REVIEW OF ULTRASONIC TESTING TECHNIQUE

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ABSTRACT

Ultrasonic testing is based on time-varying deformations or vibrations in materials, which is generally referred to as acoustics. All material substances are comprised of atoms, which may be forced into vibrational motion about their equilibrium positions. Many different patterns of vibrational motion exist at the atomic level, however, most are irrelevant to acoustics and ultrasonic testing. Acoustics is focused on particles that contain many atoms that move in unison to produce a mechanical wave. When a material is not stressed in tension or compression beyond its elastic limit, its individual particles perform elastic oscillations. When the particles of a medium are displaced from their equilibrium positions, internal restoration forces arise. It is these elastic restoring forces between particles, combined with inertia of the particles, that leads to the oscillatory motions of the medium.

Key words: Ultrasonic testing, acoustic impedance, nondestructive evaluation (nde), transducer

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Wave Propagation

In solids, sound waves can propagate in four principle modes that are based on the way the particles oscillate. Sound can propagate as longitudinal waves, shear waves, surface waves, and in thin materials as plate waves. Longitudinal and shear waves are the two modes of propagation most widely used in ultrasonic testing. The particle movement responsible for the propagation of longitudinal and shear waves is illustrated below. In longitudinal waves, the oscillations occur in the longitudinal direction or the direction of wave propagation. Since compressional and dilational forces are active in these waves, they are also called pressure or compressional waves. They are also sometimes called density waves because their particle density fluctuates as they move. Compression waves can be generated in liquids, as well as solids because the energy travels through the atomic structure by a series of compressions and expansion movements. In the transverse or shear wave, the particles oscillate at a right angle or transverse to the direction of propagation. Shear waves require an acoustically solid material for effective propagation, and therefore, are not effectively propagated in materials such as liquids or gasses. Shear waves are relatively weak when compared to longitudinal waves. In fact, shear waves are usually generated in materials using some of the energy from longitudinal waves.

Acoustic Impedance

Sound travels through materials under the influence of sound pressure. Because molecules or atoms of a solid are bound elastically to one another, the excess pressure results in a wave propagating through the solid. The acoustic impedance (Z) of a material is defined as the product of its density (**p**) and acoustic velocity (**V**).

$$Z = pV.$$

Acoustic impedance is important in

1. the determination of acoustic transmission and reflection at the boundary of two materials having different acoustic impedances.
2. the design of ultrasonic transducers.

3. assessing absorption of sound in a medium.

Sound Propagation in Elastic Materials

An ultrasonic wave may be visualized as an infinite number of oscillating masses or particles connected by means of elastic springs. Each individual particle is influenced by the motion of its nearest neighbor and both inertial and elastic restoring forces act upon each particle. A mass on a spring has a single resonant frequency determined by its spring constant **k** and its mass **m**. The spring constant is the restoring force of a spring per unit of length. Within the elastic limit of any material, there is a linear relationship between the displacement of a particle and the force attempting to restore the particle to its equilibrium position. This linear dependency is described by **Hooke's Law**. Mathematically, Hooke's Law is written as **F =-kx**, where **F** is the force, **k** is the spring constant, and **x** is the amount of particle displacement.

The Speed of Sound

Hooke's Law, when used along with Newton's Second Law, can explain a few things about the speed of sound. The speed of sound within a material is a function of the properties of the material and is independent of the amplitude of the sound wave. Newton's Second Law says that the force applied to a particle will be balanced by the particle's mass and the acceleration of the the particle. Mathematically, Newton's Second Law is written as **F = ma**. Hooke's Law then says that this force will be balanced by a force in the opposite direction that is dependent on the amount of displacement and the spring constant (**F = -kx**). Therefore, since the applied force and the restoring force are equal, **ma = -kx** can be written**.** The negative sign indicates that the force is in the opposite direction. Since the mass **m** and the spring constant **k** are constants for any given material, it can be seen that the acceleration **a** and the displacement **x** are the only variables. It can also be seen that they are directly proportional. For instance, if the displacement of the particle increases, so does its acceleration. It turns out that the time that it takes a particle to move and return to its equilibrium position is independent of the force applied. So, within a given material, sound always travels at the same speed no matter how much force is applied when other variables, such as temperature, are held constant.

What properties of material affect its speed of sound?

Sound does travel at different speeds in different materials. This is because the mass of the atomic particles and the spring constants are different for different materials. The mass of the particles is related to the density of the material, and the spring constant is related to the elastic constants of a material. The general relationship between the speed of sound in a solid and its density and elastic constants is given by the following equation:

$$V = \sqrt{\frac{C_{ij}}{\rho}}$$

Where **V** is the speed of sound, **C** is the elastic constant, and ***p*** is the material density. This equation may take a number of different forms depending on the type of wave and which of the elastic constants that are used. The typical elastic constants of a materials include:

- Young's Modulus, **E**: a proportionality constant between uniaxial stress and strain.
- Poisson's Ratio, **n**: the ratio of radial strain to axial strain
- Bulk modulus, **K**: a measure of the incompressibility of a body subjected to hydrostatic pressure.
- Shear Modulus, **G**: also called rigidity, a measure of a substance's resistance to shear.
- Lame's Constants, **l** and **m**: material constants that are derived from Young's Modulus and Poisson's Ratio.

