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Mel Schwartz

NONDESTRUCTIVE EVALUATION

MAHESH C. BHARDWAJ
SecondWave Systems
Boalsburg, PA

INTRODUCTION

Ultrasound is widely used in health care for noninvasive diagnostics and in industry for nondestructive testing. In the human body, it generates visual images from inside the test medium: the fetus, malignant tissue, stones, etc. In industrial applications, besides defect detection, ultrasound is also useful for determining significant material characteristics such as density, thickness, mechanical properties, and level sensing. Knowledge of ultrasonically analyzed information is important for human health as well as for cost-effective production of quality industrial materials.

Ultrasound operates on the same principle as other characterization methods also based on wave–material interactive phenomena, such as optical, X ray, infrared,

Table 1. Categories of Ultrasonic Measurements and Their Applications

Measurement Category	Measured Parameters	Applications
Time domain	Times-of-flight and velocities of longitudinal, shear, and surface waves	Density, thickness, defect detection, elastic and mechanical properties, interface analysis, anisotropy, proximity and dimensional analysis, robotics, remote sensing, etc.
Attenuation domain	Fluctuations in reflected and transmitted signals at a given frequency and beam size	Defect characterization, surface and internal microstructure, interface analysis, etc.
Frequency domain	Frequency dependence of ultrasound attenuation, or ultrasonic spectroscopy	Microstructure, grain size, grain boundary relationships, porosity, surface characterization, phase analysis, etc.
Image domain	Time-of-flight, velocity, and attenuation mapping as functions of discrete point analysis by raster C-scanning or by synthetic aperture techniques	Surface and internal imaging of defects, microstructure, density, velocity, mechanical properties, true 2-D and 3-D imaging.

Raman spectroscopy; nuclear magnetic resonance; and neutron, γ-ray, and mass spectrometry. By propagating a wave in a given medium, useful information about the medium can be generated by analyzing the transmitted or reflected signals. Ultrasound differs from other wave-based methods because it does not require sample preparation, is nonhazardous, and provides the means to determine mechanical properties, microstructure, imaging, and microscopy. Ultrasonic equipment is also portable and cost-effective. Most significantly, ultrasound is applicable to all states of matter, except plasma and vacuum. Furthermore, propagation of ultrasound in a material is not affected by its transparency or opacity. Table 1 provides a comprehensive introduction to ultrasound measurements and to the information revealed either directly or through correlation with measurements.

Since about 1980, both ultrasound and its applications have grown substantially. Uses in industry have gone beyond overt defect detection in metals to include characterization of elastic and mechanical properties; delaminations in multilayered, particulate and fibrous materials; proximity and dimensional analysis; measurements of anisotropy and heterogeneity; surface profiling, chemical corrosion, crystallization and polymerization; liquid and gas flow metering; imaging of surface and internal features of materials; viscosity of liquids; texture and microstructure of granular and cellular materials; applied and residual stresses; high temperature, pressure, and radiation environment applications; and robotics, artificial intelligence. These highly desirable applications have attracted the attention of a wide range of industries: structural and electronic materials and components manufacturers, aircraft and aerospace, chemical and petroleum, plastics and composites, lumber and construction, highways and aircraft landing strips, bridges and railroads, rubber and tire, food, and pharmaceutical products.

In medical diagnostics where the sophistication of ultrasound is more advanced than in industry, it can replace harmful X rays in many critical instances. Ultrasound is useful for visualizing a fetus, measuring the cornea, tissue characterization, imaging of plaque in arteries and gum disease, brain wave measurements, monitoring of the heart beat, skin and breast cancer detection, blood flow metering, etc.

In 1980, we were content if ultrasound could detect a 1-mm defect and 0.5-mm resolution in a given test material. Today, after much R&D, we have developed short-pulse and high-frequency transducers by using advanced electronics and signal processing to the point that we can measure resolution and detectability in the micrometer range. Obviously, ultrasound has come a long way since the discovery of piezoelectricity by Pierre and Jacques Curie in 1876 (1) and its first application by Richardson in 1913 for sonar (2).

Ultrasound and its applications have grown phenomenally in recent years, but the mode by which it is propagated in a given test medium is severely limited. Due to extremely high attenuation of ultrasound by air, its transmission in a test medium is done by physically contacting (coupling) the transducer to the test medium. Therefore, all conventional ultrasound has the severe limitation of physical contact between the transducer and the test medium by a liquid gel (3). If this contact could be eliminated, then we could diagnose burnt or malignant skin damage without discomfort to the patient. Similarly, a number of industrial materials sensitive to liquid contact could be tested to measure thickness, density, mechanical properties, defect detection, etc. This is significant in ensuring materials quality and process control and for cost-effective production. The development of a noncontact ultrasound (NCU) mode would allow many more useful applications of ultrasound. For example, using NCU, characteristics of materials that are porous and hygroscopic could be determined. Similarly, materials in the early stages of formation (uncured plastics, green ceramics, and powder metals) and those that are continuously rolled on a production line (plastics, rubber, paper, construction, and lumber) could also be tested under manufacturing conditions. NCU could also be applied to medical problems where contact with a patient can be harmful, as in the evaluating wounds and diagnosis of the eye.

However, for NCU to become a reality, we first need transducers and electronic systems sensitive enough to transmit and detect ultrasound without contact with the test medium. And herein lies a big problem. Conventional wisdom stipulates that ultrasound (from ~200 kHz to >5 MHz) cannot be propagated through solids or liquids without physical contact between the transducer and the test medium. Therefore, NCU has been generally considered an impossible dream due to the phenomenal mismatch of acoustic impedance between the coupling air and the test media. This mismatch can run as high as six orders of magnitude when we consider propagation of ultrasound from air to materials such as steels, superhard alloys and dense ceramics, cermets, diamond, and diamond-like materials. To realize the NCU mode, this barrier of acoustic impedance must be broken. And for this to happen, it is imperative that ultrasonic transducers be characterized by phenomenally high sensitivity. Achieving NCU is analogous to *"throwing a helium-filled rubber balloon so that it can pierce a stainless steel wall!"*

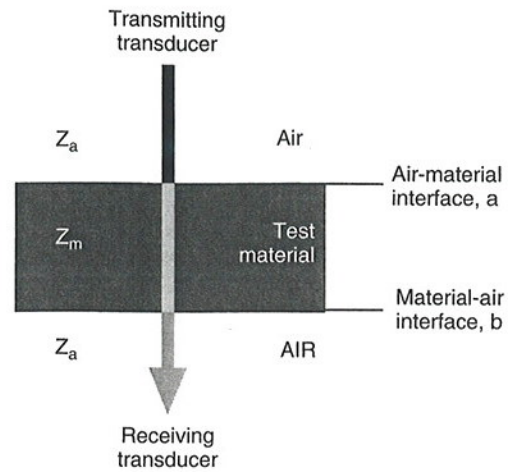


Figure 1. Interfaces to be crossed by ultrasound (shown by arrow) in the noncontact transmission mode to propagate ultrasound through a test material. Interface "a" corresponds to air–material (from acoustic impedance Z_a to Z_m) transmission. Interface "b" corresponds to material–air (from acoustic impedance Z_m to Z_a) transmission

REALITY THAT DEFIES NONCONTACT ULTRASOUND

The exorbitant mismatch between the acoustic impedance of the coupling medium, air, and that of the test material generates enormous resistance to ultrasound propagation in materials. This, in conjunction with the extremely high attenuation of ultrasound (in MHz region) by air, further compounds the problem of the NCU mode. In simple terms, when ultrasound travels from a medium of low acoustic impedance to one of high acoustic impedance, only a fraction of the energy is transmitted in the latter. The fraction of ultrasound transmission and energy transferred at the air-material interface is given by

$$T \text{ (Transmission coefficient in the propagation medium)} = 4Z_1Z_2/(Z_1+Z_2)^2 \quad (1)$$

where Z_1 is the acoustic impedance of the ultrasound carrier medium (for example, air for the NCU mode) and Z_2 is the acoustic impedance of the test medium. The transmission coefficient is derived as the ratio of transmitted acoustical energy V (measured in volts) and the input energy V_0 of a plane wave when refracted at 0° incidence on the interface between the two media:

$$T \propto V^2/V_0{}^2 \quad (2)$$

This relationship can also be described by a decibel scale:

$$T = 20\log V/V_0\,(\text{dB}), \quad (3)$$

$$\text{Energy transferred in the propagative medium} = 20\log T\,(\text{dB}). \quad (4)$$

For more details and the significance of plane wave transmission and reflection at a number of interfaces in terms of acoustical pressure and intensity, see (4).

Ultrasound in noncontact transmission must propagate from air into the test material and then again into air so that the transmitted wave can be detected by a receiving transducer (Fig. 1). Therefore, the high energy loss at the air–material interface is doubled by further loss at the material–air interface. Table 2 provides the transmission

Table 2. Transmission Coefficients and Energy Transfer in Selected Materials at Various Interfaces in the Noncontact Mode, per Fig. 1. As a Reference, Similar Data for Water Are Also Shown. Z (air) = 440 Rayl; Z (water); 1.5 Mrayl; 1 Rayl = kg/m² s.

Material Z_m (Mrayl)	Interface (Fig. 1)	Transmission Coefficient [Eq. (1)]		Energy Transfer [Eq. (4)] (dB)		Total Energy Loss at Interfaces $a+b$ (dB)	
		In Air	In Water	In Air	In Water	In Air	In Water
Steel	Air – steel, *a*	0.000034	0.11	−89	−19	178	38
51.0	Steel – air, *b*	0.000034	0.11	−89	−19		
Aluminum	Air – aluminum, *a*	0.0001	0.3	−79	−10	158	20
17.0	Aluminum – air, *b*	0.0001	0.3	−79	−10		
Acrylic	Air – acrylic, *a*	0.0005	0.84	−66	−1.5	132	3
3.5	Acrylic – air, *b*	0.0005	0.84	−66	−1.5		
Silicone	Air – rubber, *a*	0.018	0.96	−35	−0.35	70	<1
rubber	Rubber – air, *b*	0.018	0.96	−35	−0.35		
1.0							

coefficients and energy losses in selected test materials in the noncontact ultrasound mode calculated by using Eqs. (1) and (4). As a reference, similar losses for water immersion (contact technique) are also provided. The following conclusions can be drawn from the data:

1. Transmission losses decrease as the acoustic impedance of the test material comes within the vicinity of that of the coupling medium, whether it is air or water.
2. Total energy loss at various interfaces in the noncontact transmission mode can run as high as six orders of magnitude compared to similar losses by using water as the coupling medium.

