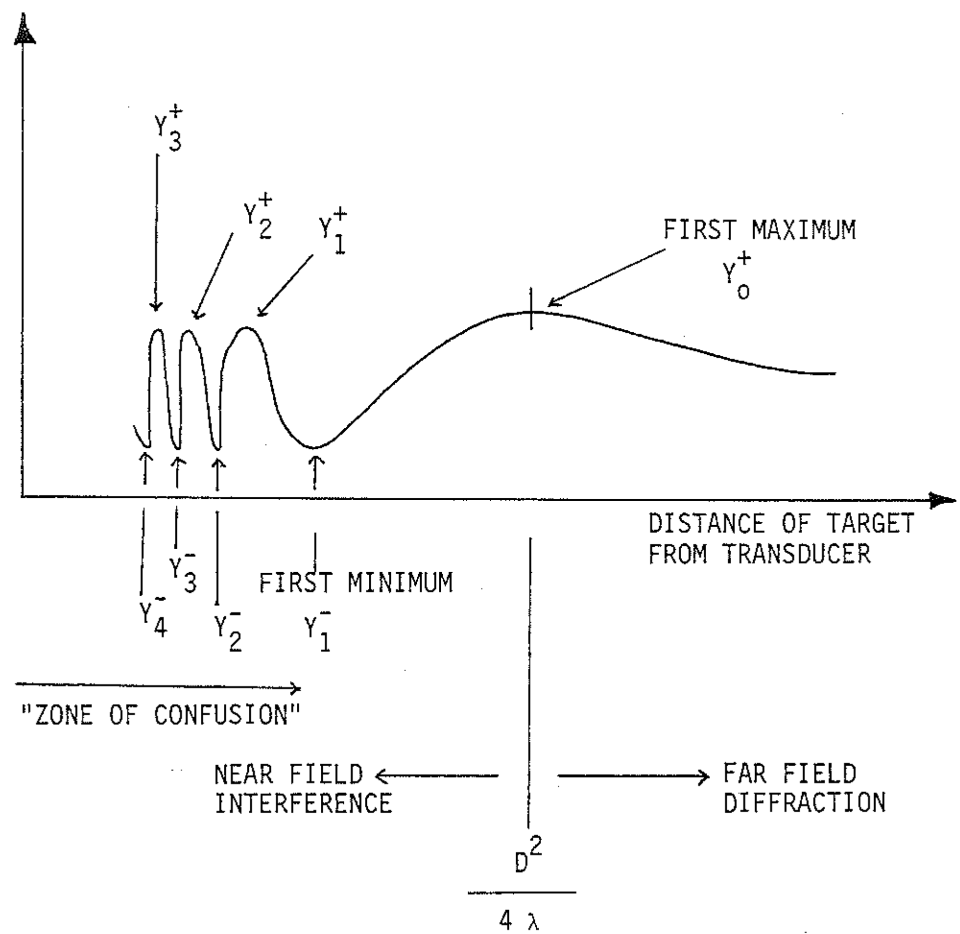

Fig. 9. Relative acoustic pressure along the central axis of an ultrasonic source - transducer - when a reflecting target is brought from infinity towards it in a medium.

D = diameter of the transducer; λ = wavelength of ultrasound in the medium; Y^+s = maxima; Y^-s = minima in the region:

$$Y_0^+ \pm 30\%$$

1.4.2 Diffraction of ultrasound: Not only is there an interference of ultrasound between the transmitted and reflected waves, but the waves also bend at certain points during their propagation in a medium. The bending of ultrasonic waves is also best explained by the well-known diffraction phenomenon in optics. When a wave encounters an aperture in its path, it tends to bend around the edge of the aperture. The amount of bending--diffraction--is directly related to the size of the aperture and the wavelength of the wave.

In order to understand the diffraction of ultrasound, the size of the transducer can be assumed as an aperture. Because of the constructive and destructive interference, the amplitude of the wave on the diffraction side, i.e., the transducer edge, is not uniform over a wave front. It varies according to the relationships in section 1.4.1 and Fig. 9.

The distance between the transducer and the first maximum pressure point is known as the near field or Fresnel zone. The region beyond the first maximum is called the far field or Fraunhofer zone. While the Fresnel zone describes the interference, the Fraunhofer zone describes diffraction of the wave. As noticed earlier, the acoustic pressure distribution in the near zone is quite complicated. This situation is somewhat simpler in the far field. Generally, the ensuing ultrasonic beam up to near field-far field transition is well-collimated. At this point, the beam suffers from diffraction due to the edge effects of the transducer, Fig. 10. Diffraction causes the beam to diverge. The amount of divergence is defined by:

$$\psi_1 = \sin^- (1.22\ \lambda/D)$$

where, ψ_1 = half the angle of divergence
λ = wavelength of ultrasound in the medium
D = diameter of the transducer.

In reality, the far field acoustic pressure distribution is more complex than what is shown in Fig. 10. The acoustic field in this region looks like a balloon, and is known as the main lobe of ultrasonic energy. The sides of this lobe, Fig. 11, define the diffraction of ultrasound. Sometimes, immediately before the main lobe, further diffraction of waves takes place due to the well-defined secondary or side lobes. This effect occurs in the near field of the sound wave. Typically, the side lobes are produced at the second minimum, the diffraction of which is defined by:

$$\psi_2 = \sin^- (2.23\ \lambda/D)$$

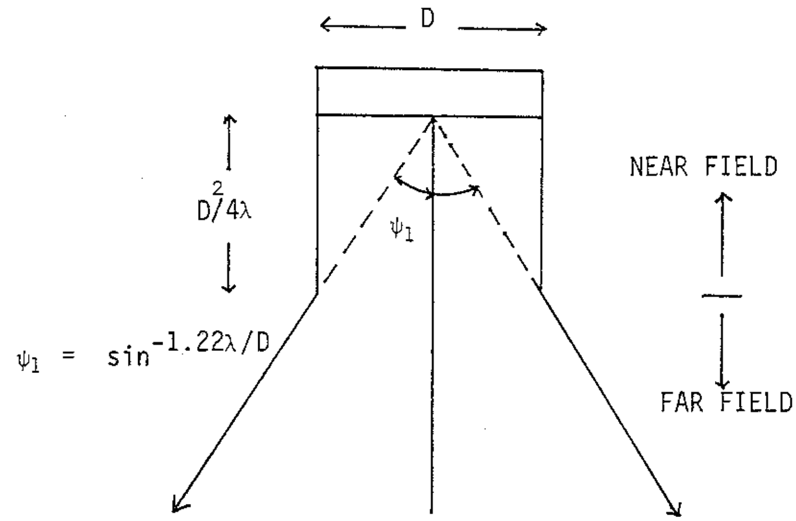

Fig. 10. Diffraction of ultrasonic wave at the edges of its source - transducer

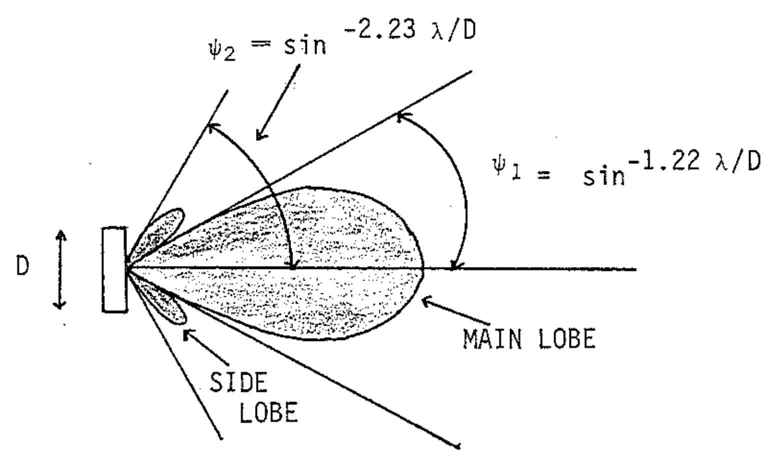

Fig. 11. Diffraction of ultrasonic wave at the first and second null points, corresponding to Y_1^- and Y_2^- in the interference zone.

Secondary lobes can introduce many unwanted effects in NDTE. For example, if the surface of the test material or that of the reflecting targets is rough relative to the wavelength, secondary lobes will be scattered by the roughness, thus introducing spurious signals. Side lobing is more prevalent in relatively large transducers, however, a transducer designer is able to minimize their effects by damping of transducers and other considerations.

Complete elimination of side lobes is possible if a transducer was designed in such a manner that:

$$\lambda/D = 1/1.22 \text{ or } 0.819$$

However, the smaller the ratio λ/D, the better is the collimation of ultrasonic beams, i.e., less pronounced are the effects of diffraction. Therefore, if a transducer is to produce a well-collimated beam, free from troublesome side lobes, its diameter should be much larger than the wavelength of ultrasound in the medium. For a majority of transducers, the far field diameter is always less than the diameter of the transducer. Therefore, the generation of narrow beam well-collimated transducers requires both small diameters and very short ultrasonic wavelengths. In order to get further familiarity with interference and diffraction relations, the reader should consult the tables of near field and diffraction angles for a variety of materials as functions of frequency and diameters in Appendices I and II.

Ultrasonic beam profiles can be altered by using acoustic lenses directly in front of the active piezoelectric element. A concave lens, if its focal length is shorter than the near field--far field transition, will suppress all the acoustic pressure maxima and minima towards the transducer. This will allow NDTE closer to the transducer region otherwise the "zone of confusion". Transducer focusing will obviously reduce the size of the ultrasonic beam at the focal point, thus permitting the detection of even very minute discontinuities.

In the selection of and design of ultrasonic transducers, the effects of diffraction must be fully understood vis-a-vis the specific objectives of NDTE application. With practice and experience, it will be noticed that while an ideal shape of an ultrasonic field is highly desired, it is seldom achieved. One such example of acoustic beam perfection is our laboratory's LAMBDA series transducers. In general, one has to compromise between the realities of physical acoustics and the specific test objectives.

