Modern Ultrasonic Concepts of NDC

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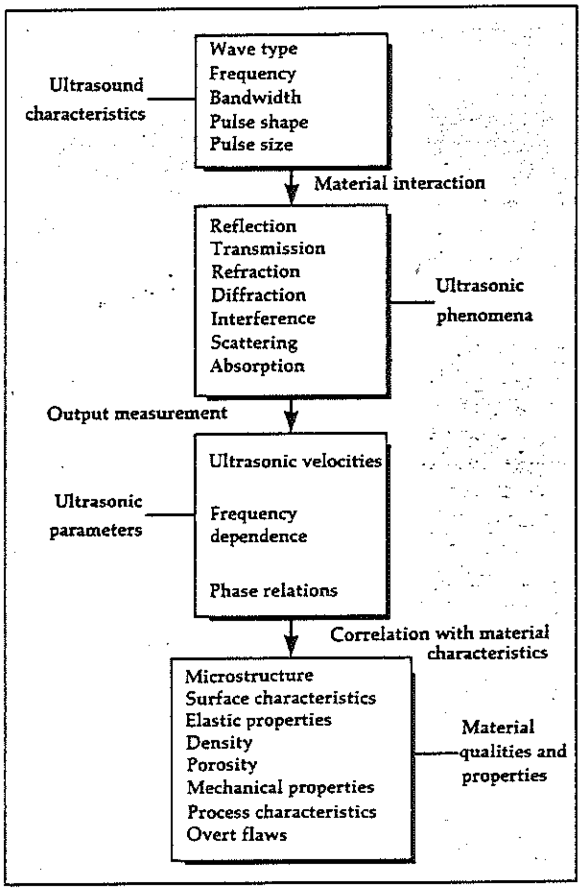
Nondestructive characterization (NDC) has become an important analytical tool in the world of materials.

New superstrength, ultralight-weight, environmentally insensitive, and cost-effective materials must be fully characterized before they can be used with confidence. Characterization is defined by the Materials Advisory Board, National Research Council as describing those features of composition and structure (including defects) of a material that are significant for a particular preparation, study of properties, or use, and suffice for reproduction of the material. Nondestructive characterization (NDC) is a way to evaluate materials without altering them. The analytical technique must not only detect overt flaws, but must be scientifically sound and provide a basis to characterize material parameters such as density, porosity, elastic and mechanical properties, and other process- and applications-related parameters.

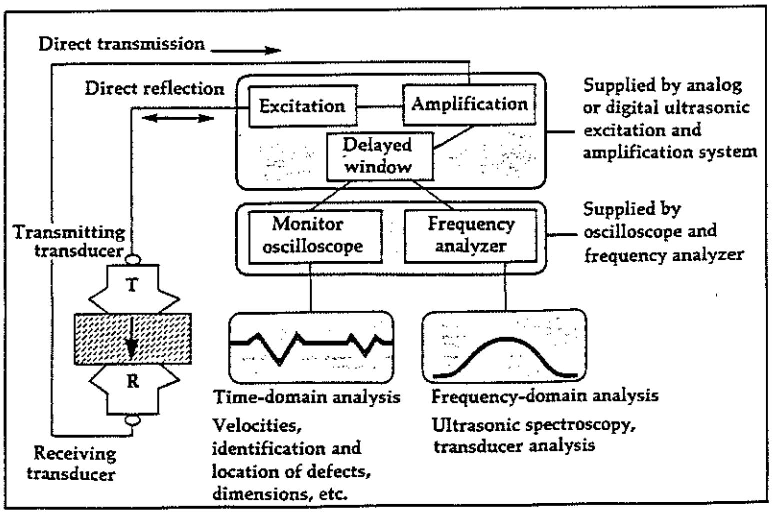
Among current NDT techniques, including visual examination, liquid penetrant examination, magnetic particle and eddy current testing, and radiography, only the ultrasonic technique is capable of providing such a wide range of information about the test material. While ultrasonic nondestructive testing is nearly 100 years old, it has become very popular with materials scientists, engineers, and physicists only during the past 15 years. The theoretical basis for ultrasonic NDC has been in existence for a long time, but the operating methods and tools needed for its practical use have only recently been developed.