While conducting this exercise, we did not address the issues of the interrogating frequency of the transducer and the frequency dependence of ultrasound attenuation by air. When these factors are combined with the inherent loss of ultrasound energy at various interfaces in the NCU mode, the problem of noncontact transmission in solids is only exacerbated. Relatively speaking, the attenuation of ultrasound in air is intrinsically high compared to that in solids and liquids. And because attenuation in a medium increases as a function of the fourth power of the frequency, transmission of megahertz frequencies in air becomes almost incomprehensible. To overcome these NCU-defying realities, first we need to create ultrasonic transducers that have high sensitivity (or very low insertion loss). Sensitivity is needed to overcome interfacial transmission losses (Table 2) and also to facilitate transducer excitation by relatively low power voltages. This will help avoid unwanted heating of transducers and their subsequent destruction. Once optimum sensitivity is achieved, we can increase the transducer frequency to make it comparable to that used in conventional contact testing. Accomplishing this task has captivated the imagination of materials and transducer researchers.

PURSUIT OF NONCONTACT ULTRASONIC TRANSDUCERS

A few researchers have tried to develop noncontact material characterization by using wave phenomena, which include optics, thermal, infrared, X ray, and nuclear magnetic resonance. In pursuit of bulk ultrasonic wave propagation in 1963, White (5) reported generating elastic waves in solid materials by momentarily heating a material surface. This technique eventually led to the development of the thermographic method which has been used for surface and subsurface imaging of composites, metals, etc. by sensing minute temperature fluctuations as a function of material texture, microstructure, defects, and other variables. This method has been applicable to those materials that can sustain heat or emanate heat during the testing.

Next came laser-induced ultrasound (6) that was used to characterize Rayleigh waves in metals (7) and for subsurface materials evaluation (8). The laser-based method has been applied to those materials that can withstand the impact of a high-power laser beam. Laser-based ultrasound has become acceptable for high melting point metals and ceramics. The nondestructiveness of this laser-based ultrasound method is questionable when analyzing heat and shock-sensitive materials, such as polymers, green ceramics and powder metals, pharmaceutical and food products, and tissue. Ultrasound generated by electromagnetic acoustic transducers has been used in the NCU mode for nondestructive testing (9). This method is applicable only to ferromagnetic materials.

Table 3. Transmission Coefficients and Energy Transferred in Air as a Function of the Final Acoustic Impedance Matching Layer on the Piezoelectric Element. As a Reference, Similar Data Are Also Shown Using Water as the Coupling Medium. Z (air): 440 Rayl; Z (water): 1.5 MRayl.

Final Layer on Piezoelectric Element Z (Mrayl)	Transmission Coefficient, T		Energy Transferred, $20 \log T$ (dB)	
	In Air	In Water	In Air	In Water
Bare piezoelectric, PZT, 31.0	0.00006	0.17	−85	−15
Hard epoxy, 4.0	0.0004	0.79	−68	−2
Silicone rubber, 1.0	0.001	0.92	−58	−0.7
Porous rubber, 0.9	0.002	0.94	−54	−0.5
[a]Pressed fiber, 0.1	0.018	–	−35	–

[a]Worldwide patents pending and in process.

The various noncontact analytical methods outlined do provide useful information about the test materials. However, all of them are limited to specific materials and are partially destructive, complex, or expensive. The difficulty of propagating ultrasound in test media by the noncontact mode, as shown in Table 3, presents limited alternatives for achieving this mode in practical terms. These involve the techniques of ultrasound generation based upon true production of ultrasound, so that its propagation in the test medium is not affected by its (medium) exclusive properties.

Researchers and transducer experts have been designing piezoelectric devices by manipulating the acoustic impedance transitional layers in front of the piezoelectric element. In the materials industry, one of the early applications of noncontact ultrasound was testing Styrofoam blocks by using a 25-kHz frequency (10). A precursor to high-frequency, noncontact transducers was the 1982 development of piezoelectric dry coupling longitudinal and shear wave transducers up to 25-MHz frequency. Since 1983, these transducers have been commercially available for characterizing the thickness, velocity, and elastic and mechanical properties of green, porous, and dense materials (11–13). Dry coupling transducers feature a solid compliant and acoustically transparent transitional layer in front of the piezoelectric materials such as lead metaniobates and lead zirconate–lead titanate. These devices, which eliminate the use of a liquid coupling agent, do require contact with the material.

An important by-product of dry coupling devices was the development of air/gas propagation transducers, which use less than a 1-Mrayl acoustic impedance matching layer of a nonrubber material on the piezoelectric material. These

commercially available transducers have been successfully produced in planar and focused beam configurations for transmitting ultrasound in air up to ~5 MHz frequency and receiving up to 20 MHz. Air/gas propagation transducers, between 250 kHz to ~5 MHz, quickly found applications in aircraft/aerospace industries for imaging and for defect detection in fibrous, low- and high-density polymers, and composites. For such applications, these transducers have been used with high energy or tone burst excitation and high signal amplification systems. However, for applications such as level sensing and surface profiling, the low energy spike or square wave transducer excitation mechanism has been sufficient.

Similar transducers of 1-MHz and 2-MHz frequency were also produced at Stanford University by using silicone rubber as the front acoustic impedance matching layer (14). By using such a transducer at 1 MHz, the distance in air could be measured from 20 to 400 mm at an accuracy of 0.5 mm. Further improvements in transduction efficiency were shown by planting an acoustic impedance matched layer that is composed of tiny glass spheres in the matrix of silicone rubber on piezoelectric elements (15,16). Researchers at Strathclyde University (17) have reported air-coupling transducers based on piezoelectric composites between 250-kHz to 1.5-MHz frequencies. By using tone burst transducer excitation, they have been successful in producing millivolt level transmitted signals through a composite laminated honeycomb structure at 500 kHz.

More recently, piezoelectric transducers featuring perfect acoustic impedance matched layers for optimum transduction in air have been successfully developed from <100 kHz to 5 MHz (18).[1] The sensitivity of these new transducers in air is merely 30 dB lower than their conventional contact counterparts. As a result, ultrasound in the megahertz region can be easily propagated through practically any medium, including even very high acoustic impedance materials such as steel, cermets, and dense ceramics. This advancement, the major focus of this paper, is discussed in detail along with the various medical and industrial applications in the noncontact ultrasound mode.

Air-coupled transducers based upon capacitance (electrostatic) phenomena have also undergone substantial developments in recent years. Researchers at Kingston and Stanford Universities have successfully produced micromachined capacitance air transducers; the latter claim a high 11-MHz frequency (19,20). These transducers that are characterized by high bandwidths have been used to evaluate composites and other materials. Ultrasound experts at the University of Bordeaux, have reported generating and detecting Lamb waves in the noncontact mode in anisotropic viscoelastic materials by using capacitive transducers (21).

Though much progress has been made in enhancing the transduction efficiency of transducers based on piezoelectric and capacitive phenomena, from a practical standpoint these advancements have by no means reached a saturation point. In the subsequent sections of this article, we describe the successful development of piezoelectric transducers that are characterized by extraordinarily high sensitivities in the frequency range from 100 kHz to 5 MHz. The evidence of the high sensitivity of these new transducers can be seen from the fact that even very high frequencies such as 2–5 MHz can be propagated through a number of solids in the NCU mode.

[1]U.S. and international patents pending and in process.

PIEZOELECTRIC TRANSDUCERS FOR UNLIMITED NONCONTACT ULTRASONIC TESTING

The efficiency of an ultrasonic transducer depends on the coupling coefficients and other electromechanical properties of the piezoelectric material. It also depends on the mechanism by which ultrasound is transferred from the piezoelectric material to the medium in which ultrasound needs to be propagated. In the noncontact mode, this medium is air. Because the acoustic impedances of piezoelectric materials are several orders of magnitude higher than that of air, it is usually necessary to implant transitional (acoustic impedance matching) layers of various materials in front of it (the piezoelectric material). Ultimately, the characteristics of the final layer determine the transduction efficiency of a transducer device. The significance of the final acoustic impedance matching layer in the noncontact transducers cannot be overemphasized. Because the properties of a given piezoelectric material can be considered constant for a given device, the ultimate transfer of ultrasonic energy in air is entirely controlled by the acoustic characteristics of the final matching layer on the piezoelectric material (Fig. 2). To understand this, we examine the effect of the final acoustic impedance matching layer on the piezoelectric material with respect to transmitting ultrasound from it (piezoelectric element) to air, as per Eqs. (1) and (4). Table 3 shows the transmission coefficients and the transfer of ultrasonic energy in air as well as in water (as a reference) by assuming a number of final acoustic impedance matching materials on the piezoelectric material. The following conclusions can be drawn from the data:

1. The transmission coefficient in air increases as the acoustic impedance of the front layer on the piezoelectric material is reduced.

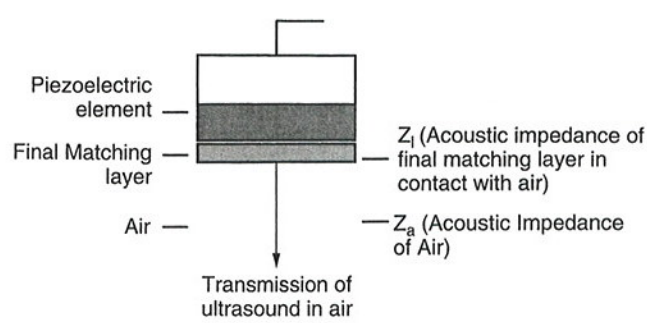


Figure 2. Schematic of an ultrasonic transducer showing the critical final acoustic impedance matching layer relative to the piezoelectric element and the coupling medium, air.

2. There is a significantly high transfer of ultrasonic energy in water compared to that in air due to better acoustic impedance matching of the final layer on the piezoelectric element with that of water.

In the light of (14–17) and this author's 1983 design (commercially available as air/gas propagation transducers from Ultran Laboratories), the best final piezoelectric matching layer for maximum ultrasound transmission in air is composed of soft polymers. The polymer layer in these transducer designs can be porous or nonporous or can have embedded hollow spheres (in the polymer layer). For the sake of simplicity, we will identify all polymer acoustic impedance matched layer transducers as air-coupled (AC) transducers. These transducers yield a −58 to −54 dB transfer of ultrasonic energy in air, which is significant for propagating up to ~2-MHz ultrasound in some solids in the noncontact mode. For example, by using a suitable transducer excitation mechanism and high received signal amplification, ultrasound can be transmitted in low acoustic impedance materials (typically materials that are lower than ~3 Mrayl) by using AC transducers. However, ultrasound propagation by such transducers in materials >3 Mrayl is arduous, if not impossible.