1.5 Absorption and attenuation of ultrasound: Ultrasonic waves are attenuated and absorbed by the medium through which they propagate. The new intensity of ultrasound, i.e., after it has been transmitted through the medium is given by:

$$I_x = I_o \cdot \exp^{-(\alpha x)}$$

or

$$\ln I_o - \ln I_x = -\alpha x$$

where, I_x = the intensity of the wave after it has traversed through a material of thickness x.

I_o = the intensity of incident wave

α = a proportionality constant, known as the linear absorption co-efficient, or simply as the attenuation co-efficient.

In ultrasound, attenuation and absorption are defined by what is popularly known as the attenuation co-efficient, α. However, the mechanism is different for both of them. Attenuation is described as the energy losses of the incident ultrasonic radiation by its interaction with the material texture--inter-granular relationships. Thus, attenuation is caused by the scattering of ultrasonic waves by grain boundaries, defects, porosity and other physical heterogeneities in the material. All attenuative materials are dispersive.

Energy losses of incident ultrasound in non-dispersive or homogeneous materials such as single crystals, glasses free from secondary gaseous or solid phases, etc., may be denoted by the term attenuation. However, the mechanism of their occurrence is different. This includes the visco-elastic and damping behavior of materials.

The attenuation co-efficient and the way it is applied and determined in ultrasound is a volumetric property that takes into consideration the chemical composition as well as the texture of the material. Therefore, it is valid to conclude that the ultrasonic attenuation co-efficient is similar in principle to the mass absorption co-efficient used in electromagnetic wave absorption, i.e.,

$$I_x = I_o \cdot \exp^{-(\alpha\rho x)}$$

where, α = the linear absorption co-efficient of the wave

ρ = density of the material.

All other terms have their usual meanings.

Linear absorption in ultrasound is applicable only at small material travel distances for a particular wavelength. This is due to the alteration of propagating beam directions by diffraction. For similar reasons, mere comparisons of the amplitudes of successive reflections from a material for the estimation of "attenuation" by

$$\text{attenuation} = -20 \log \frac{A_2}{A_1}$$

where, A_2 = amplitude or voltage of a multiple reflection

A_1 = amplitude or voltage of another reflection immediately preceding A_2,

should not be regarded as a measure of accurate and precise attenuation of the wave.

In order for ultrasonic attenuation to assume a meaningful relationship with properties of a material, it must be defined as a function of frequency. A mere statement of attenuation without reference to the involved frequency is highly misleading. A general relationship of frequency dependence of ultrasonic attenuation is shown in Fig. 12.

A corollary of ultrasonic attenuation involves the measurement of transmitted frequencies, not their attenuation co-efficients, when wide bandwidth ultrasound is transmitted into a material. This phenomenon is significantly observed when a given material is investigated with a number of frequencies. Up to some frequencies, the material may be transparent; however, beyond certain frequencies, it may become opaque. This observation is analogous to the transmission of white light through materials, yielding absorption or transmission spectra. A general relationship of ultrasonic frequency transmission is shown in Fig. 13.

It is sufficient to say that the subjects of ultrasonic attenuation--absorption, scattering, and frequency transmission--are very current and need to be studied properly and thoroughly. It is no secret that this study, ultrasonic spectroscopy, holds the key to the ultimate application of ultrasound in nondestructive materials characterization.

2. ULTRASONIC METHODS AND THEIR SIGNIFICANCE

Depending upon the modes of ultrasound transmission and reception in a test material, the methods used in NDTE can be classified as follows:

2.1 Single transducer or "pulse-echo" method: A single transducer can be used simultaneously as the transmitter and receiver of ultrasound as shown in Fig. 14. This method is most widely used in NDTE. There are various ways of coupling the transducer to the test parts.

2.1.1 Direct contact: In this case the transducer is directly placed or coupled to the test material surface by a liquid couplant, such as oil, grease, glycerene, etc., Fig. 15. When the propagating ultrasound encounters a discontinuity, such as a defect, pore, solid inclusion, crack, etc., in its path, a part of ultrasonic energy is reflected by it along with a reference reflection--generally the material's bottom surface. This information is displayed on the oscilloscope screen in the form of real time rf trace, Fig. 15a.

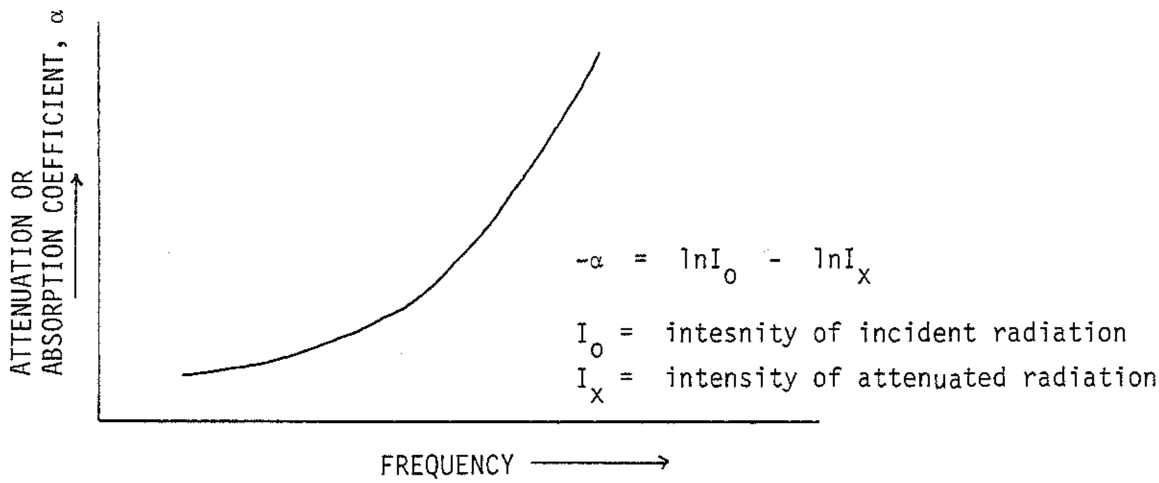

Fig. 12. A schematic relationship between frequency and attenuation or absorption co-efficient, α. Frequency dependence of attenuation.

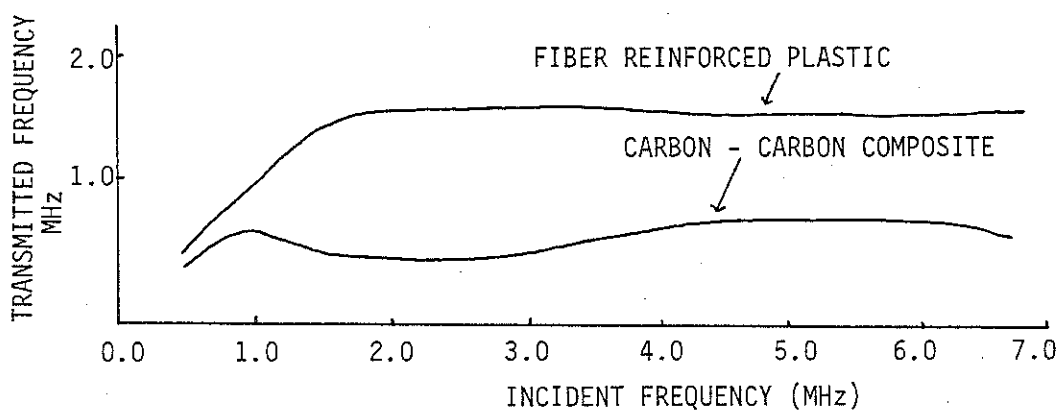

Fig. 13. Transmission of ultrasound through materials when excited by broad bandwidth ultrasonic sources.

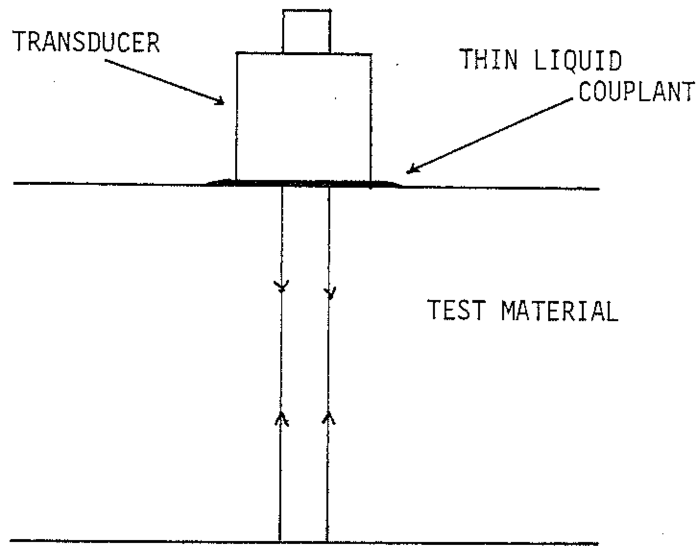

Fig. 14. Single transducer or "pulse-echo" method of ultrasonic testing.

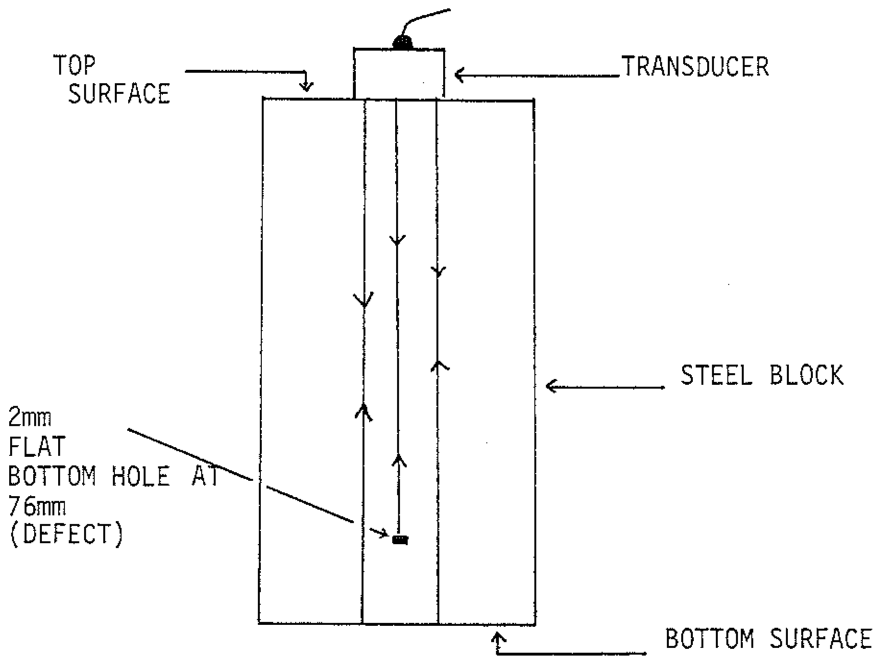

Fig. 15. Direct contact method illustrated on a reference block of steel.