Principles are well established

Ultrasonic NDC is a way of characterizing materials by transmitted ultrasound waves (longitudinal, shear, surface, and their complex components) through the materials and studying the characteristics of the transmitted waves. Wave characteristics include ultrasonic velocities and frequency dependence of ultrasonic attenuation/absorption.



Sequence of interaction of ultrasound with test material and its interpretation in terms of material characteristics.



Pulsed ultrasonic set-up for time-domain and frequency-domain analysis.

Only ultrasonic NDC is capable of providing such a wide range of information.

Sources of ultrasound are magnetostriction, electrostriction, and, most commonly, piezoelectricity. Ultrasound is generated by a piezoelectric transducer that is excited by an oscillating electrical burst or by a short electrical pulse. The majority of ultrasonic NDC is conducted by exciting the transducer with a half-cycle electrical oscillator.

Ultrasound is propagated through a material by physically coupling an excited piezoelectric transducer with the material surface. The transducer can be placed directly on the test material and coupled to it by a liquid such as oil, grease, or glycerin. Alternatively, physical coupling can be achieved through delayed buffer zones of solids such as plastic, quartz, or glass, or liquids such as water, glycerin, or oil.

Since the development by Ultran Laboratories of dry-coupling, or "self-coupling," ultrasonic devices in 1982, the use of liquid couplants for ultrasonic NDC by direct reflection or transmission is no longer mandatory. These dry-coupling devices can be placed directly on the test-material surface for efficient ultrasound propagation through the material because a solid, compliant transitional layer that is acoustically transparent is incorporated on the face of the active piezoelectric element. When ultrasonic NDC is carried out on green-stage material containing an organic binder, a dry coupling must be used because liquid coupling will damage or alter the characteristics of the material. For similar reasons, dry coupling also is used to characterize porous and other liquid-sensitive material. Dry-coupling methods have been perfected for longitudinal- and shear-wave propagation at frequencies from <200 kHz to >25 MHz. There are limitations to these methods, however. For example, dry-coupling devices cannot be slid over a test material's surface; also, they cannot be used effectively when the material's surface is too rough.

It also is possible to propagate high-frequency ultrasound through gaseous media. Transducers with very high efficiencies and low acoustic impedances for this application were also developed by Ultran in 1982, and ultrasound up to 10 MHz has been successfully propagated through air. However, despite the relatively high frequency of the ultrasound propagated through the gaseous media, the transmitted frequencies are much lower. For example, the optimum high-frequency transmission through air is approximately 1 MHz; beyond this frequency, ultrasound undergoes excessive attenuation. The immediate and potential uses of ultrasound propagation through gaseous media are remote sensing, object identification, noncontact dimensional and proximity analysis characterization of gases, and measurement of turbulence.

The frequencies used in ultrasonic NDC range from <50 kHz to >100 MHz, but specific frequencies should be determined for a given test material and the test objectives. However, as a rule, denser materials can be examined with frequencies between 2 and >50 MHz, and coarser grained and attenuative materials with frequencies between 100 kHz and >1 MHz. The most commonly used range for all ultrasonic NDC is from <500 kHz to >20 MHz.