The AC transducers based on polymer matching layer transducers do demonstrate the feasibility of noncontact ultrasound, but they are far from the most efficient. To enhance transduction efficiency in air, this author has been developing and applying a number of low acoustic impedance final matching layer materials since 1978. In 1995, we produced and evaluated (18) a transducer that had compressed fiber as the final matching layer. For the sake of simplicity and comparison, we will identify them as noncontact (NC) transducers. This transducer design exhibited unprecedented and phenomenal transduction in air which was found sufficient for NCU transmission in practically all material types. Perfected in 1997, the NC transducers can increase ultrasonic energy transfer from the transducer to air from −54 dB (AC transducers) to −35 dB; see Table 2 (18). An increment of sensitivity by an order of magnitude is extremely significant and warrants special attention. After initial trials at 200 kHz, 500 kHz, 1 MHz, and 2 MHz, NC transducers have been produced up to ~8 MHz. However, from a practical standpoint, it has been shown that they propagate up to 5-MHz ultrasound in nearly all material types in the NCU mode in ambient air. Leaving aside transmission in plastics and composites, the sensitivity of NC transducers is also high enough for transmission in materials that have extremely high acoustic impedance such as steel, dense ceramics, and cermets. In the following sections, we provide detailed observations about NC transducers and their sensitivity compared to AC types.

Transducer Characterization Scheme

NC transducers, like their contact or water-coupled counterparts, can also be characterized in the transmission or in the reflection (pulse-echo) modes. Figure 3 shows the setup for characterizing transducers in the transmission mode which is used to analyze NC and AC transducers. Here, the

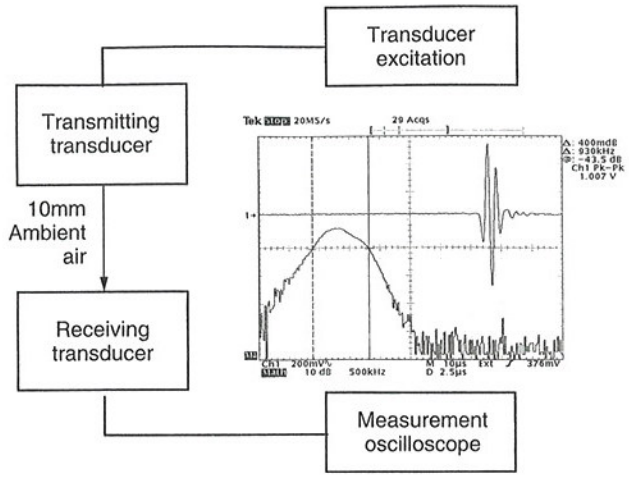


Figure 3. Noncontact ultrasonic transducer characterization scheme in transmission mode. Frequency, bandwidth, pulse width, and signal-to-noise ratio are read directly from the oscilloscope. Sensitivity = 20Log (V_x/V_0). V_0 = Excitation in volts. V_x = Received signal amplitude in volts.

transmitting and receiving transducers are aligned and separated by a 10-mm (or more, depending on the transducer frequency) column of ambient air. In this case, the transmitting transducer is excited by a pulse of known voltage, V_0. The output from the receiving transducer is directly fed into a measurement oscilloscope that has a mechanism to measure the frequency domain characteristics. Frequency and bandwidth are measured directly from the frequency domain envelope, and V_x, the received signal amplitude in volts, and the pulse width are measured from the time domain RF trace. The signal-to-noise-ratio (SNR) is determined by the following relationship when measurements are made without signal averaging. It is understood that while doing so, the instrument and cable noise also factor into the measurement.

$$\mathrm{SNR} = 20 \log V_x/V_n \,(\mathrm{dB}), \tag{5}$$

where V_n is the amplitude of the noise in volts. Sensitivity (insertion loss) is determined by

$$S = 20 \log V_x/V_0 \,(\mathrm{dB}). \tag{6}$$

By using this characterization scheme, several NC transducers were analyzed in ambient air. Figures 4–7 show typical time and frequency domains for 200-kHz, 1.5-MHz, 3.0-MHz, and 5.0-MHz NC transducers and their salient acoustic characteristics.

Sensitivity Comparison of NC and AC Transducers with Conventional Contact Transducers

Because sensitivity is the most critical requirement for NC or AC transducers, it is important to develop some kind of comparison scheme. To this effect we chose conventional contact, water immersion transducers as a reference. A number of NC transducers were characterized for sensitivity in the transmission mode according to Fig. 3. Similar

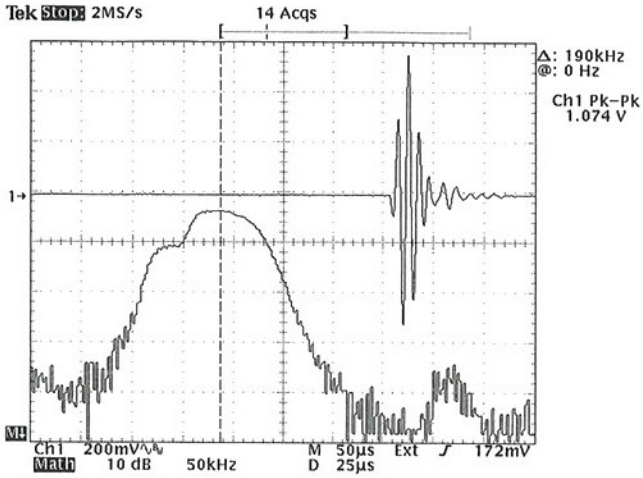


Figure 4. Time and frequency domain of broadband 200-kHz, 50-mm active area transducers in transmission mode. T–R air separation: 100 mm. Bandwidth center frequency: 200 kHz. Bandwidth at −6dB: 100 kHz (50%). Pulse width: <20 μs. Sensitivity: −46 dB. SNR: 50 dB.

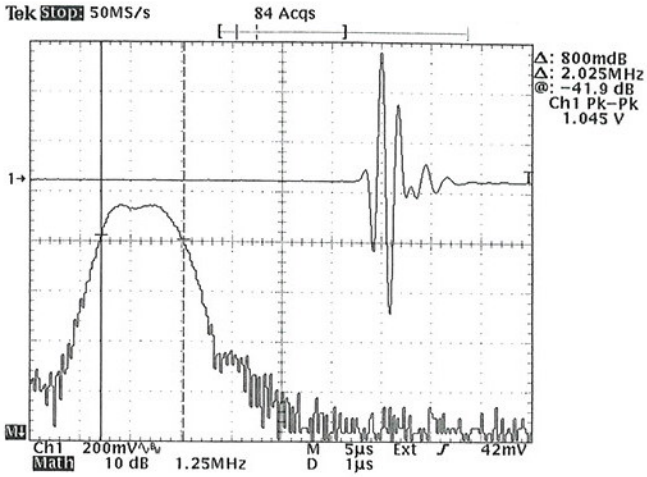


Figure 6. Time and frequency domain of broadband 3.0 MHz, 12 mm active area transducers in transmission mode. T–R air separation: 10 mm. Bandwidth center frequency: 2.6 MHz. Bandwidth at −6 dB: 2.0 MHz (75%). Pulse width: <700 ns. Sensitivity: −62 dB. SNR: 40 dB.

transducers, suitable for conventional contact water immersion operation where acoustic impedance matches that of water, were characterized in water for sensitivity measurements. The setup for such transducer characterization is the same as in Fig. 3, except that in this case the 10-mm air column was replaced by a 10-mm column of water. Sensitivities for both transducer types, calculated according to Eq. (6), are shown in Table 4. From this comparison, it is quite clear that the sensitivity of the new noncontact transducers is approximately 30 dB below their contact counterparts. AC transducers were approximately 50 dB below their conventional contact water immersion counterparts.

Application Related Experiments and Sensitivity Comparison

In the previous section, we demonstrated the high sensitivity of new NC and AC transducers by analyzing them according to a transducer characterization scheme and by comparing them to similar observations of conventional contact transducers. Although this comparison provides substantial evidence of the superiority of NC transducers over the AC types, it still does not present a convincing argument. Graphical evidence is needed to prove this point. To this effect, we performed several application-related experiments aimed at propagating ultrasound in an NCU

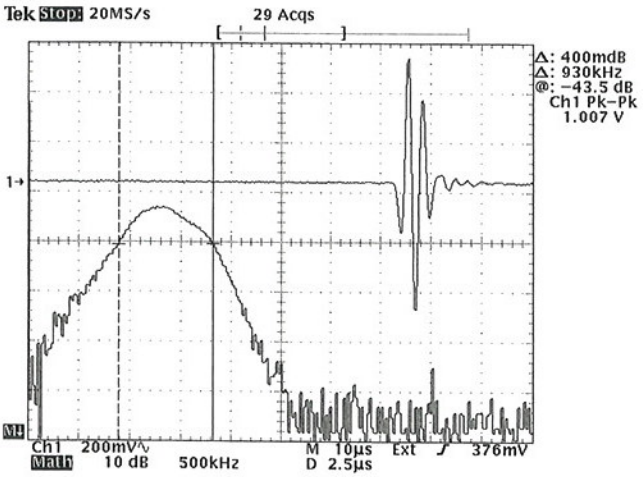


Figure 5. Time and frequency domain of broadband 1.5-MHz, 25-mm active area transducers in transmission mode. T–R air separation: 10 mm. Bandwidth center frequency: 1.4 MHz. Bandwidth at −6 dB: 0.92 MHz (65%). Pulse width: <2 μs. Sensitivity: −58 dB. SNR: 46 dB.