When calculating the velocity of a longitudinal wave, Young's Modulus and Poisson's Ratio are commonly used. When calculating the velocity of a shear wave, the shear modulus is used. It is often most convenient to make the calculations using Lame's Constants, which are derived from Young's Modulus and Poisson's Ratio. It must also be mentioned that the subscript **ij** attached to **C** in the above equation is used to indicate the directionality of the elastic constants with respect to the wave type and direction of wave travel. In isotropic materials, the elastic constants are the same for all directions within the material. However, most materials are anisotropic and the elastic constants differ with each direction.

Nondestructive Evaluation (NDE)

Nondestructive testing has been practiced for many decades, with initial rapid developments in instrumentation spurred by the technological advances that occurred during World War II and the subsequent defense effort. During the earlier days, the primary purpose was the detection of defects. As a part of "safe life" design, it was intended that a structure should not develop macroscopic defects during its life, with the detection of such defects being a cause for removal of the component from service. In response to this need, increasingly sophisticated techniques using ultrasonics, eddy currents, x-rays, dye penetrants, magnetic particles, and other forms of interrogating energy emerged. In the early 1970's, two events occurred which caused a major change in the NDT field. First, improvements in the technology led to the ability to detect small flaws, which caused more parts to be rejected even though the probability of component failure had not changed. However, the discipline of fracture mechanics emerged, which enabled one to predict whether a crack of a given size will fail under a particular load when a material's fracture toughness properties are known. Other laws were developed to predict the growth rate of cracks under cyclic loading. With the advent of these tools, it became possible to accept structures containing defects if the sizes of those defects were known. This formed the basis for the new philosophy of "damage tolerant" design. Components having known defects could continue in service as long as it could be established that those defects would not grow to a critical, failure producing size.

Present State of Ultrasonics

Ultrasonic testing (UT) has been practiced for many decades. Initial rapid developments in instrumentation spurred by the technological advances from the 1950's continue today. Through the 1980's and continuing through the present, computers have provided technicians with smaller and more rugged instruments with greater capabilities. Thickness gauging is an example application where instruments have been refined make data collection easier and better. Built-in data logging capabilities allow thousands of measurements to be recorded and eliminate the need for a "scribe." Some instruments have the capability to capture waveforms as well as thickness readings. The waveform option allows an operator to view or review the A-scan signal of thickness measurement long after the completion of an inspection. Also, some instruments are capable of modifying the measurement based on the surface conditions of the material. Cathode ray tubes, for the most part, have been replaced with LED or LCD screens. These screens, in most cases, are extremely easy to view in a wide range of ambient lighting. Bright or low light working conditions encountered by technicians have little effect on the technician's ability to view the screen. Screens can be adjusted for brightness, contrast, and on some instruments even the color of the screen and signal can be selected. Transducers can be programmed with predetermined instrument settings. The operator only has to connect the transducer and the instrument will set variables such as frequency and probe drive.Along with computers, motion control and robotics have contributed to the advancement of ultrasonic inspections. Early on, the advantage of a stationary platform was recognized and used in industry. Computers can be programmed to inspect large, complex shaped components, with one or multiple transducers collecting information. Automated systems typically consisted of an immersion tank, scanning system, and recording system for a printout of the scan. The immersion tank can be replaced with a squirter systems, which allows the sound to be transmitted through a water column. The resultant C-scan provides a plan or top view of the component. Scanning of components is considerably faster than contact hand scanning, the coupling is much more consistent. The scan information is collected by a computer for evaluation, transmission to a customer, and archiving.Today, quantitative theories have been developed to describe the interaction of the interrogating fields with flaws. Models incorporating the results have been integrated with solid model descriptions of real-part geometries to simulate practical inspections. Related tools allow NDE to be considered during the design process on an equal footing with other failure-related engineering disciplines. Quantitative descriptions of NDE performance, such as the probability of detection (POD), have become an integral part of statistical risk assessment. Measurement procedures initially developed for metals have been extended to engineered materials such as composites, where anisotropy and inhomogeneity have become important issues. The rapid advances in digitization and computing capabilities have totally changed the faces of many instruments and the type of algorithms that are used in processing the resulting data. High-resolution imaging systems and multiple measurement modalities for characterizing a flaw have emerged. Interest is increasing not only in detecting, characterizing, and sizing defects, but also in characterizing the materials. Goals range from the determination of fundamental microstructural characteristics such as grain size, porosity, and texture (preferred grain orientation), to material properties related to such failure mechanisms as fatigue, creep, and fracture toughness. As technology continues to advance, applications of ultrasound also advance. The high-resolution imaging systems in the laboratory today will be tools of the technician tomorrow.