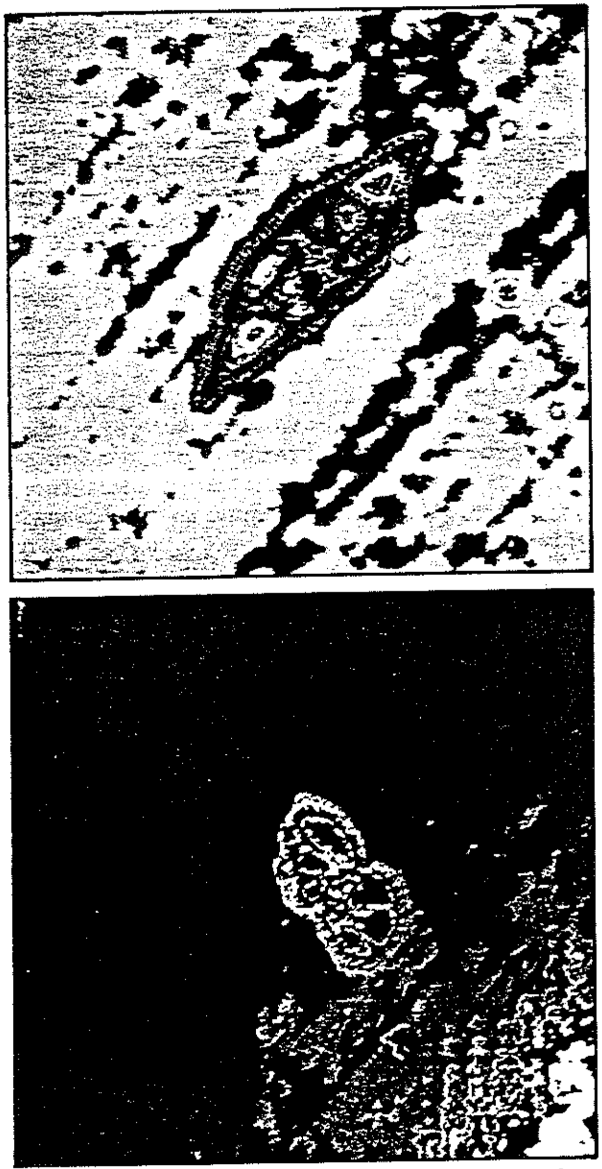
The optimum ultrasonic frequency is the highest acceptable for given material that still results in minimal attenuation. Analysis of a material at frequencies beyond its optimum creates an ultrasonic attenuation spectrum that is directly related to the test material's texture, composition, and atomic structure. When examining such relationships, it is very important that proper wavelength and scattering-target relations be established.

While higher frequencies usually provide greater resolution, indiscriminate incremental increases of frequency do not always provide increased resolution. Short-pulse-width transducers, such as Ultran's λ-series, can yield very high resolutions without resorting to frequencies greater than 20 MHz.

The most important parameter in ultrasonic NDC is not the frequency of the transducer, but its pulse width. Transducer-pulse width is the distance occupied by a resonating transducer in the time-domain ultrasonic trace on an oscilloscope and can be denoted in either time or wavelength units. Optimum transducer-pulse width establishes optimum resolution and accuracy of a given measurement, and creates a "clean" ultrasonic signal. As the transducer-pulse width decreases, its sensitivity and output also decreases; frequency should be reduced when this occurs.

The acoustic impedances of a transducer and the test material should be closely matched to increase the efficiency of ultrasound propagation from the transducer to the material. The impedance of a transducer may have to be modified somewhat to achieve matching because the acoustic impedances of test materials vary dramatically relative to those of usable piezoelectric materials. Modification is achieved by implanting one or more suitable layers of materials on the faces of piezoelectric elements. Thicknesses of matching layers are controlled by the wavelength, λ, and, for high-quality transducers, are generally about $\lambda/4$. The most frequently used matching layers are low-impedance polymers and high-impedance ceramics. The polymers are used to facilitate analysis of low-impedance materials such as polymers and their composites, while the ceramics are used for high-impedance materials such as metals and ceramics, and their composites. Transducer matching layers, in addition to improving the transducer's efficiency, also protect the fragile piezoelectric elements.

Ultrasound also experiences interference and diffraction in its propagation medium, analogous to those phenomena occurring in electromagnetic waves. The field within the interference zone (near zone) is quasicollimated,



Two views of impacted region in a graphite-fibre-reinforced plastic composite 1.4 mm thick. View obtained by high-resolution ultrasonic scanning system (Ultran NDC 7000) shows damaged area (blue) approximately 6 mm long, top. View obtained with same scanning system, but generated by monitoring ultrasonic scatter from the internal regions of the composite, bottom.

while in the diffraction zone (far zone), it is diffracted or diverged. The extent of the near field and of the diffraction region at the far field are direct functions of the transducer dimensions and the wavelength of ultrasound in its propagation medium. At the transition point of these zones, the acoustic pressure, or the intensity of ultrasound, is at its peak. For the most accurate and reliable ultrasonic NDC, the field of ultrasound should be well-collimated, and the examination should be carried out within approximately ±30% of the near-field and far-field transition zones.