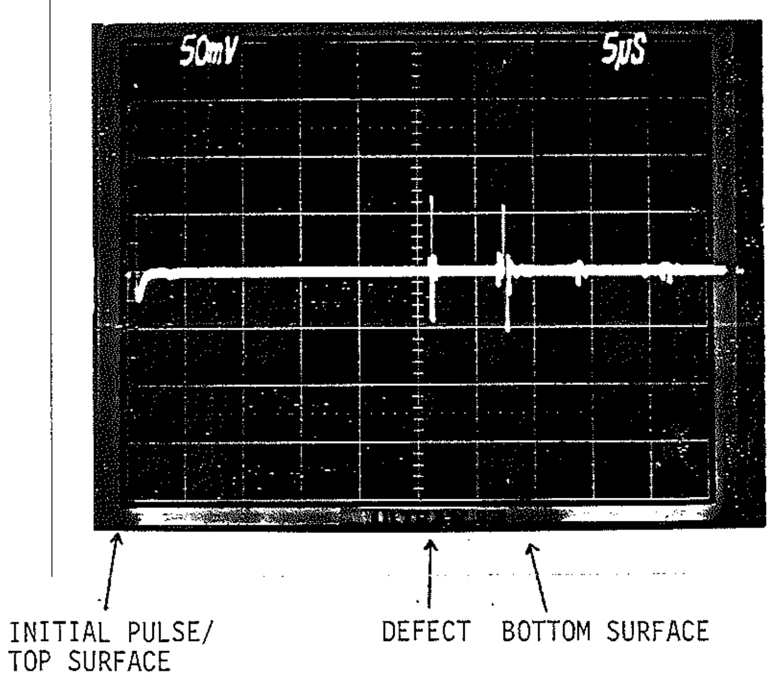

Fig. 15a. Real time oscilloscope trace of test set up in Fig. 15.

2.1.2 Solid delay line contact: In this method of coupling, first ultrasound is introduced inside a solid material such as plastic, quartz, glass, etc., by placing a liquid couplant between the transducer and the solid delay. The tip of the delay is then coupled to the test material surface, Fig. 16. The ultrasound reflected from a target in the material is displayed as real time rf trace, Fig. 16a. This method is used to gain the time/distance resolution by eliminating the interfering effects of the initial pulse of the pulser.

2.1.3 Liquid delay line contact: This method is similar to the one 2.1.2, except that the delay medium here is liquid, generally water, Fig. 17. The real time trace of this set-up is shown in Fig. 17a. This method is known as the immersion method and is widely used where free lateral and vertical motion of the transducer and automation in testing are required.

2.1.4 Angular delay contact: In order to achieve maximum ultrasonic response from a reflecting target, it is highly desired that the target--generally some defect--be perpendicular to the incident beam. However, the orientation of defects in certain materials, particularly in the welded materials, is generally less than perfect. In order to characterize such defects, the incident beam must be angulated relative to the orientation of the defect. This is done by mounting an appropriate refracting wedge, section 1.2.2. Most frequently, shear waves are used for this purpose. Longitudinal oblique incident beams may also be used for such defect characterization; however, in doing so, there are several practical difficulties. Furthermore, by virtue of the slower velocity for the shear waves in a given material, the time/distance resolution is nearly doubled when compared with the use of longitudinal waves, Figs. 18 and 18a.

Angular delay contact can also be used to generate surface waves in the test materials.

2.2 Through transmission method: In this method two transducers are placed opposite each other on the two surfaces of a test material. One transducer acts as the transmitter, while the other is the receiver, Fig. 19. If the transmitting ultrasonic beam encounters a discontinuity in its path, a portion of ultrasonic energy will be attenuated by it (discontinuity), thus reducing the amplitude of the received signal, Fig. 20. This method is not suitable for determining the location of targets 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, refractories, rubbers, etc.

2.3 Transmission and reflection or "pitch-catch" method: In this method, two transducers are placed side-by-side with one acting as the transmitter

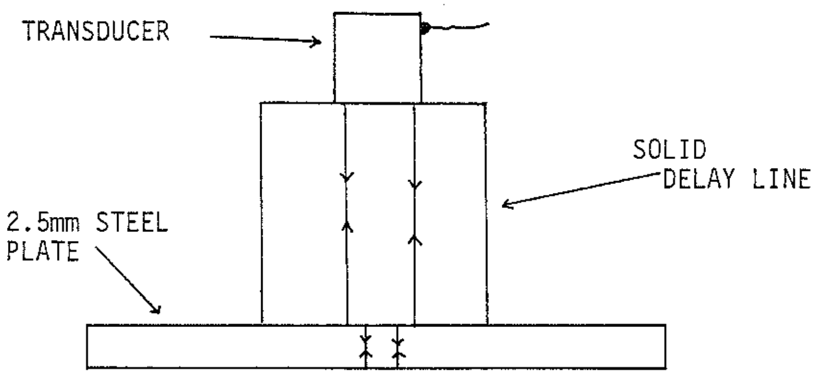

Fig. 16. Solid delay line contact method illustrated on 2.5mm steel plate.

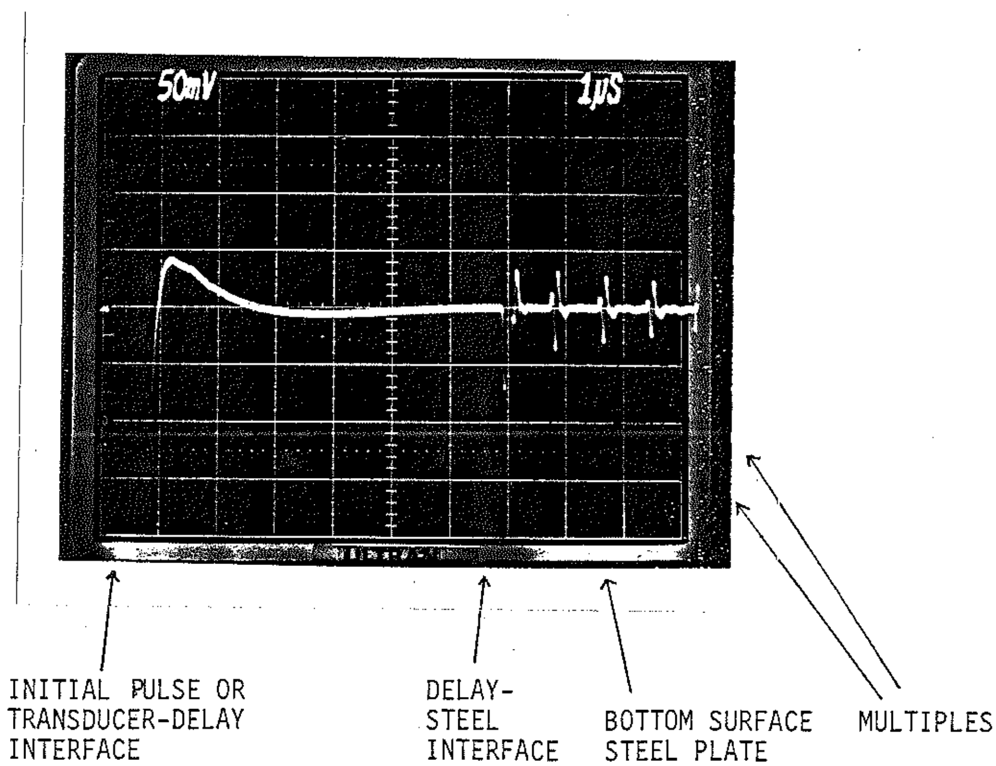

Fig. 16a. Real time oscilloscope trace of test set up shown in Fig. 16.

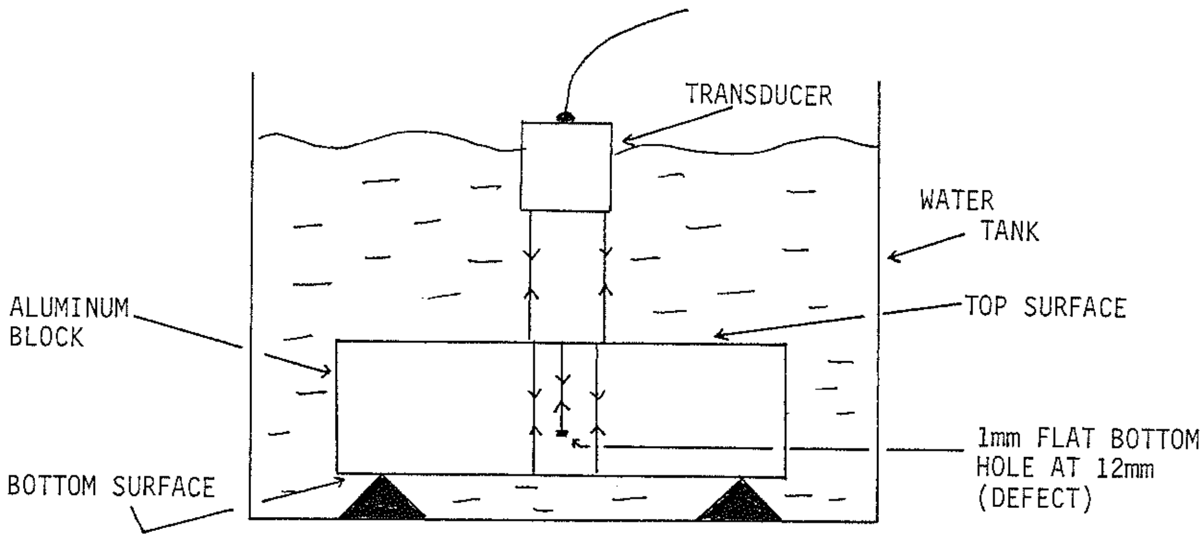

Fig. 17. Liquid delay line contact method illustrated on a reference aluminum block.