Future of Ultrasonic testing

Looking to the future, those in the field of NDE see an exciting new set of opportunities. The defense and nuclear power industries have played a major role in the emergence of NDE. Increasing global competition has led to dramatic changes in product development and business cycles. At the same time, aging infrastructure, from roads to buildings and aircraft, present a new set of measurement and monitoring challenges for engineers as well as technicians. Among the new applications of NDE spawned by these changes is the increased emphasis on the use of NDE to improve the productivity of manufacturing processes. Quantitative nondestructive evaluation (QNDE) both increases the amount of information about failure modes and the speed with which information can be obtained and facilitates the development of in-line measurements for process control. Advanced simulation tools that are designed for inspectability and their integration into quantitative strategies for life management will contribute to increase the number and types of engineering applications of NDE. With growth in engineering applications for NDE, there will be a need to expand the knowledge base of technicians performing the evaluations. Advanced simulation tools used in the design for inspectability may be used to provide technical students with a greater understanding of sound behavior in materials. UTSIM, developed at Iowa State University, provides a glimpse into what may be used in the technical classroom as an interactive laboratory tool.

Transducer Types

Ultrasonic transducers are manufactured for a variety of applications and can be custom fabricated when necessary. Careful attention must be paid to selecting the proper transducer for the application. A previous section on Acoustic Wavelength and Defect Detection gave a brief overview of factors that affect defect detectability. From this material, we know that it is important to choose transducers that have the desired frequency, bandwidth, and focusing to optimize inspection capability. Most often the transducer is chosen either to enhance the sensitivity or resolution of the system. Transducers are classified into groups according to the application.

- **Contact transducers** are used for direct contact inspections, and are generally hand manipulated. They have elements protected in a rugged casing to withstand sliding contact with a variety of materials. These transducers have an ergonomic design so that they are easy to grip and move along a surface. They often have replaceable wear plates to lengthen their useful life. Coupling materials of water, grease, oils, or commercial materials are used to remove the air gap between the transducer and the component being inspected.
- **Immersion transducers** do not contact the component. These transducers are designed to operate in a liquid environment and all connections are watertight. Immersion transducers usually have an impedance matching layer that helps to get more sound energy into the water and, in turn, into the component being inspected. Immersion transducers can be purchased with a planer, cylindrically focused or spherically focused lens. A focused transducer can improve the sensitivity and axial resolution by concentrating the sound energy to a smaller area. Immersion transducers are typically used inside a water tank or as part of a squirter or bubbler system in scanning applications.

Contact transducers are available in a variety of configurations to improve their usefulness for a variety of applications. The flat contact transducer shown above is used in normal beam inspections of relatively flat surfaces, and where near surface resolution is not critical. If the surface is curved, a shoe that matches the curvature of the part may need to be added to the face of the transducer. If near surface resolution is important or if an angle beam inspection is needed, one of the special contact transducers described below might be used.

Dual element transducers contain two independently operated elements in a single housing. One of the elements transmits and the other receives the ultrasonic signal. Active elements can be chosen for their sending and receiving capabilities to provide a transducer with a cleaner signal, and transducers for special applications, such as the inspection of course grained material. Dual element transducers are especially well suited for making measurements in applications where reflectors are very near the transducer since this design eliminates the ring down effect that single-element transducers experience.Dual element transducers are very useful when making thickness measurements of thin materials and when inspecting for near surface defects. The two elements are angled towards each other to create a crossed-beam sound path in the test material.

Delay line transducers provide versatility with a variety of replaceable options. Removable delay line, surface conforming membrane, and protective wear cap options can make a single transducer effective for a wide range of applications. As the name implies, the primary function of a delay line transducer is to introduce a time delay between the generation of the sound wave and the arrival of any reflected waves. This allows the transducer to complete its "sending" function before it starts its "listening" function so that near surface resolution is improved. They are designed for use in applications such as high precision thickness gauging of thin materials and delamination checks in composite materials. They are also useful in high-temperature measurement applications since the delay line provides some insulation to the piezoelectric element from the heat.

Angle beam transducers and wedges are typically used to introduce a refracted shear wave into the test material. Transducers can be purchased in a variety of fixed angles or in adjustable versions where the user determines the angles of incidence and refraction. In the fixed angle versions, the angle of refraction that is marked on the transducer is only accurate for a particular material, which is usually steel. The angled sound path allows the sound beam to be reflected from the backwall to improve detectability of flaws in and around welded areas. They are also used to generate surface waves for use in detecting defects on the surface of a component.

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