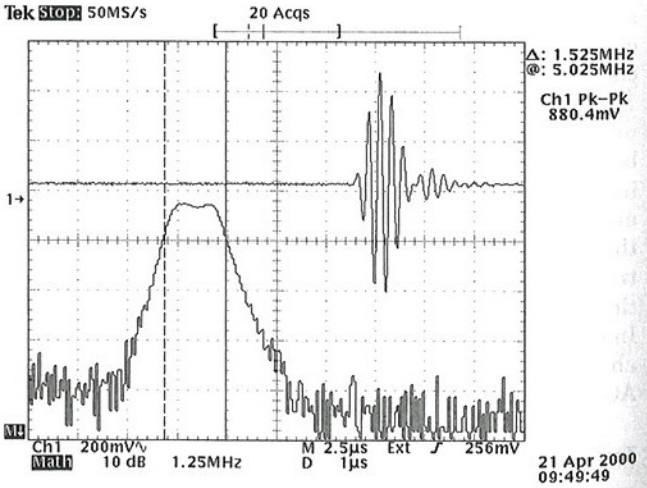


Figure 7. Time and frequency domain of narrowband 5.0 MHz, 12-mm active area transducers in transmission mode. T–R air separation: 5 mm. Bandwidth center frequency: 4.5 MHz. Bandwidth at −6 dB: 1.5 MHz (33%). Pulse width: <800 ns. Sensitivity: −68 dB. SNR: 40 dB.

Table 4. Sensitivity Comparison of Noncontact and Conventional Contact Transducers.[a] Mode of Testing: Transmission. Medium of Testing: 10 mm Ambient Air for Noncontact and 10 mm Water for Contact Transducers

Frequency (MHz)	Active Diameter (mm)	Sensitivity in Ambient Air (dB)	Sensitivity w.r.t Water Immersion[b] (dB)
0.25	50	−38	Below 18
	25	−46	Below 26
0.5	50	−44	Below 24
	25	−50	Below 30
1.0	25	−52	Below 32
	19	−54	Below 34
	12.5	−56	Below 36
	3.2	−62	Below 38
1.5	12.5	−58	Below 38
2.0	12.5	−58	Below 38
	1.5	−66	Below 40
3.0	12.5	−62	Below 40
5.0	12.5	−68	Below 44

[a]Sensitivities reported here were obtained by exciting the transmitting transducer using a broadband and 15-ns pulse. Tone burst excitation sensitivities will be 12 dB higher.
[b]For some contact transducers, a −20-dB sensitivity is assumed.

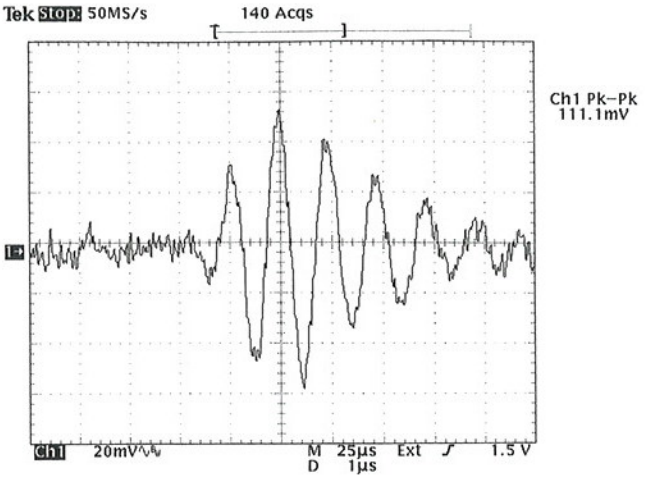


Figure 9. A 1-MHz noncontact transmitted signal through 20-mm aluminum by using new transducers based on a compressed fiber matching layer. Excitation of the transmitting transducer: 400 V into 4-Ω input impedance. Receiving transducer amplification: 64 dB. Transmitting and receiving transducers are 5 mm away from the material surfaces. Under these conditions, the transmitted signal amplitude is 111.1 mV. Compare with Fig. 8.

mode through a solid material by using AC and NC transducers. Figures 8 and 9 present observations in support of this. Both observations correspond to NCU transmission through 20-mm thick aluminum by 1-MHz and 20-mm active area diameter transducers in the direct transmission mode. In both cases, transducers are separated from the test material surfaces by an ~5-mm air column. Furthermore, in Figs. 8 and 9, the transmitting transducer was excited by a high-energy 400-volt (into 4Ω input impedance) pulser, and the signal received from the receiving transducer was amplified by a 64-dB gain. The key difference is that Fig. 8 was obtained by AC transducers and Fig. 9 by NC transducers. Under these conditions, the amplitude of the transmitted signal through 20-mm aluminum by AC transducers is 13.1 mV, whereas it is 111.1 mV for NC transducers. This clearly establishes the superiority of the new noncontact transducer design over the other air-coupled transducers described in (14–17),

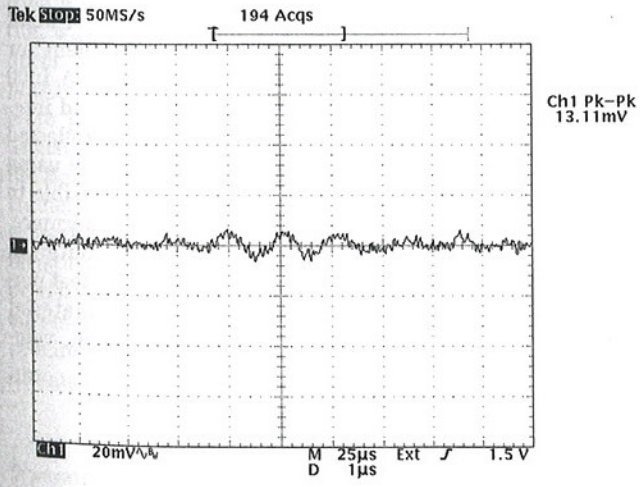


Figure 8. A 1-MHz noncontact transmitted signal through 20-mm aluminum by using transducers based on a soft, porous, polymer matching layer. Excitation of the transmitting transducer: 400 V into 4-Ω input impedance. Receiving transducer amplification: 64 dB. Transmitting and receiving transducers are 5 mm away from the material surfaces. Under these conditions, the transmitted signal amplitude is 13.1 mV. Compare with Fig. 9.

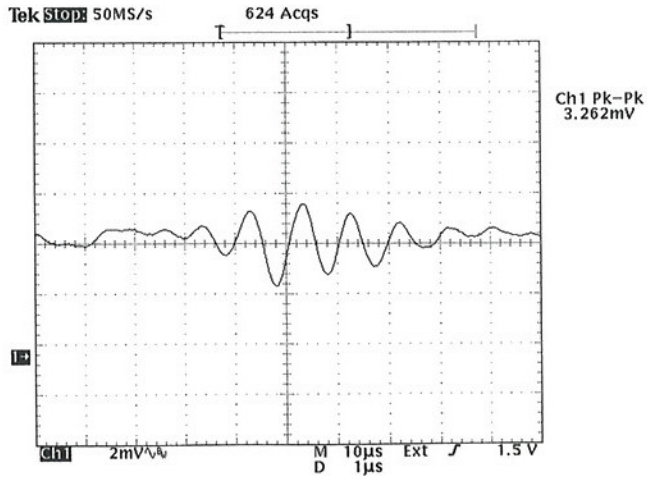


Figure 10. A 1-MHz noncontact transmitted signal through 20-mm aluminum by using new transducers based on compressed fiber matching layer. Excitation of the transmitting transducer: one burst 16-V sine wave. Receiving transducer amplification: 64 dB. Transmitting and receiving transducers are 5 mm away from the material surfaces. Under these conditions, the transmitted signal amplitude is 3.26 mV. No other air-coupled transducer can transmit ultrasound under similar conditions in high acoustic impedance materials by very low level excitation.

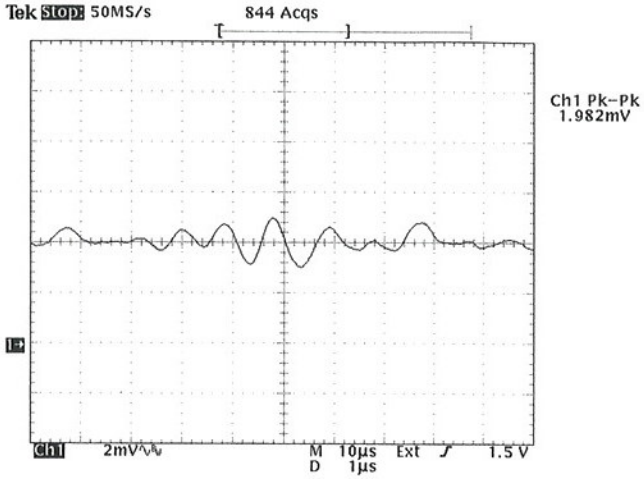


Figure 11. Ultrasound transmission through 25-mm carbon steel (Z, 51Mrayl) by using the new noncontact transducers (1-MHz, 20-mm active area diameter) with a single burst of 16-volt sine wave excitation and 64-db amplification of the received signal by an equivalent transducer. No other air-coupled transducer can transmit ultrasound under similar conditions in high acoustic impedance materials by very low level excitation.

including this author's air/gas propagation transducers that are commercially available from Ultran Laboratories since 1983.

To demonstrate further the exceptionally high sensitivity of NC transducers, we decided to conduct an experiment that would normally be considered impossible! An experiment analogous to that described before was performed, except that in this case the NC transmitter was excited merely by a single burst of a 16-volt sine wave and 64-dB amplification of the received signal. Figure 10 presents the observation from this, showing a 3.26-mV signal transmitted through 20-mm aluminum in the noncontact mode. AC transducers (based on soft polymer matching layers, that is, porous or nonporous or have hollow spheres) were unsuccessful in generating ultrasound transmission through 20-mm aluminum by 16-volt excitation, despite high signal averaging! It is also interesting to note that by low energy excitation, using NC transducers, we propagated megahertz frequencies even in steel, whose acoustic impedance is 51 Mrayl, six orders of magnitude higher than in air! We show an example of this startling conclusion in Fig. 11. It is important to note that the purpose of observations shown in Figs. 8–11 was to demonstrate the high sensitivity of NC transducers relative to any other similar device. The purpose of these experiments is not to recommend or suggest the usage of low-energy transducer excitation for testing materials.