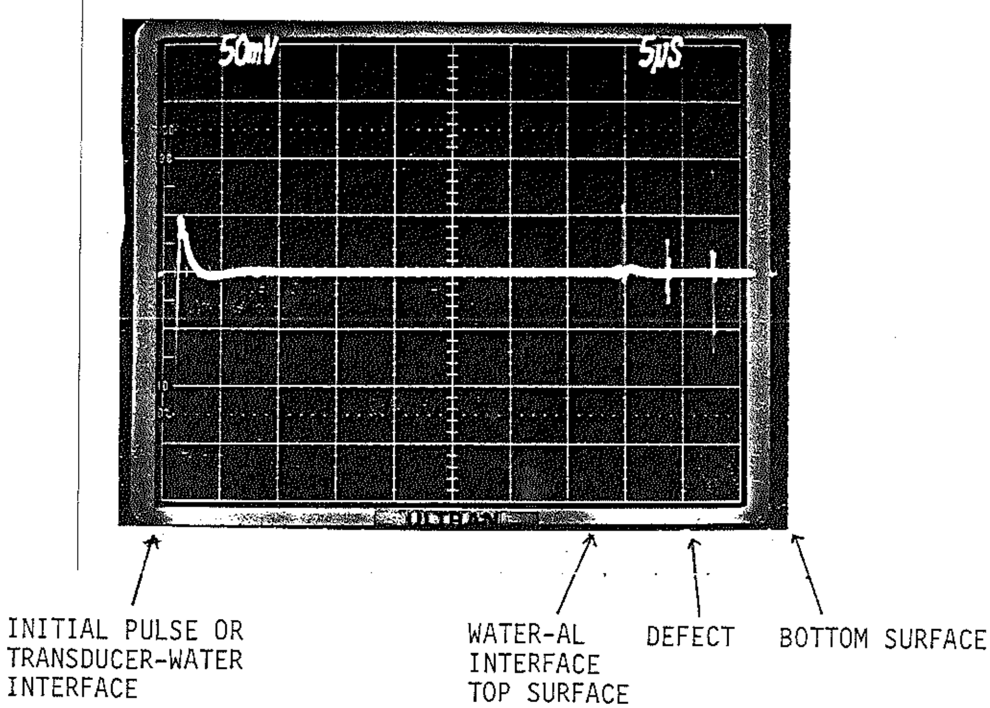

Fig. 17a. Real time oscilloscope trace of set up shown in Fig. 17.

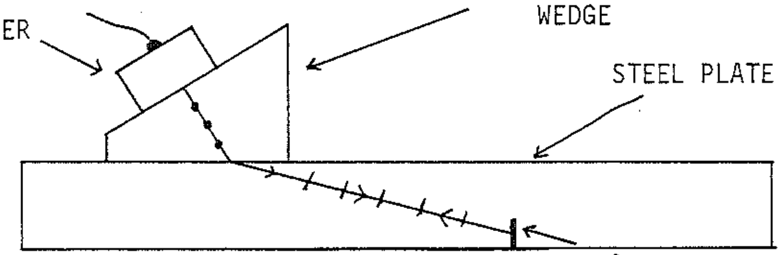

Fig. 18. Angular delay contact method illustrated on a reference steel plate with a transversely oriented defect.

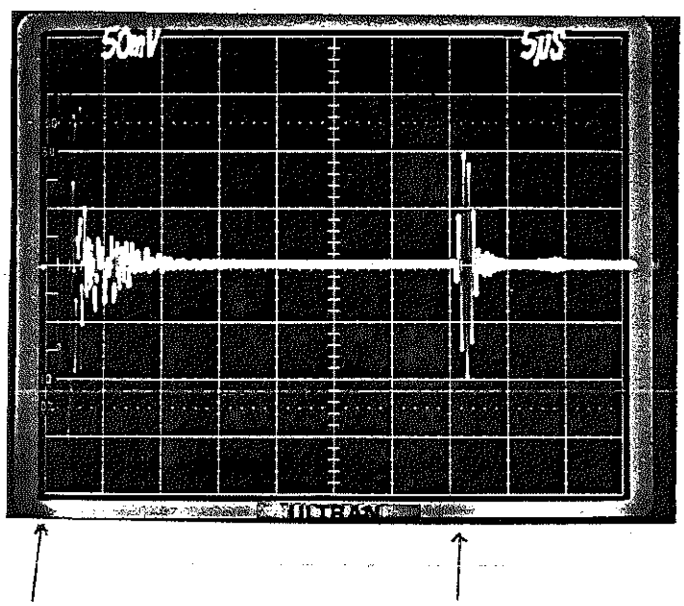

Fig. 18a. Real time oscilloscope trace of the set up shown in Fig. 18.

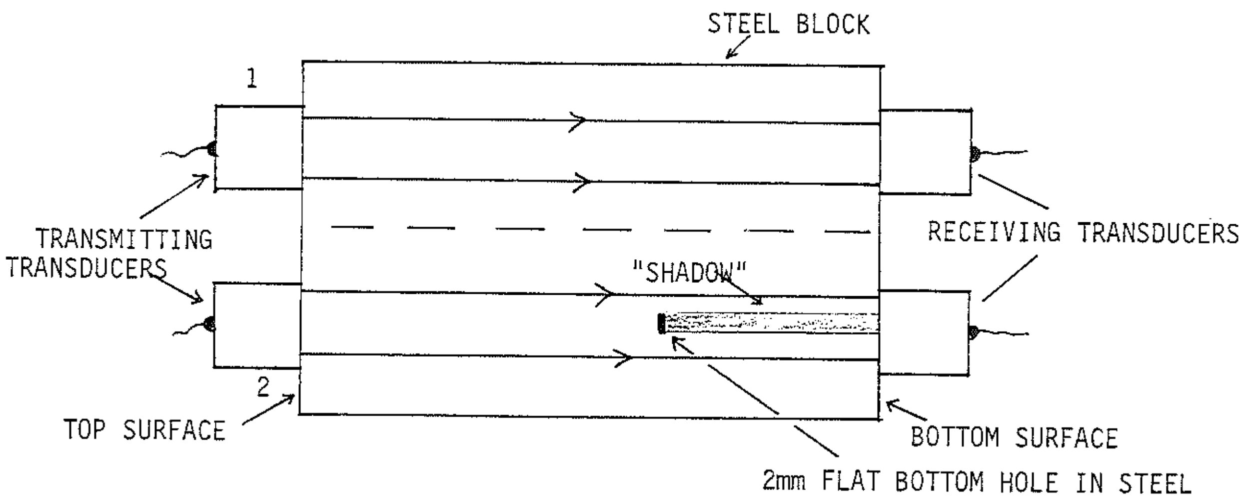

Fig. 19. Through transmission method illustrated on a reference steel block, same as the one used in Fig. 15. 1. In the defect free zone of the test block; 2. in the defect zone.

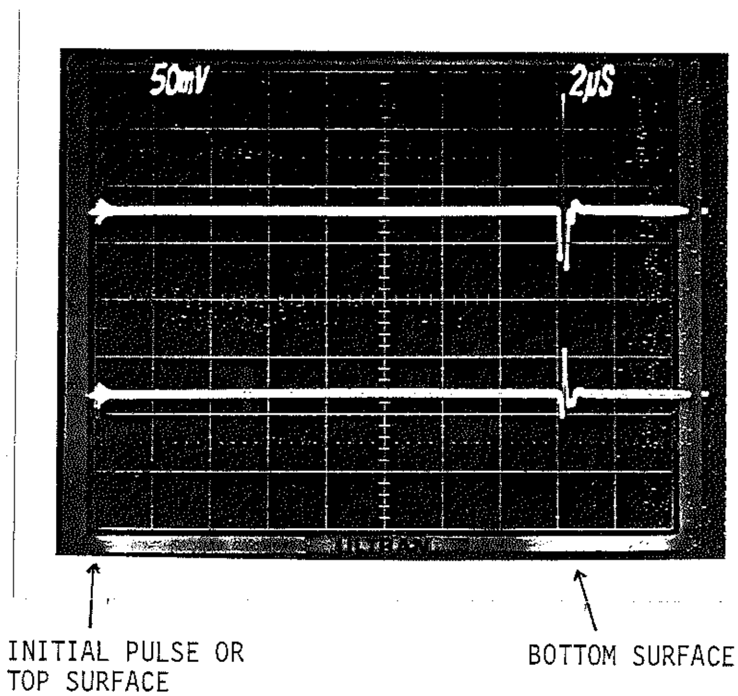

Fig. 20. Real time oscilloscope trace of the set up shown in Fig. 19. Top trace corresponds to defect free zone, and the bottom trace to the defect zone. Note the reduction in the amplitude in bottom trace caused by the "shadow" of ultrasound.