An ultrasonic field emanating from a planar piezoelectric transducer can be focused by implanting an "acoustic lens" on the piezoelectric element. Focused ultrasound is predominantly used with water as the coupling medium, but it also is possible to focus ultrasound without using liquid media by implanting appropriately focused buffer rods on the active ultrasonic transducers. Focusing effects are most pronounced within the near zone. Ultrasound cannot be truly focused in the far zone. However, any attempt to increase the focal length beyond the transition zone of a planar transducer will result in restructuring of the diffracted beam. Such restructuring techniques are used when the thickness of a test material is well-beyond that of the transition zone.

Originally, ultrasound was used to detect overt flaws in metals.

Wide-ranging information is revealed

Originally, ultrasound was used to detect overt flaws in metals. However, the information about a test material yielded by the characteristics of the waves transmitted through it also includes density, elastic and mechanical properties, dimensional analysis, particle size, porosity, corroded areas, and bonded/disbonded areas. Ultrasonic scanning of a material can be used further to generate nondestructive microscopic images corresponding to the test material's surface and internal features. The key to ultrasonic NDC is correlating acoustic observations with those of the test-material characteristics.

Because ultrasonic NDC methods are applicable to a wide range of materials, it is important to classify them in ultrasonic terms in order to establish guidelines for proper transducer selection, as well as to enhance the knowledge of this subject. One ultrasonic parameter that can be used to classify a material into a broad category, is the velocity, or wavelength, of ultrasound transmitted through it. The bulk of current ultrasonic NDC applications concerns metals, and use frequencies between 2 to 10 MHz because metals do not vary significantly in their compositions, microstructures, and physical properties. However, conventional, as well as advanced ceramics and composites, vary dramatically in their compositions and textures. Therefore, while a given set of ultrasonic parameters may be useful in metals testing, it may not be applicable to more complex materials.

For example, a ceramic in the green stage is an entirely different material from that in the ~~sintered stage, yet it is desirable to characterize~~ it nondestructively in both forms. Similarly, porous composites and dense composites are characterized by very different sets of ultrasonic properties. Also, the acoustic characteristics of metals and their oxides, nitrides, carbides, and borides vary dramatically. For example, the velocity of ultrasound in aluminum is 6,325 m/s (20,750 ft/s), while the velocity in its oxide is 11,000 m/s (36,090 ft/s).

Ultrasonic NDC is performed by studying the time and frequency domains corresponding to the ultrasound transmitted through a test material. In time-domain ultrasonics, the signal typically is represented on an oscilloscope and is known as real-time rf trace. The horizontal and vertical axes of such traces represent time and

Ultrasonic classification of ceramic materials

Ultrasonic classification	Material category (velocity range)	Example material (velocity, wavelength)[1]
Short-wavelength materials	Highly porous, large-grain, and generally attenuative ceramics and refractories, and green-stage materials **(<400 to 4,000 m/s)**	Alumino-silicate foam **(584m/s, 0.584mm)**
Medium-wavelength materials	Relatively nonporous fibrous and particulate composites, relatively dense and medium-grained ceramics, glasses and green-stage materials **(4,000 to 7,000m/s)**	Float glass **(5815m/s, 5.81mm)**
Long-wavelength materials	Nonporous superhard and superdense oxides, nitrides, carbides, and borides of metals and nonmetals and their composites **(7,000 to >12,000m/s)**	BeO substrate **(12,000m/s, 12.0mm)**

[1] *All wavelengths were measured by using 1.0-MHz frequency.*

amplitude of the transmitted signal. Material characterization information that can be obtained by time-domain ultrasonics includes the velocities of longitudinal and shear waves, elastic properties, identification and location of defects and their dimensions, dimensional analysis, phase relations, and boundary conditions in layered media.

Characteristics of basic acoustic transducers

Series	Frequency range	Bandwidth, % at -6db
W	<100 kHz to >25 MHz	50-100
P	<500 kHz to >25 MHz	40-70
K	<100 kHz to >20 MHz	20-50
M	<100 MHz to >100 MHz	30-100
λ	<500 kHz to 30 MHz	100-300
GA	<1 MHz to 100 MHz	100-200

Conversion of a sinusoidal time-domain ultrasonic signal into its frequency coordinates generates what is known as the frequency domain of that signal. This analysis is performed by Fast Fourier Transformation (FFT) of a real-time signal by an analog spectrum analyzer or by mathematical analysis of digitized signals. This method of analysis is known as frequency-domain ultrasonics, or ultrasonic spectroscopy. Because the intrinsic nature of a material — composition, atomic structure, and texture — is sensitive to the frequency characteristics of input ultrasound, ultrasonic spectroscopy (analogous to optical spectroscopy) can yield extremely important information about the test material. It is possible to determine frequency dependence of ultrasonic attenuation/absorption as a function of various test-material properties such as grain size, anisotropy, fracture strength, and grain growth.