NONCONTACT ULTRASONIC ANALYZER

As is evident from the preceding sections, NC transducers can be used with any suitable commercially available pulser-receiver to transmit and to detect ultrasound through any material. However, our ultimate goal was to generate an NCU mode that would rival the performance

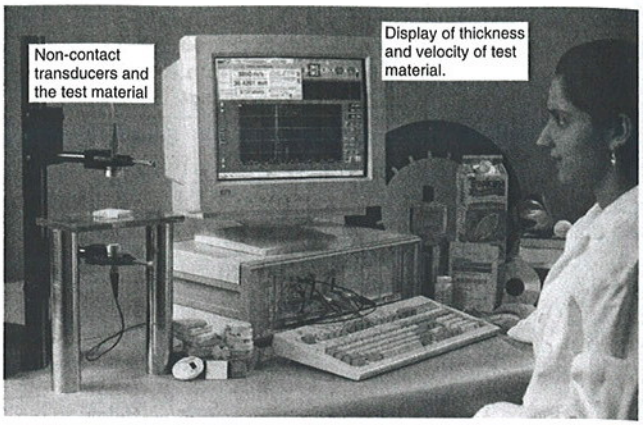


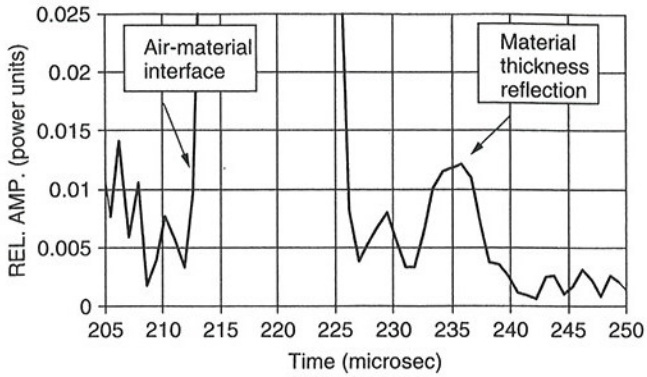
Figure 12. Ultrasonic noncontact analysis system, the NCA 1000, using noncontact transducers and a monitor screen displaying the thickness and velocity through the test material.

of conventional contact or immersion ultrasound. The high transduction of NC transducers is not enough to accomplish this task. For example, we still need to overcome the natural barrier of acoustic impedance mismatch between the coupling air and the test medium. From Table 2, we see that losses due to this mismatch are formidable. To circumvent this and not jeopardize our objective of equating NCU performance with that of conventional contact-based ultrasound, a new mechanism of transducer excitation and signal amplification was needed. Nevertheless, this seemingly impossible task, too, was overcome. In 1997–1998, a novel ultrasonic system was conceived and produced. Identified as the NCA 1000,[2] this instrument was developed by Leon Vandervalk and Ian Neeson of VN Instruments, Canada. It is based on synthesizing a computer-generated chirp combined with the best attributes of noncontact transducers. Signal processing in the NCA 1000 is done by synthetic aperture imaging techniques. The NCA 1000 is characterized by a dynamic range of >150 dB and a time-of-flight (TOF) measurement accuracy of ±10 ns in ambient air and better than ± 1ns in closed conditions. The NCA 1000 (Fig. 12) measures the TOF, thickness, velocity, and integrated response (area underneath transmitted or reflected signals in dB) of materials in the time domain. By using the FFT mechanism of this system, it is also possible to conduct noncontact ultrasonic spectroscopy. Furthermore, by raster scanning the transducers or the test material, we can generate surface or internal images of the test material. Such images can be representative of the material surface roughness, TOF, transmission attenuation, velocity, or thickness.

REFLECTION AND TRANSMISSION IN NONCONTACT MODE

Analogous to conventional contact or immersion ultrasound, ultrasound in the non-contact mode is also reflected and transmitted at various interfaces as well as through a test medium. In this section, we provide examples of

[2]U.S. patent pending and in process.



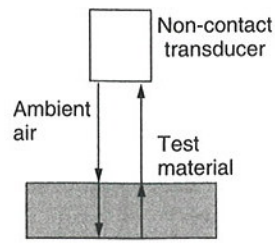


Figure 13. Noncontact ultrasound pulse-echo reflection from 9-mm thick silicone rubber. Transducer: 1-MHz, 12.5-mm active area diameter, and 76-mm point focused. Transducer to material distance in air: 40 mm. It is important to note that the material thickness reflection is ~40 dB lower than that of the air–material interface.

various paths of ultrasound reflection and transmission as functions of test material's interfaces and its volume.

Single-Transducer Operation (Pulse-Echo)

By operating one transducer simultaneously as a transmitter and receiver (analogous to the pulse-echo technique), it is very easy to generate reflection from an air–material interface due to the extremely high reflection coefficient at this interface. However, in this mode, it is nearly impossible to produce a far side reflection corresponding to the test material thickness in ambient air. This difficulty stems from several factors, such as the extremely small transmission of ultrasound in the test material, the extremely high beam spread on the surface of the material, and the inherent electrical noise associated with single transducer operation from the initial pulse. To a degree, the adverse effects of these factors can be minimized by a focused transducer, which will reduce the beam spread and focus ultrasound (thus intensify the reflected energy) within the test material. Figure 13 shows pulse-echo reflection signals from a 9 mm thick silicone rubber sample. This observation was generated by using a 1-MHz focused NC transducer. Similar results have also been observed for other plastic materials. However, at this time, we have no concrete proof of generating these observations from high acoustic impedance materials, such as metals and ceramics. Because reflection from an air–material interface is extremely strong in single transducer operation, ultrasonic reflectivity can be used to characterize the surface characteristics of the material. Such applications include surface acoustic impedance, surface roughness, particle size measurement, surface texture and microstructure, distance, proximity, and level sensing, and any other surface conditions that are sensitive to noncontact ultrasound.

Separate Transmitter and Receiver Operation on the Same Side (Pitch-Catch)

By using two noncontact transducers, one a transmitter (T) and the other a receiver (R), on the same side of the test material, (Fig. 14), it is possible to launch and measure the characteristics of longitudinal, shear, and surface waves in practically all types of material. Generation of these waves

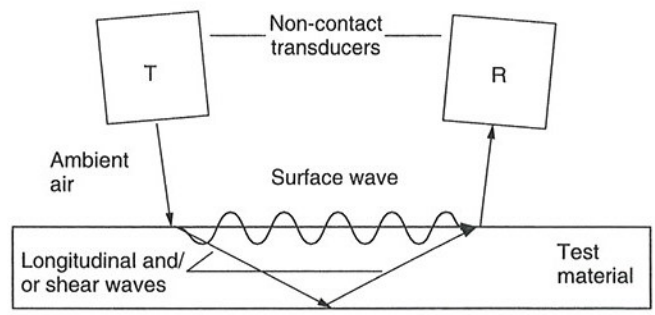


Figure 14. Schematic of a setup for same side operation of separate transmitting (T) and receiving (R) transducers, also showing various types of wave propagation in the test material.

is determined by Snell's law,

$$\mathrm{Sin}\, i/\mathrm{Sin}\, r = V_a/V_m, \tag{7}$$

where i is the incident angle in air, r the refraction angle in the test material, V_a is the ultrasound velocity in air, and V_m the velocity in the test material.

By manipulating the incident angle in air, a variety of wave types can be produced in a test material. Figure 15 shows the far side thickness reflection of a longitudinal

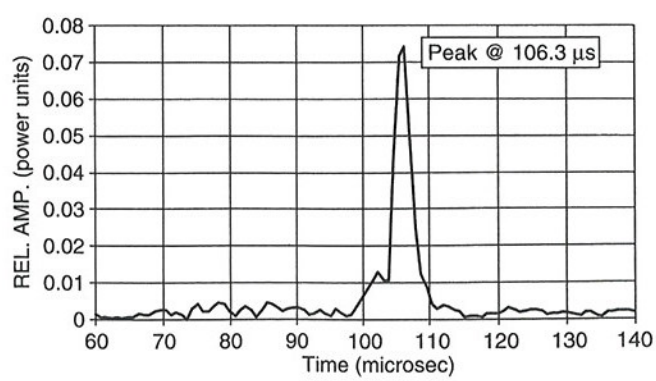


Figure 15. Thickness reflection of longitudinal wave propagation in 12-mm thick aluminum per Fig. 14 setup. Distance between the transducers and the material surface: ~15 mm ambient air. Distance between T and R: ~50 mm. Incident angle in air: ~3.0°.

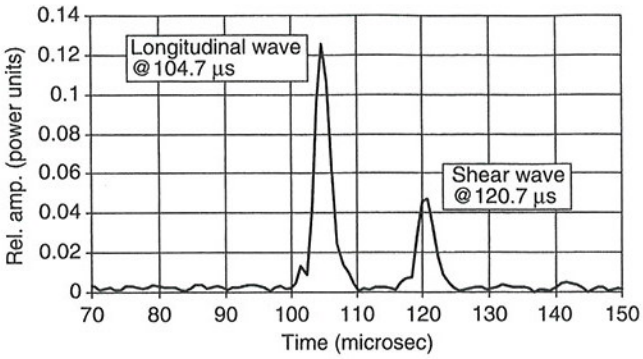


Figure 16. Thickness reflections of longitudinal and shear waves in 32-mm thick transparent polystyrene per Fig. 14 setup. Distance between the transducers and the material surface: ~13 mm ambient air. Distance between T and R: ~50 mm. Incident angle in air: ~6.0°.

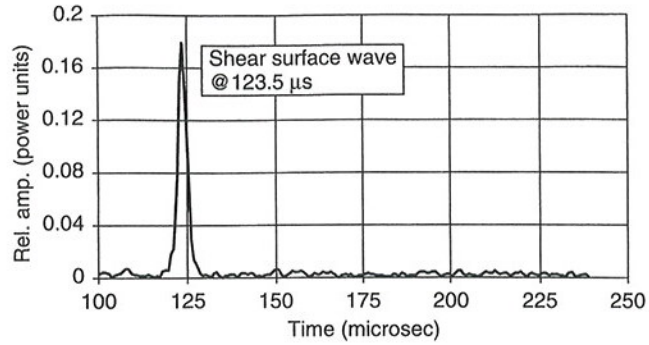


Figure 18. Surface wave in aluminum produced by total reflection of shear wave when the incident angle is equal to the second critical angle. Setup for this is shown in Fig. 14. Distance between the transducers and the material surface: ~15 mm ambient air. Distance between T and R: ~100 mm. Incident angle in air: ~6.5°.

wave from 12-mm thick aluminum. Figure 16 shows the far side thickness reflection of longitudinal and shear waves from 32 mm thick transparent polystyrene. Figure 17 is a longitudinal wave refracted surface wave in aluminum produced by an incident angle equal to the first critical angle (i.e., total reflection of a longitudinal wave) which is 3.16° for aluminum. Figure 18 shows a shear wave refracted surface wave in aluminum, generated by an incident angle equal to the second critical angle (i.e., total reflection of a shear wave), which is 6.3° for aluminum. It is important to note that while performing these experiments, distances—corresponding to transducers and the test materials and angles of transmitting and receiving transducers—were not measured accurately. The primary function of this exercise is to show the feasibility of various types of bulk and surface wave generation by noncontact ultrasound. Applications of such measurements include NCU evaluation of materials from one side, defect detection, anisotropy measurements, and relationships of ultrasonic velocities to test material elastic and mechanical properties.