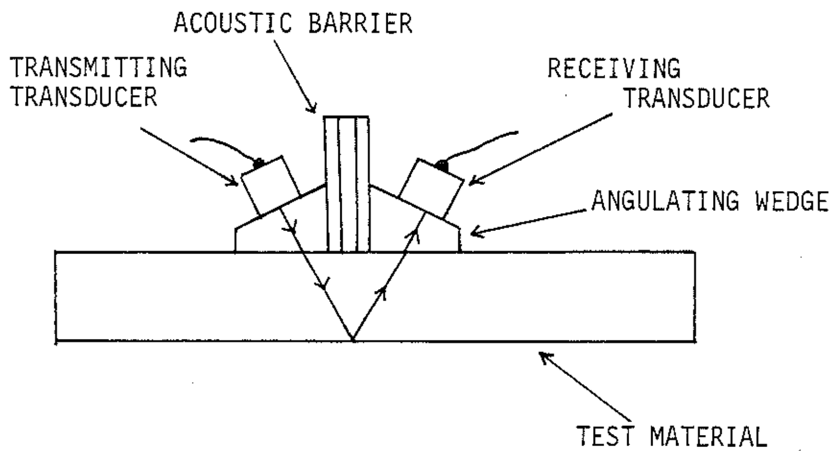

Fig. 21. Transmission and reflection or "pitch-catch" method.

and the other as the receiver. Both transducers are slightly angulated and separated by a thin wedge in order to maximize the ultrasonic response from within the test material, Fig. 21. This method is used for defect detection and thickness measurement, particularly when one of the surfaces of the test material is rough, such as in corroded parts.

3. ULTRASONIC PARAMETERS AND THEIR SIGNIFICANCE

Until recently, the most common use of ultrasound in NDT was the detection of overt flaws in materials. However, nearly a decade ago scientists at some government, university, and industrial laboratories began the task of determining the significance of ultrasonic parameters vis-a-vis material properties. While ultrasonic parameters are the material's velocities and frequency dependent attenuation, there are several material properties of interest: density, porosity, texture, elastic moduli, and engineering properties. Knowledge of engineering properties, such as the modulus of rupture, fracture strength, fatigue, etc., by reliable nondestructive testing methods would not only make confident applications of materials possible, but they would also throw light on the conditions that cause a material to fail. Since this subject is new, not much is known about the relationships between ultrasonic parameters and material properties.

3.1 Velocity of ultrasound: In section 1.1 we described three main types of ultrasound characterized by the modes of particle vibration relative to the direction of the wave propagation. These are longitudinal, shear, and surface waves. All of these velocities can be easily measured by the various methods described in section 2. They are directly related to the following various elastic constants:

a. $$v_l = \left(\frac{Y\,(1 - \sigma)}{\rho\,(1 + \sigma)\,(1 - 2\sigma)} \right)^{1/2}$$

$$= \left(\frac{K + (3/4G)}{\rho} \right)^{1/2}$$

b. $$v_t = \left(\frac{Y}{\rho} \; \frac{1}{2\,(1 + \sigma)} \right)^{1/2} = \left(\frac{G}{\rho} \right)^{1/2}$$

c. $$= 1 - \frac{8 - 8a^2}{8a^2 - 8a^4 + a^6}, \quad \text{where } a = \frac{v_r}{v_t}$$

$$= \frac{1 - 2b^2}{2 - 2b^2}, \quad \text{where } b = \frac{v_t}{v_l}$$

d. $K = \dfrac{Y}{3\,(1 - 2\,\sigma)}$

where, v_l = longitudinal wave velocity

v_t = transverse or shear wave velocity

v_r = Rayleigh or surface wave velocity

Y = Young's modulus of elasticity in the direction of measurement.

G = shear modulus of elasticity in the direction of measurement

ρ = density of the material in the direction of measurement

σ = Poisson's ratio

K = bulk modulus of elasticity.

Longitudinal and shear wave velocities are unaffected by frequency or wavelength changes in non-dispersive materials. However, the dispersion of incident radiation, within its bandwidth, may be caused by the material texture--inter-granular relationships. In general, the amount of dispersion in solids is very small; however, it is significant enough to provide useful information about the material texture.

Velocity of dispersed ultrasound can be measured by using a variety of mono-chromatic ultrasonic frequencies, each yielding a phase velocity,

$$v\,(f,\lambda) = f \cdot \lambda$$

If all the frequencies were present at the same time in the incident radiation, such as in white frequency spectra, the velocity so measured would be the material's group velocity,

$$U\,(f,\lambda) = -\lambda^2\ \delta f/\delta\lambda.$$

where f = frequency, and λ = wavelength.

Group velocity varies with frequency, f, depending upon the slope $\delta f/\delta\lambda$ which in turn is a function of v, the phase velocity. Group and phase velocities are the same in a material up to those frequencies that are not dispersed by it. Once the dispersion begins to take place, the group velocity may be dramatically affected as a function of frequency, Fig. 22. At resonant frequencies, the velocity variations are more complex.

3.2 Attenuation and absorption of ultrasound: Attenuation and absorption of ultrasound as a function of incident frequency can provide the most significant information about the material characteristics. The term attenuation applies to dispersive materials, and absorption to the non-dispersive ones. A general relationship of frequency dependence of ultrasonic attenuation is shown in Fig. 12. There are no really well-established methods of measuring the frequency dependent attenuation of ultrasound; however, some techniques are possible within the constraints of ultrasonic sources and analyzing instruments.

3.2.1 Wide band ultrasonic spectroscopy: In this method, a broad bandwidth ultrasound is scanned at discrete frequencies after it has been transmitted or reflected through the test material.

Scanning of the transmitted wave is possible, either through the introduction of high pass filters, or through the utilization of several narrow-band, discrete ultrasonic frequency receiving transducers. In both cases, the received signals are converted into their respective frequency components by a spectrum analyzer or by other fast Fourier transformation techniques.

An alternate method of wide band ultrasonic spectroscopy would be to compare and contrast the frequency domain spectra of the incident and reflected ultrasonic radiations. Here the characteristics of the incident radiation are measured from a standard stable and ultrasonically "transparent" material such as quartz glass. Fig. 23 shows the characteristics of ultrasound attenuation by aircraft quality--7075a--aluminum measured by this method.

3.2.2 Mono-chromatic ultrasonic spectroscopy: Narrow band discrete frequencies can be generated by using the tone burst method. Specific frequencies are transmitted into the test material and they are received by an equivalent accurately matched receiving transducer. Loss of energy is measured by the amplifier, which defines the attenuation or absorption of a particular frequency by the material.

Another aspect of ultrasonic spectroscopy involves selective frequency absorption or transmission of wide band ultrasound. Here, the transmitted frequencies are measured, not their attenuation co-efficients. Fig. 13 shows such a relationship for fiber-reinforced plastic and carbon-carbon composites. Such relationships are not only significant in the determination of optimum frequency response of a material for the transducer design, but they are also important in the characterization of materials analogous to optical absorption and transmission spectroscopies.

All aspects of ultrasonic spectroscopy, including transducers and analyzing instruments, need to be understood and developed further

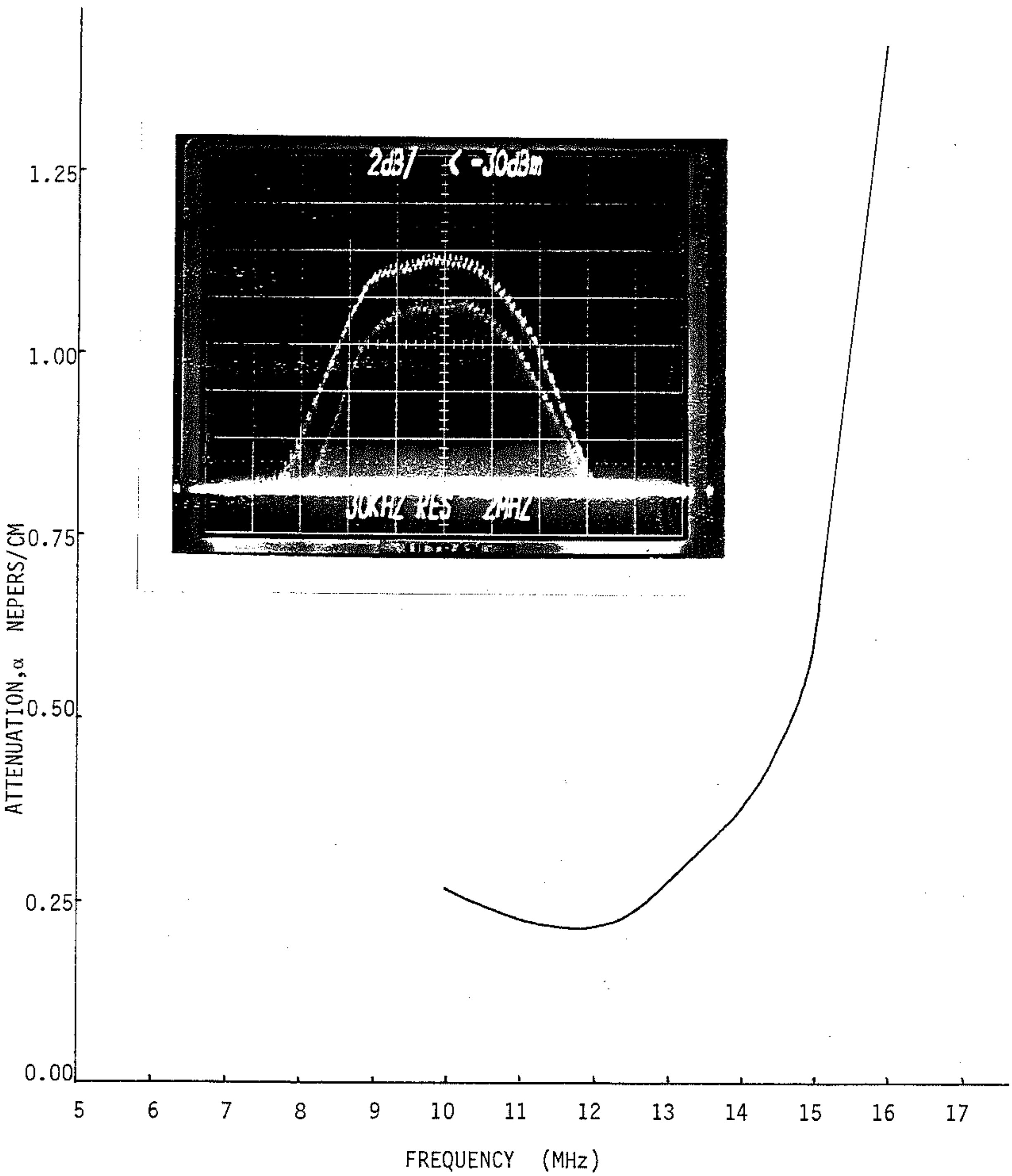

Fig. 23. Frequency attenuation by 7075a aluminum. The outer frequency spectrum corresponds to the reference spectrum from quartz glass, the inner spectrum corresponds to aluminum.

before reliability and confidence are established in their applications and interpretations. We know that in other characterization techniques--atomic absorption, optical transmission and absorption, x-ray fluorescence and absorption and many more utilizing electromagnetic waves--such relationships are fully developed, well-understood, and widely applied. Ultrasonic spectroscopy must undergo a similar treatment; otherwise, it is bound to be confined to the "scrubbers" in the metals industries.