Ultrasonic spectroscopy methods have been by the introduction of the λ-series of transducers, which are characterized by nearly flat ("white") frequency response. Investigation of ultrasound transmitted from a λ-series transducer through a material can relatively easily determine various types of microstructural information. For example, because ultrasonic attenuation increases with increasing particle size in a composite, a plot of attenuation *vs* particle size for a particular reinforcement/matrix combination can be used to investigate particle-size variations in production composites.

One of the simplest correlations is that of ultrasonic longitudinal-wave and shear-wave velocities to test-material characteristics such as density, porosity, and elastic properties. For example, the velocities of both waves increase with increasing material density, and with the availability of dry-coupling transducers, the densities of both green and sintered compacts can now be easily determined with ultrasonics.

There are several other applications of ultrasonic NDC. By investigating the time-domain and frequency-domain ultrasonic signals obtained from a material, it is possible to characterize liquid and crystalline solubility in the

Pulse width,λ	Relative sensitivity	Applications
1-2	Moderate-low	Resolution and velocity
2-4	Moderate-high	General purpose
3-6	Very high	Deep penetration
1-6	Moderate-high	VHF
0.5-1	Low-moderate	VH res. and Spec.
0.5-1	Very low	Surface def. and VH res.

material, as well as to investigate processes such as polymerization and crystallization.

Suitable transducers are keys to success

The key to the success of any ultrasonic NDC application is the selection of a suitable transducer — one with optimum frequency response, pulse width and shape, and the dimensions of the active transducer that most closely satisfy the objectives of the application. NDC transducers are characterized by their controlled acoustic and field parameters. The availability of a wide range of transducers is essential, particularly considering the diversity of materials examined by ultrasound. Transducer characteristics are achieved through the use of modern piezoelectric materials such as lead zirconate-lead titanate, lead metaniobates, polymer piezoelectrics, and other advanced ferroelectric materials.

Transducer characteristics also may vary from one test material to another, even when the experimental setup is held constant. This is because each material is characterized by its own specific response to the input ultrasonic parameters. For example, a 1-MHz input frequency through 1-cm (0.4 in.) thick specimens of quartz glass, carbon steel, stainless steel, and acrylic is likely to transmit exactly 1 MHz. However, if a 25-MHz frequency is input through these materials, the transmitted ultrasound may not correspond to the input frequency; in one experimental setup, quartz glass emitted 25 MHz, carbon steel emitted 21 MHz, stainless steel emitted 17 MHz, and acrylic emitted 8 MHz. With the reduced frequency response from these materials, the strength of transmitted signals also is reduced. When frequencies higher than an optimum frequency are used for a given material, the transmitted signals are distorted. The degree of such distortion is determined by the magnitude of discrepancy between the optimum and higher-than-optimum frequencies. When this happens, interpretation of ultrasonic observations becomes cumbersome and accuracy of measurements is reduced. This distortion phenomenon is called "material dependence of frequency attenuation," and is useful in understanding and establishing optimum ultrasonic parameters for a given material's analysis.

Experience shows that when problems, such as loss of ultrasound penetration, decrease of resolution and detectibility, and appearance of "ghost signals," are encountered, modifications in transducer characteristics generally will solve such problems. ■

Transducer characteristics for selected test materials

Test material category	Frequency range, MHz	Pulse width, wavelength (λ)
Super hard and dense metal and nonmetal oxides, nitrides, carbides, and borides and their composites; high-silica glasses; most single crystals.	<5 to >100	0.5 to 3
Nonporous fibrous and particulate composites, dense ceramics; medium-grained materials; metals; glasses.	<2 to >20	0.5 to 3
Refractories (granular and porous), concretes, porous fiber and particulate composites, lumber and wood products, and viscoelastic materials.	<0.1 to >2	2 to 6
Gases	<10	3 to several

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