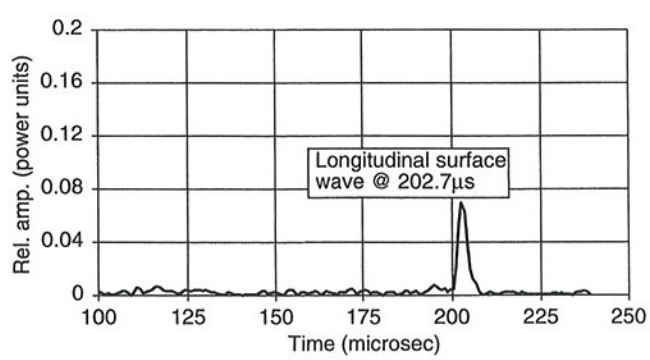


Figure 17. Surface wave in aluminum produced by total reflection of longitudinal wave when the incident angle is equal to the first critical angle. Setup for this is shown in Fig. 14. Distance between the transducers and the material surface: ~15 mm ambient air. Distance between T and R: ~100 mm. Incident angle in air: ~3.2°.

Direct Transmission

When a test material is inserted between two noncontact transducers facing opposite each other in air, then ultrasound is transmitted and reflected from all interfaces corresponding to air and the material. Details of this are shown in Figs. 19 and 20. Direct transmission is relatively the easiest technique in noncontact ultrasound. Therefore, it has been quite extensively studied and developed. Applications of this technique are numerous: thickness and velocity measurements, defect detection, textural and

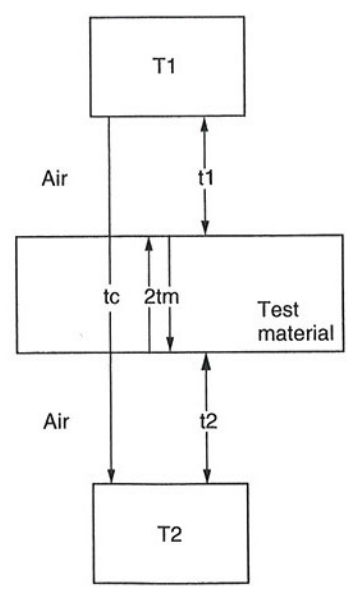


Figure 19. Propagation of ultrasound in the direct transmission noncontact mode. Here, t_c is the complete time of flight (TOF) corresponding to the propagation of ultrasound in air and the test material, $2t_m$ is the round-trip TOF through the test material thickness, t_1 and t_2 are, respectively, TOFs from transducer T_1 to the top surface of the material, and transducer T_2 to the bottom surface of the material. For the further significance of this, see Fig. 20.

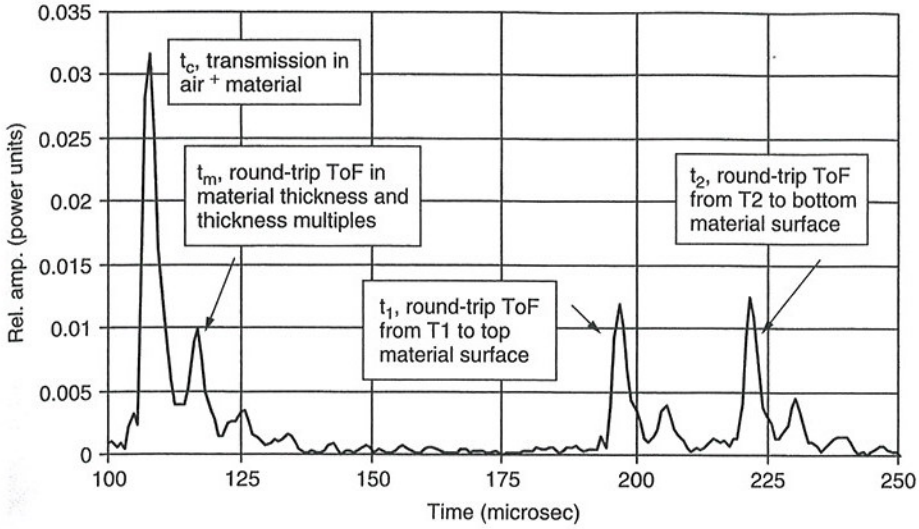


Figure 20. Direct transmission noncontact ultrasound propagation through a test material (7-mm thick cheese) per Fig. 19 setup.

microstructural evaluation, transmission, velocity, thickness, and TOF imaging, detection of the presence or absence of liquids in containers, and many more.

VERY HIGH FREQUENCY NCU PROPAGATION IN MATERIALS

By using NC transducers in ambient air, we have amply demonstrated that frequencies as high as 2 MHz can be easily propagated through a variety of materials, including fibrous and particulate, plastics, ceramics, metals, and composites. However, frequencies even higher than 2 MHz have been successfully investigated for propagation through solids. Figure 21 shows an example of 4-MHz propagation through 4.5-mm thick multilayer graphite fiber-reinforced plastic composite in ambient air. Similar observations have also been made for soft polymers, thin metals, and fibrous and particulate materials. As expected, the magnitude of transmitted signals through solids increases substantially when examined under high gas pressures. Figure 22 shows the propagation of 4-MHz transmission through 8-mm thick steel under 60 bars nitrogen by using a single transducer in the pulse-echo technique.

NONCONTACT ULTRASONIC MEASUREMENTS

Because ultrasound can be reflected and transmitted through a test material and its surfaces, one can use the respective signals to make significant measurements in the time and frequency domains. Such measurements can be further related to important test material characteristics, such as velocity, thickness, defects, internal and surface texture or microstructure, and other ultrasound-dependent parameters.

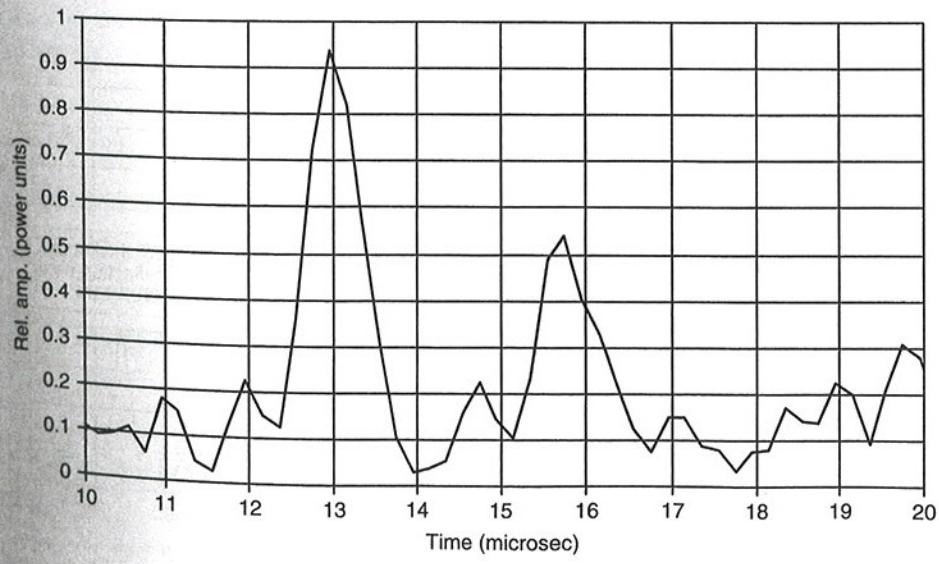


Figure 21. Noncontact ultrasound direct transmission through 4.5-mm thick multilayer graphite fiber-reinforced plastic composite at 4 MHz in ambient air per Fig. 19 setup. Transducers are 4-MHz and 12.5-mm active area diameter. Distances from transducers to test materials surfaces are ~3 mm. First peak: directly transmitted signal through air and the test material. Subsequent peaks: test material thickness reflection and its multiples.

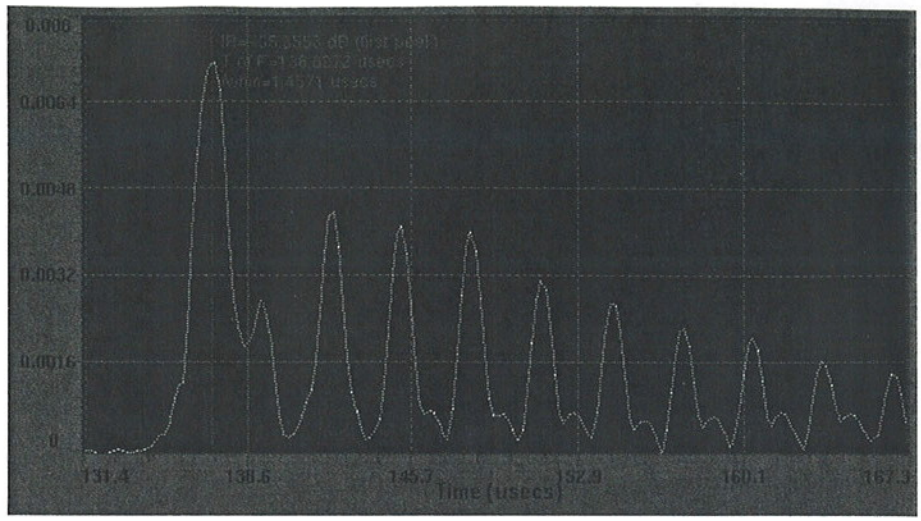


Figure 22. Single transducer (pulse-echo) signal through 8-mm thick section of steel at 4 MHz under 60 bar nitrogen pressure. Transducer used is 4-MHz and 12.5-mm active area diameter. Distance from transducer to the surface of test material is ~25 mm. First peak: gas–materials interface. Subsequent peaks: thickness and thickness multiples corresponding to the test material.

Velocity and Thickness Measurements

There are several ways to determine longitudinal wave velocity in test materials by noncontact ultrasound. For example, if multiple reflections corresponding to the thickness of the test material are observed (Fig. 23), then one can measure the TOF, t_m, between the two successive peaks to determine the velocity of a material of known thickness. The TOF measured this way corresponds to the round-trip TOF in the test material. Therefore,

$$V_m = 2d_m/t_m. \tag{8}$$

For example, t_m measured between any two successive peaks from Fig. 23 is 10.4 μs for a 13.5-mm thick material (in this case, isotropic graphite); thus, the velocity is 2595 m/s.