4. ACOUSTICS OF ULTRASONIC TRANSDUCERS

As stated earlier, the source of ultrasound is the device known as the transducer. In any given application of ultrasound, the transducer is both the "mouth" as well as the "ear" of the system. Materials scientists should know that the importance of an ultrasonic transducer is as great as that of the crystal detectors used in x-ray, optical, and neutron particles analytical techniques. It is sufficient to say that the awareness of the transducer is about "90% success" in NDTE, while the remaining lies in the interpretation of ultrasonic observations.

From a practical standpoint, it is also very important to know the transducer acoustics, how they are achieved, and what their limitations are.

4.1 Transducer frequency, pulse shape, and size: Frequency of a transducer is determined by the resonance characteristics of the piezoelectric material, section 1.3, and is defined by:

$$f = \frac{fc}{t}$$

where, f = resonant frequency, fc = frequency constant of the piezoelectric material (KHz--meters, KHz--inches, or MHz--meters), and t = thickness of the piezoelectric material corresponding to the vibration direction in it.

If a piezoelectric material disc is pulsed or oscillated, it would resonate "indefinitely" yielding narrow band mono-chromatic source of ultrasound, Fig. 24. The envelope containing the resonance or ringing is called the rf envelope and the trace is known as the real time domain. At resonance the transducer has maximum energy, sensitivity, output, or loop gain.

In nearly all ultrasonic NDTE applications, it is desirable to have the "shortest" width of this envelope, thus facilitating maximum time/distance resolution corresponding to the minimum thickness of a material that can be studied at a given frequency. It is an important subject and is treated more thoroughly in the following section.

4.1.1 Damping of the transducers: In order to shorten the width of a transducer pulse, one side of the piezoelectric disc is damped in a manner similar to what a musician does with cymbals. Damping

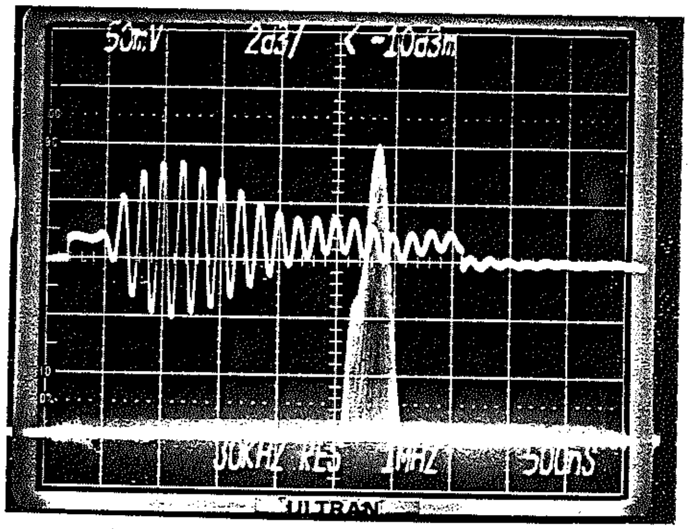

Fig. 24. Real time and frequency domain analysis of a freely resonating piezoelectric element of nominal resonant frequency, 5MHz. Note the exponential rise and slow decay of the pulse in real time trace.

Measured peak frequency: 5.7MHz
Bandwidth at -6dB: 800KHz

Pulse width or ring time: 3us.

cuts down "excess" ringing. In ultrasonic NDTE transducers, damping is very critical. While several damping models have been developed in theory, none is of real world significance. This is so, because there are nearly infinite NDTE applications and equally large numbers of test materials. Ideally, each material and each application should dictate its own specific transducer damping needs vis-a-vis the given set of test objectives. Thus, a given theoretical model of transducer damping would have limited application. In order to circumvent this problem, a transducer designer uses a flexible system of damping. It is generally composed of heavy metal--tungsten, molybdenum, nickel, iron, etc.,--immersed in an organic binder, epoxies. By varying the compaction density, the acoustic impedance of the damping, a variety of dampings are possible. This yields a variety of pulse shapes and sizes. A transducer maker considers damping an art. Actually, this phenomenon is neither properly understood, nor accurately reproduced.

Generally, a damping material must have two characteristics:

a. It should efficiently transmit excess transducer energy into its bulk.

b. It should also absorb the transmitted energy completely so that it (energy) does not rebound from the far end of the damping into the piezoelectric disc.

Obviously, these are contradictory requirements! And they become immensely difficult to obtain over a wide range of frequencies. Metal powder assists in efficient energy transmission, also scattering the wave, which is beneficial to transducer damping. The organic binder absorbs transmitted energy, thereby making difficult the path of ultrasound into the piezoelectric disc. It should be noted that if ultrasound did get reflected from the other end of the damping, it would interfere with signals from the medium of interest. By using this technique of damping, it is possible to obtain reasonable acoustics from nearly 300KHz to approximately 30MHz frequencies.

Besides the preceding problems, damping may significantly alter the resonant frequency and sensitivity of its undamped counterpart. At a given frequency, one cannot expect to increase the transducer size "at will," and expect the damped transducer to yield the desired acoustic response. Similarly, at a given transducer size, one cannot expect to increase the frequency in an unlimited manner. In such situations, besides the effects of damping on resonant frequencies, the piezoelectric material properties should also be taken into account in order to establish their limitations relative to their usable dimensions and frequencies. It is a complex subject and beyond the scope of this article. However, for the user of ultrasound, it is sufficient to bear the following in mind. See Appendix III for more general treatment of effects of damping on transducer frequency.

a. MERITS OF DAMPING

1. Reduces the excess ringing of the transducer.
2. Improves time/distance resolution.
3. Increases the signal to noise ratio.
4. Minimizes the width of the initial pulse of electrical pulser or oscillator.
5. Increases the bandwidth of the transducer.

b. LIMITATIONS OF DAMPING

1. Reduces the transducer sensitivity.
2. Distorts the frequency domain characteristics of the transducer, particularly at higher frequencies. This problem is also related to the "less-than-perfect" quality of pulsers and receivers and other electrical interactions.
3. At a given frequency, increase in transducer size reduces frequency, when compared to undamped counterparts.
4. At a given dimension, increase in frequency reduces the frequency, when compared to their undamped counterparts.

4.2 Acoustic impedance matching of the transducers: In order to obtain efficient and optimum transmission of ultrasound from the transducer into the test material, it is also important that the face of the transducer directly in front of the piezoelectric disc be acoustically matched, section 1.2. Again, ideally each test material should be "perfectly" matched to this condition. In practice, it is cumbersome. For the sake of simplicity, one can assume two types of materials: the high impedance--metals, ceramics, some composites, cermets, etc., and the low impedance--plastics, FRPs, water, tires and rubbers, lumber, etc. A special case for gaseous matching may also be considered. Acoustic impedance matching is achieved in the following manner:

4.2.1 High impedance matching: The face of the piezoelectric material is bonded to high impedance materials such as, alumina, tungsten carbide, or other super-hard materials. Such transducers when directly coupled to metals, ceramics, some composites, refractories, etc., would produce the maximum transmission of ultra sound.

4.2.2 Low impedance matching: The face of the piezoelectric material is bonded to low impedance materials, such as organic polymers. Applications of such transducers in water, plastics, rubbers, and tires, lumber, etc., would yield maximum transmission of ultrasound.

4.2.3 Gaseous impedance matching: Due to several orders of magnitude variations in the acoustic impedances of gases and the piezoelectric materials, and due to fast absorption of ultrasound in gases, it is almost impossible to imagine the transmission of ultrasound in gases. However, our laboratory's research and development of "transitional" materials of extremely low impedances has made it possible to acoustically match the transducers for reasonable transmission of ultrasound in gases as well. The matching of this sort has been achieved to such an extent that even frequencies as high as 10MHz can be transmitted into air! This development should open doors for the characterization of gases, besides having obvious uses in remote sensing and object identification in air.

4.3 Acoustical quality of transducers: Despite the variety of problems and limitations described thus far, it is possible to design a wide variety of transducers, each characterized by its own unique parameters of value in NDTE. As a guideline to the qualities of transducers required in NDTE, they can be classified as characteristic (narrow band) and white (broad band) frequencies. Examples of these two are shown for 5MHz transducers in Figures 25 and 26. A special case exhibiting near perfect acoustic response, i.e., the shortest possible pulse width and nearly flat frequency response is also shown, Fig. 27. This transducer is a new addition to the ones already known in the industry, and was developed in our laboratory about 8 years ago. Table I shows the comparison of all salient features of these transducers:

TRANSDUCER TYPE	f_n MHz	f_p Mhz	bcf MHz	bw %	pw time	SENSITIVITY dB
Characteristic frequency	5	4.8	4.8	30	1μs	- 32
White frequency	5	4.5	4.5	90	500ns	- 42
Lambda frequency	5	--	5.7	170	100ns	- 52

TABLE I. Acoustical comparison of various transducer types.

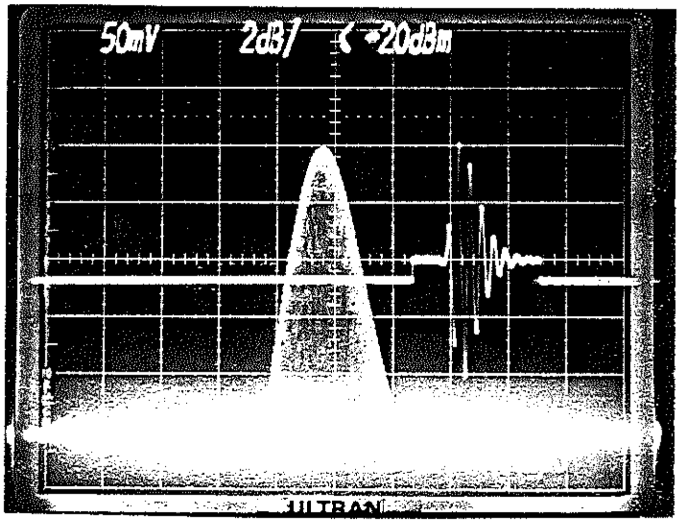

Fig. 25. Characteristic frequency transducer. A "slightly" damped version of freely resonating piezoelectric element shown in Fig. 24.

Peak frequency: 4.8MHz
Bandwidth at -6dB: 30%
Pulse width: 1us

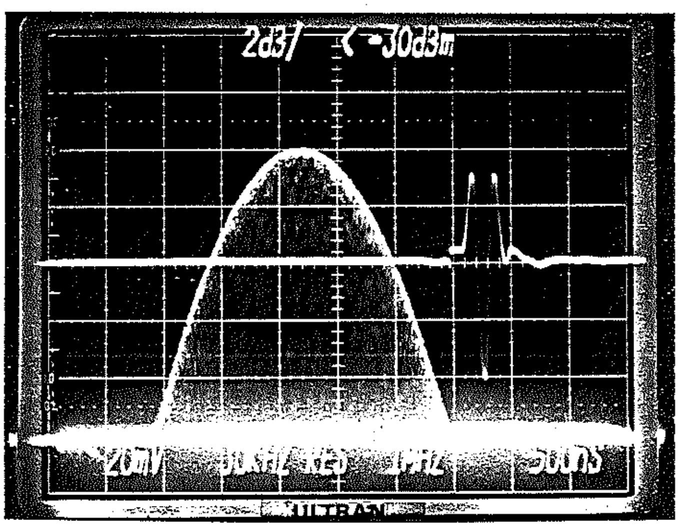

Fig. 26. White frequency transducer. A "highly" damped version of the freely resonating piezoelectric element shown in Fig. 24.

Peak frequency: 4.5MHz
Bandwidth at -6dB: 90%
Pulse width: 500ns.

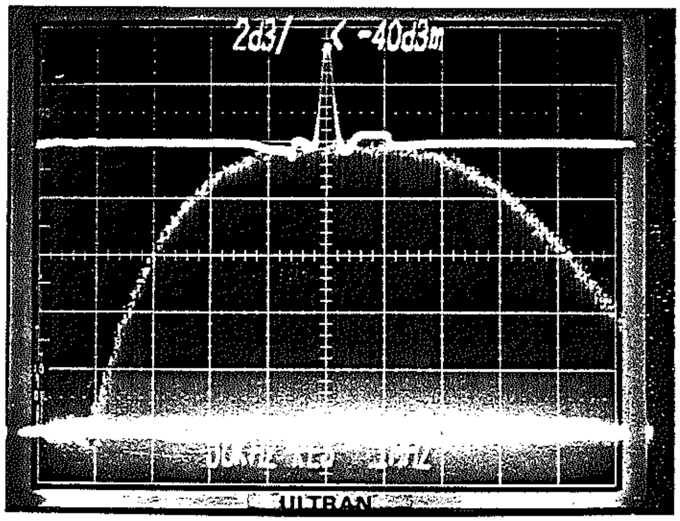

Fig. 27. A special case of piezoelectric damping - Lambda transducer - exhibiting near perfect acoustics by yielding UNIPOLAR, half wavelength pulse with an "extremely" broad bandwidth frequency spectrum.

Measured frequency: 5.7MHz
Bandwidth at -6dB: 170%
Pulse width: 100ns.

TABLE I--CONTINUED.

Features common to all transducers: Active area diameter: 6mm; nominal frequency: 5MHz.

All measurements were made in the pulse-echo mode with a water delay method and instrument layout as shown in Fig. 8.

f_n = Nominal frequency,

f_p = peak frequency measured from the frequency domain spectrum,

bcf = bandwidth center frequency; measured by averaging the lower and higher values of frequencies at -6dB points of the frequency spectrum,

bw = bandwidth of the transducer measured by subtracting the lower value of the frequency from the higher one at -6dB points of the frequency spectrum--expressed as % of bcf.

pw = pulse width of the rf envelope, measured in time from the real time oscilloscope trace, and

$$\text{SENSITIVITY (dB)} = -\log 20 \frac{V_o}{V_i}$$

where, V_o = voltage of the reflected wave. Usually taken from a standard target. In the above observations, the standard target was optically flat quartz glass surface separated by 25mm of water column,

V_i = voltage of the initial pulse, directly measured from the oscilloscope.

It is obvious from the observations in Table I and Figures 25, 26, and 27 that as the pulse width decreases, so does the sensitivity of the transducer. In practical terms, short pulse width transducers cannot be expected to produce ultrasound capable of travelling relatively longer materials distances. However, such transducers would be ideal choices for closer surface materials testing. Similarly, a broad pulse width transducer may not be suitable for near surface testing, yet it would be ideal for longer materials travel and bulk-body flaw detection.

In view of a given test material type and the objectives of NDTE, the selection of a transducer may become more complex. For example, "very" close surface testing of a powder metallurgy or of other texturally alike material may not be possible due to the inherent scattering of ultrasound by such materials. Therefore, while making a transducer selection, ultrasonic phenomenon, materials characteristics, system limitations, and method of testing have to be properly understood relative to the test objectives.

5. AREAS OF IMMEDIATE ATTENTION

While acoustic methods have been in use for materials "characterization" for a very long time, methods involving detailed and precision-oriented ultrasonics are new. For nearly fifty years, the applications of ultrasound in NDT have been largely confined to the steel and aluminum industries. Since they provided the major market share, and since their primary objective was the detection of overt flaws in metals, ultrasound until very recent times did not come to the attention of modern materials scientists. This important field of applied science is undergoing a transition and a transformation. From the practical standpoint, the majority of relationships involving "ultrasound-material" interaction are not fully developed or understood. Similarly, the hardware used in NDTE is also not fully developed. In order to explain the terms "fully developed" and "fully understood," an analogy is made with other characterization methods involving some wave phenomenon. A newcomer to ultrasound should be aware of this, while the "pioneers," in particular, those who do not know the practices of materials characterization, should look into the possibilities of refining the "art of ultrasound."

This investigator's "intense" interaction with ultrasound during the last decade has resulted in the identification of several specific and general areas needing urgent attention.

5.1 Education in ultrasound: There is a need for capable educational institutions to create disciplines within mechanical engineering, materials science and technology, and electrical engineering, in order to develop courses in both basic and applied ultrasound. The thrust of such an education should be in ultrasonic materials characterization and the development of broad-range reproducible ultrasonic hardware.

The curriculum involving NDTE engineering should include the rigorous treatment of basic ultrasound and real materials testing problems in the industry. Today a majority of such engineers are "self-made," while the rest are "trained" by the "self-styled schools of NDT." The latter have commercial connotations, thus, by definition, they are not impartial. It should be seriously noted that these individuals are involved in making important decisions concerning safety and economy for the suitability of materials in nuclear, aerospace/aircraft, petro-chemical, transportation, and other crucial industries. It is obviously highly desirable that such decisions be made by competent and realistic individuals. Formal education and training is the only answer.

5.2 Materials research: With the advent of plastic and carbon composites and "yesterday's test tube ceramic materials" in modern industry, it is all the more imperative to conduct experimental research into ultrasound to establish empirical relationships between ultrasonic parameters and material properties. While the elastic constant can be estimated with relative ease, there is an immense need to develop similar relationships with the engineering properties of materials. These should be done not only under RTP conditions, but also under extreme physical environments.

Ultrasonic spectroscopy constitutes the possibility of being the best NDTE technique for materials characterization. While theory on this subject is well-developed, the experimental side remains confusing. There is a need for the development of reproducible and unbiased methods in ultrasonic spectroscopy.

A considerable amount of industrial research involves situations caused by "panic." Materials science, being more developed, is bringing newer and newer materials for possible industrial applications. Most of these materials are compositionally and structurally complex and the industry seeks their immediate characterization through NDTE. Without the aid of previously established methods and well-defined empirical relations, it is not uncommon to find a researcher totally confused and frustrated. The only solution to this problem is the investigation by ultrasonic methods of well-characterized materials such as alumina, silica, etc. Mere examination of one or two samples, varying in a property or two, is not sufficient to make conclusions and mathematical equations!

5.3 Transducers and electronics development: An important application of modern research into ferro-electric materials is the design of transducer devices that, in principle, can operate at ultra high frequencies and at very high temperatures. Current NDTE transducer designs may not be suitable for operational devices with advanced ferro-electric materials. This needs to be further developed.

There is also the need to develop advanced reproducible ultrasonic electronics for commonly used frequencies as well as for ultra high frequency applications. Research in our laboratory has made it possible to generate extremely broad bandwidth transducers. There is a need for electronics that would fully utilize the capabilities of this transducer development.

There is confusion in the industry relative to the electrical matching of ultrasonic transducers. Before conclusions are made, this problem should be realistically addressed.

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REFERENCES

1. Leonard, B.E. and Gardner, C.G., Ultrasonic, Nondestructive Testing a survey. NASA SP-5113.

2. Jenkins, R. and DeVries, J.L., Practical X-ray Spectrometry, Phillips Technical Library, 1969.

3. Halliday, D. and Resnick, R., Fundamentals of Physics, John Wiley and Sons, Inc., 1974.

4. Vary, A., Ultrasonic Measurement of Materials Properties, in Research Techniques in Nondestructive Testing, Vol. IV, Academic Press, 1980.