It is important to note that the appearance of multiple thickness reflections in the NCU mode depends on the attenuation and acoustic impedance of the test material and the frequency of transducers. For example, the lesser the attenuation, the lower the acoustic impedance, and at thicknesses greater than one wavelength in the test material, material thickness reflections are observable. On the other hand, when only the transmission signal is observed (i.e., without thickness multiples for attenuative materials), one can determine the TOF of the known thickness of the test material similarly to using contact delay line transducers. In such a case, the solid delay lines on the transducers are replaced by air columns in front of the transmitting and receiving transducers as functions of air distances between the test material surfaces.

As seen in the aforementioned technique, to determine the test material velocity, its thickness must be known. However, in the NCU mode, the thickness of the test material can also be measured. For simultaneous measurements of material thickness and its velocity in the NCU mode, we must examine all paths of ultrasound transmission and reflection to and from the test material. These paths relate to propagation of ultrasound relative to transmitting and receiving transducers "taking to each other" in the air column, ultrasound transmitted through the test

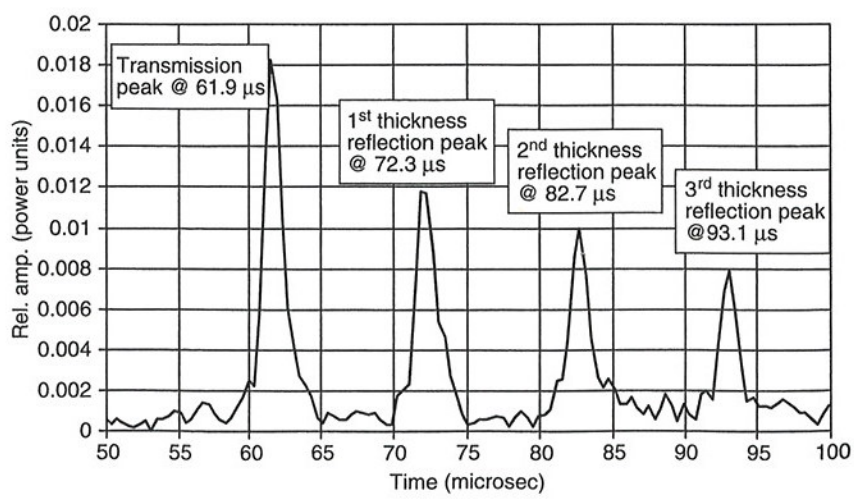


Figure 23. Velocity in material determined by direct transmission NCU propagation in a test material (in this case, 13.5-mm thick isotropic graphite) characterized by multiple thickness reflections. Note that the TOF (round-trip TOF through the material) between any two successive peaks is 10.4 μs; thus, the velocity in the material is 2595 m/s.

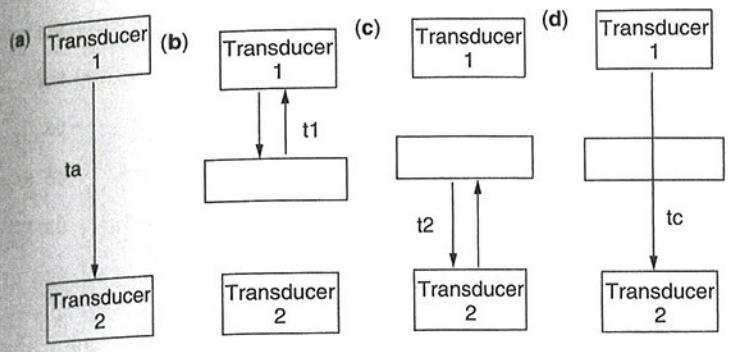


Figure 24. Propagation of ultrasound with respect to a test material in the noncontact transmission mode. The NCA 1000 measures and calculates all times of flight shown in this figure and then displays them on the monitor screen (Fig. 25). See text for details.

material, and ultrasound reflections from the test material surfaces in air. These paths of ultrasound propagation in the NCU transmission mode—needed to determine the test material thickness and velocity—are shown in Fig. 24. The signals generated by these paths of propagation and their significance are as follows:

Path (a) is the transmission from transducer 1 to transducer 2 in air—measures TOF, t_a. If ultrasound is propagated from transducer 2 to transducer 1, the same TOF is measured. Path (b) is the reflection from transducer 1 to the material surface in air—measures TOF, t_1. Path (c) is the reflection from transducer 2 to the material surface in air—measures TOF, t_2. Path (d) is the transmission from transducer 1 to transducer 2, and the test material is in between—measures TOF, t_c. If ultrasound is propagated from transducer 2 to transducer 1, the same TOF is measured.

From these times of flight measurements, the test material thickness and its velocity are determined according to the following relationships:

$$V_m = d_m/t_m \tag{9}$$

$$d_m = V_a t_{am} \tag{10}$$

$$t_{am} = t_a - (t_1 + t_2)/2 \tag{11}$$

$$t_m = t_{am} - (t_a - t_c) \tag{12}$$

In these equations, d_m is the test material's thickness, V_m, the velocity of ultrasound in the test material V_a, the velocity of ultrasound in air (determined from a reference material), t_{am}, the time of flight in air corresponding to the test material thickness d_m, and t_m is the time of flight in the test material.

By proper substitutions,

$$d_m = V_a\,[t_a - (t_1 + t_2)/2] \tag{13}$$

$$V_m = d_m/t_{am} - (t_a - t_c) \tag{14}$$

As an example, Fig. 20 shows actual transmitted and reflected signals when a test material is examined in the noncontact transmission mode. Identification and location of these signals with respect to the test material are shown in Fig. 19. As can be seen from Eqs. (13) and (14), to determine the thickness and velocity according to this scheme, one only needs the measurements of four times of flight (t_a, t_1, t_2, t_c) and the velocity of ultrasound in air. These parameters were measured and calculated by the NCA 1000 computer and are displayed with the velocity and thickness of the test material on the monitor screen (Fig. 25).

Integrated Response, Transmissivity, and Reflectivity Measurements

In the time domain, the NCA 1000 measures and displays the times of flight of the signals and also shows the integrated response (IR) of these signals. IR is a measurement of the area underneath a particular peak in power dB units. Due to the very high, >150-dB, linear dynamic range of the NCA 1000, the IR can be used to measure the amount of ultrasonic energy transmitted (transmissivity) or reflected (reflectivity) from a test material and relate it (IR) to subtle changes in the material. For example,

$$\mathrm{IR_m} = \mathrm{IR_c} - \mathrm{IR_a}, \tag{15}$$

where $\mathrm{IR_m}$ is the amount of ultrasonic energy transmitted in the test material, $\mathrm{IR_c}$ is the ultrasound transmission through air and the material (between the transmitting and receiving transducers), and $\mathrm{IR_a}$ is the amount of ultrasound energy transmitted only through air. $\mathrm{IR_c}$ and $\mathrm{IR_a}$ are measured directly by the NCA 1000.

If a given test material is homogeneous, then the measurement of $\mathrm{IR_m}$, it has been found, is related to the transmission coefficient [Eq. (1)]. To illustrate this, we evaluated a flat polished specimen of polystyrene. Figure 26 shows the $\mathrm{IR_c}$ (−21.72 dB) of the transmitted peak of ultrasound from air into the specimen, and Fig. 27 shows a similar peak, but only through air, corresponding to $\mathrm{IR_a}$ (+41.7 dB), thus yielding $\mathrm{IR_m}$ −63.42 dB for the specimen. It is important to note that this measurement corresponds very closely to

$$IR_m = 20 \log T, \tag{16}$$

where T, the transmission coefficient, is defined by Eq. (1).

For example, the calculated value for ultrasonic energy transmitted in polystyrene [Eqs. (1) and (4)] is −63.34 dB, which is very close to −63.42 dB determined by measuring integrated response peaks. It should be pointed out that the transmission coefficient is assumed to be independent of ultrasonic attenuation and the thickness of the test medium. In reality, this is not absolutely true. For example, varying thicknesses of polystyrene samples at different frequencies yield different values of T. Though these variations are

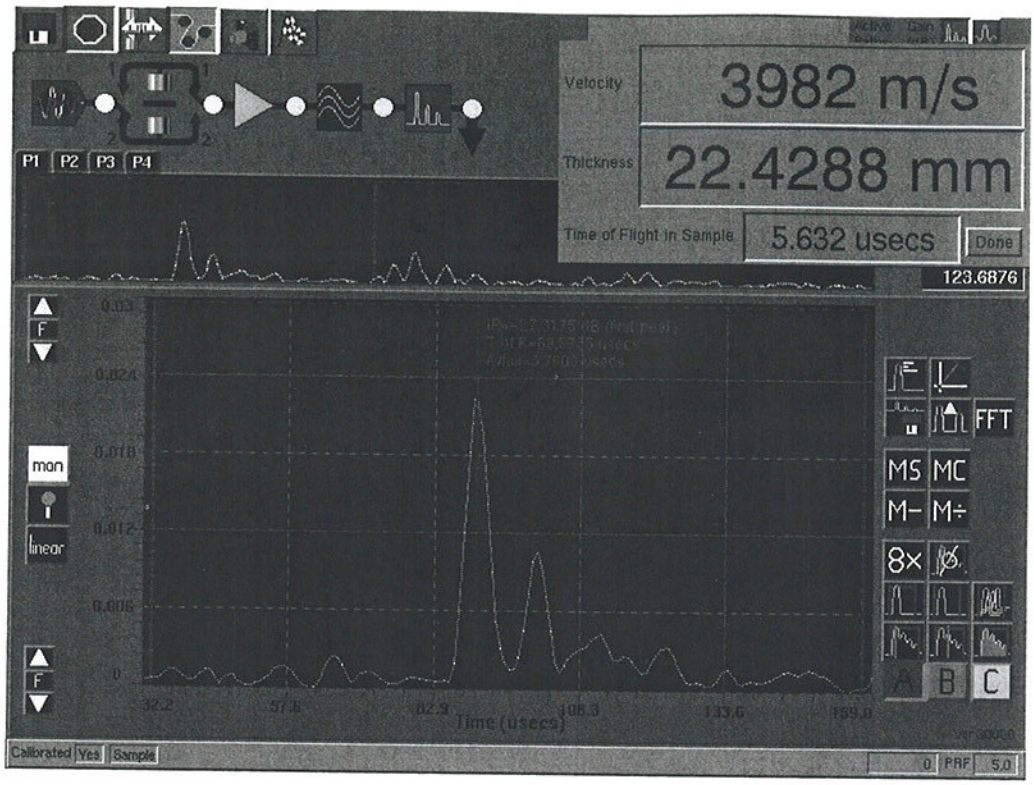


Figure 25. The NCA 1000 screen displaying velocity of ultrasound and thickness of a material. The test material is a 22.5-mm porous sintered ceramic.