5. Papadakias, E.P., In Physical Acoustics: Principles and Methods, Vol. XI, Academic Press, 1975.

6. McMaster, R.C., Nondestructive Testing Handbook, Vol. II, The Ronald Press Company, 1963.

7. Kinra, V.K. and Ker, E.L., An Experimental Investigation of Pass Bands and Stop Bands in Two Periodic Particulate Composites, Int. J. Solids Structures, Vol. 18, No. 0, 1982.

8. Goldman, R., Ultrasonic Technology, Reinhold Publishing Co., 1962.

9. Ultran Laboratories, Inc., The Advanced Ultrasound--Lambda Series Transducers, λ-701, 1984.

10. Ultran Laboratories, Inc., Dry Coupling and Air Propagation Transducers, D-500, 1984.

APPENDIX - I

NEAR FIELD DISTANCES AS FUNCTIONS OF FREQUENCIES & DIAMETERS
WATER

DIAMETER/ mm	0.5MHz		1.0MHz		2.25MHz		5.0MHz		10.0MHz	
	Y_o^+	Y_1^-	Y_o^+	Y_1^-	Y_o^+	Y_1^-	Y_o^+	Y_1^-	Y_o^+	Y_1^-
3.2	0.1	-1.1	1.3	0.1	3.6	1.6	8.3	4.1	16.8	8.3
6.4	2.6	0.2	6.4	2.6	15.0	7.2	33.5	16.6	67.3	33.5
9.5	6.8	2.3	14.8	6.8	34.0	16.7	75.7	37.8	151.6	75.7
12.7	12.7	5.2	26.4	12.7	60.2	30.0	134.4	67.1	269.2	134.4
19.1	29.7	13.7	60.5	29.7	136.1	68.1	302.3	151.6	607.1	302.3
25.4	53.1	25.4	107.2	53.1	241.8	120.9	538.5	269.2	1077.0	538.5
28.6	67.6	32.5	136.4	67.3	307.3	152.9	683.3	340.4	1366.5	680.7
31.8	83.3	40.4	167.6	83.3	378.5	188.7	838.2	419.1	1678.9	838.2
38.1	120.4	58.9	241.8	120.4	543.6	271.8	1211.6	604.5	2420.6	1211.6

APPENDIX - I CONTINUED

NEAR FIELD DISTANCES AS FUNCTIONS OF FREQUENCIES & DIAMETERS
PLASTIC

DIAMETER/ mm	0.5MHz		1.0MHz		2.25MHz		5.0MHz		10.0MHz	
	Y_o^+	Y_1^-	Y_o^+	Y_1^-	Y_o^+	Y_1^-	Y_o^+	Y_1^-	Y_o^+	Y_1^-
3.2	-0.9	-2.5	0.3	-0.8	1.8	0.5	4.5	2.1	9.3	4.5
6.4	0.5	-1.8	3.1	0.6	8.2	3.6	18.6	9.1	37.3	18.6
9.5	2.9	-0.6	7.8	2.9	18.7	8.9	42.2	20.8	84.3	42.2
12.7	6.1	1.0	14.3	6.2	33.5	16.3	74.7	37.1	149.6	74.7
19.1	15.5	5.7	33.0	15.6	75.9	37.6	168.9	84.1	337.8	168.9
25.4	28.7	12.3	59.2	28.7	134.9	67.1	299.7	149.6	599.4	299.7
28.6	36.6	16.2	75.4	36.6	171.2	84.8	381.0	189.0	762.0	378.5
31.8	45.5	20.7	92.7	45.5	210.6	104.9	467.4	233.4	934.7	467.4
38.1	66.0	31.0	134.1	66.0	304.8	151.4	673.1	337.8	1348.7	673.1

APPENDIX - I CONTINUED

NEAR FIELD DISTANCES AS FUNCTIONS OF FREQUENCIES & DIAMETERS
ALUMINUM

DIAMETER/ mm	0.5MHz		1.0MHz		2.25MHz		5.0MHz		10.0MHz	
	Y_o^+	Y_1^-	Y_o^+	Y_1^-	Y_o^+	Y_1^-	Y_o^+	Y_1^-	Y_o^+	Y_1^-
3.2	-2.9	-6.2	-1.2	-2.9	0.2	-0.9	1.7	0.4	3.8	1.7
6.4	-2.4	-5.9	0.3	-2.4	2.9	0.4	7.7	3.4	15.8	7.7
9.5	-1.3	-5.4	2.0	-1.3	7.4	2.7	17.7	8.4	36.1	17.7
12.7	0.1	-4.7	4.8	0.1	13.7	5.8	31.5	15.4	63.8	31.8
19.1	4.1	-2.7	12.9	4.1	31.8	14.9	71.9	35.6	144.3	71.9
25.4	9.7	0.1	24.0	9.7	57.2	27.4	127.8	63.5	256.5	127.8
28.6	13.1	1.8	31.0	13.0	72.6	35.1	162.3	80.3	325.1	161.5
31.8	16.8	3.7	38.4	16.8	89.4	43.7	199.4	99.3	398.8	199.4
38.1	25.7	8.1	56.1	25.7	128.8	63.5	287.0	143.5	576.6	287.0

APPENDIX - II

DIFFRACTION ANGLES AS FUNCTIONS OF FREQUENCIES & DIAMETERS
WATER

DIAMETER/ mm	0.5MHz (^{o})	1.0MHz (^{o})	2.25MHz (^{o})	5.0MHz (^{o})	10.0MHz (^{o})
3.2	-----	35.16	14.82	6.61	3.30
6.4	35.16	16.73	7.35	3.30	1.65
9.5	22.58	11.07	4.89	2.20	1.10
12.7	16.73	8.28	3.67	1.65	0.82
19.1	11.07	5.51	2.44	1.10	0.55
25.4	8.28	4.13	1.83	0.82	0.41
28.6	7.35	3.67	1.63	0.73	0.37
31.8	6.61	3.30	1.47	0.66	0.33
38.1	5.51	2.75	1.22	0.55	0.27

APPENDIX - II CONTINUED

DIFFRACTION ANGLES AS FUNCTIONS OF FREQUENCIES & DIAMETERS
PLASTIC

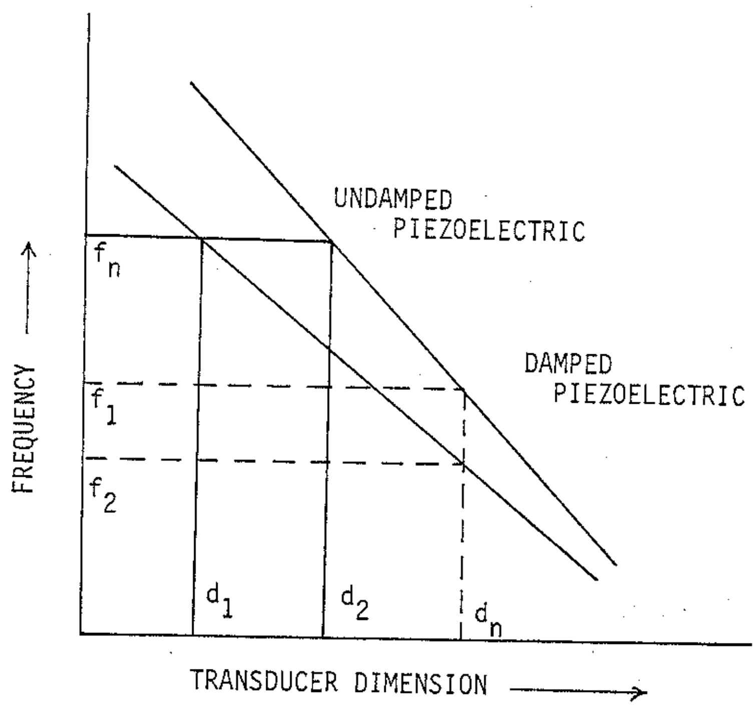
DIAMETER mm	0.5MHz (^{o})	1.0MHz (^{o})	2.25MHz (^{o})	5.0MHz (^{o})	10.0MHz (^{o})
3.2	-------	-------	27.30	11.94	5.94
6.4	-------	31.15	13.26	5.94	2.97
9.5	43.61	20.17	8.80	3.95	1.98
12.7	31.15	14.99	6.59	2.97	1.48
19.1	20.17	9.93	4.38	1.98	0.99
25.4	14.99	7.43	3.29	1.48	0.74
28.6	13.29	6.60	2.92	1.32	0.66
31.8	11.94	5.94	2.63	1.19	0.59
38.1	9.93	4.95	2.19	0.99	0.49

APPENDIX - II CONTINUED

DIFFRACTION ANGLES AS FUNCTIONS OF FREQUENCIES & DIAMETERS
ALUMINUM

DIAMETER/ mm	0.5MHz (^{o})	1.0MHz (^{o})	2.25MHz (^{o})	5.0MHz (^{o})	10.0MHz (^{o})
3.2	-------	-------	-------	28.95	14.01
6.4	-------	-------	32.47	14.01	6.95
9.5	-------	53.79	20.97	9.29	4.63
12.7	-------	37.24	15.57	6.95	3.47
19.1	53.79	23.79	10.31	4.63	2.31
25.4	37.24	17.61	7.71	3.47	1.73
28.6	32.54	15.60	6.85	3.08	1.54
31.8	28.95	14.01	6.16	2.77	1.39
38.1	23.79	11.64	5.13	2.31	1.16

APPENDIX III



Schematic relationship between frequency and dimension of undamped and damped transducers.

CASE I. Consider a frequency f_n. While this frequency is obtained by a larger, d_2 undamped transducer, for the damped version in order to obtain f_n the dimension is reduced, d_1.

CASE II. Consider a dimension d_n. An undamped transducer of this size may yield higher frequency, f_1, its damped version may reduce the frequency to f_2.