very small, yet they are measurable. On the other hand, if the transmission coefficient can be measured with a very high degree of certainty and precision, then it should also be possible to measure the absolute density of the test material by first determining the acoustic impedance Z_m of the test material:

$$Z_m = \frac{Z_1}{T}[(2 - T) + 2(1 - T)^{1/2}], \tag{17}$$

$$\rho_m = Z_m / V_m. \tag{18}$$

Measurement of IR_m and solving Eqs. (17) and (18) provide approximate ideas about the acoustic impedance and density of the test material. For accurate determination of these characteristics, factors such as ultrasound attenuation (analogous to absorption coefficient in X-ray absorption) and material thickness must also be considered:

$$T = I_2/I_0 = Z_1 Z_2/(Z_1 + Z_2)^2 = \exp(-\mu\rho x), \tag{19}$$

where T is the transmission coefficient, I_2 the ultrasound energy transmitted into the material (acoustic impedance

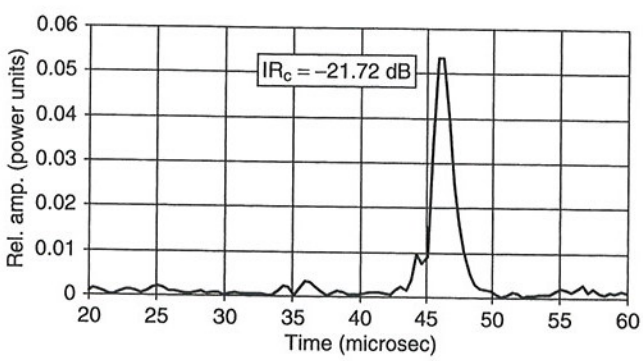


Figure 26. Noncontact transmission through a 20-mm thick flat polished polystyrene sample showing the integrated response IR_c of the transmitted peak.

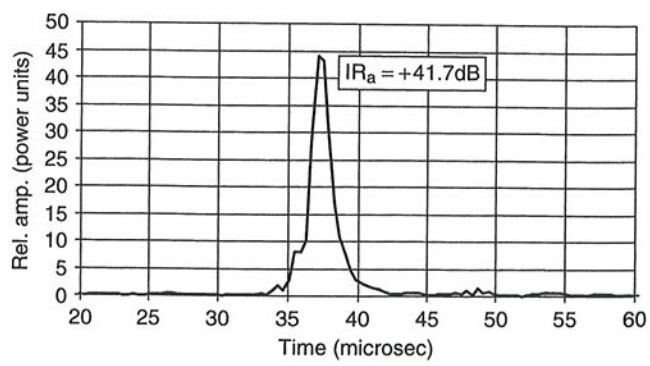


Figure 27. Noncontact transmission through air column showing the integrated response IR_a of the transmitted peak. Note that while making this measurement, the distance between the transmitting and receiving transducers was compensated for the 20 mm thickness of the specimen in Fig. 26.

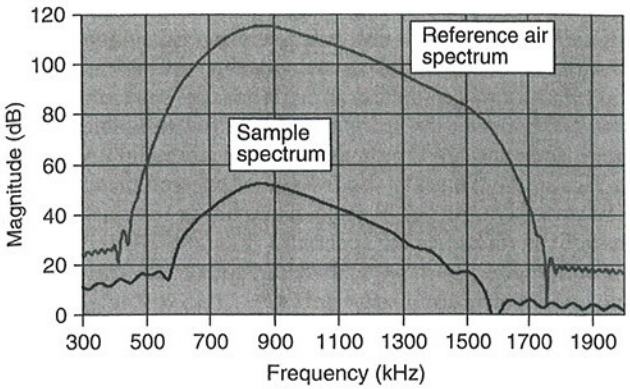


Figure 28. Procedure for noncontact ultrasonic spectroscopy. Top: FFT magnitude spectrum of ultrasound transmission through air as a reference. Bottom: FFT magnitude spectrum of ultrasound transmission where the test material (composite rubber) is between the transmitting and receiving transducers in air.

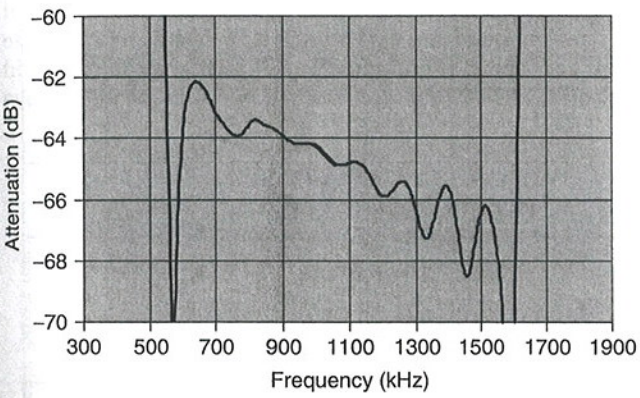


Figure 29. Frequency dependence of ultrasonic attenuation by subtracting the air reference from that of the sample spectrum (Fig. 28).

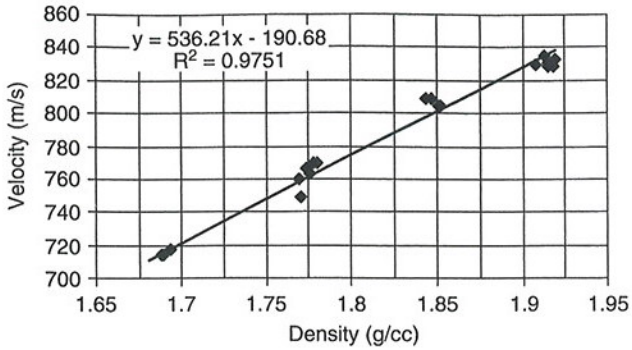


Figure 30. Relationship between density and noncontact ultrasonic velocity in low-density green alumina. Transducer: 1-MHz, 12.5-mm active area diameter.

Z_2) from air (acoustic impedance Z_1), I_0 the input ultrasound energy, μ the material ultrasound attenuation coefficient, ρ the material density, and x the material thickness. At this time, the development of these relationships and techniques for measuring T, Z, μ, and ρ by noncontact ultrasound are in progress (21).

Because the measurement of the transmission coefficient still needs to be validated, it is best to refer to IR_m as transmissivity (when propagating ultrasound through the material in the direct transmission mode) or reflectivity (when ultrasound is reflected from the surface of the material). Such measurements are useful in evaluating the test material's internal and surface characteristics, such as defects, texture, microstructure, and roughness.

Noncontact Ultrasonic Spectroscopy

By performing the fast Fourier transformation (FFT) of transmitted or reflected time domain signals, test materials can also be characterized to investigate the frequency dependence of ultrasonic attenuation. Such examinations are important while testing microstructurally complex materials or those for which time domain velocity measurements are not sensitive enough. The first step for

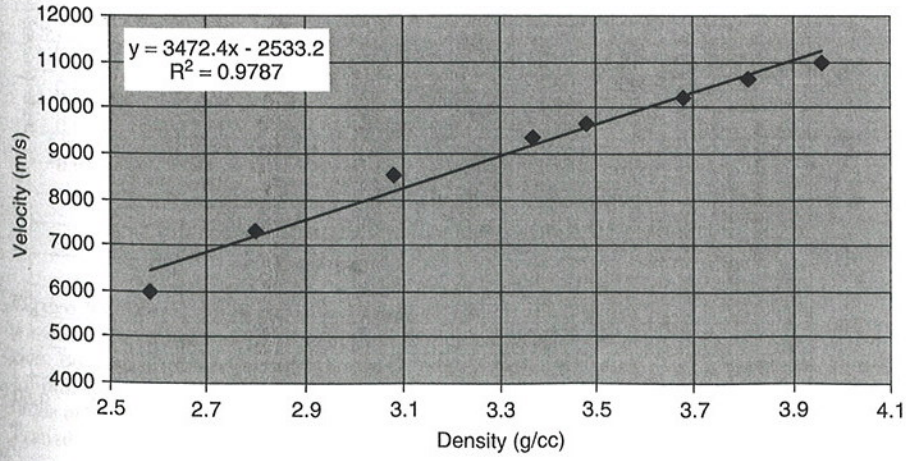


Figure 31. Relationship between density and noncontact velocity in sintered alumina. Transducers: 1 MHz for samples less dense than 3.5 g/cc and 2 MHz for samples denser than 3.5 g/cc.

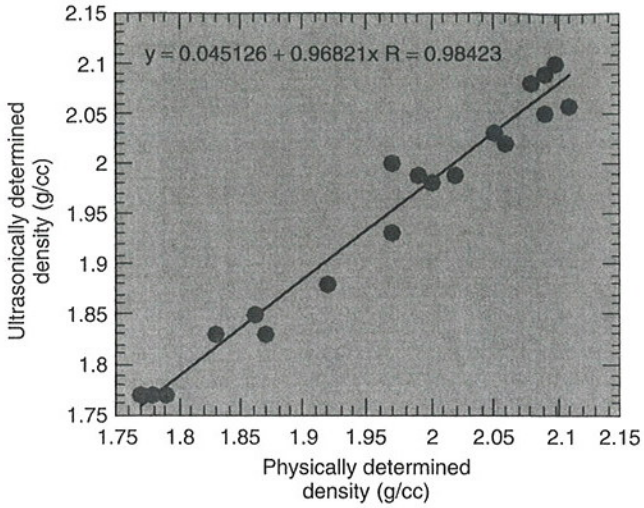


Figure 32. Comparison of ultrasonically and physically determined density of green alumina.

frequency dependence of ultrasonic characterization is the acquisition of a reference frequency magnitude spectrum of a transmitted signal in air without the test material. The next step is to do the same when the test material is inserted between the transducers. As an example, the FFT magnitude spectra for air and the test material are shown in Fig. 28. To generate the frequency dependence of ultrasonic attenuation, the sample spectrum is subtracted from that of the reference air spectrum (Fig. 29). By performing a similar analysis, the surfaces of materials can also be analyzed in the frequency domain. Frequency-dependent attenuation can be related to the test material's internal and surface characteristics, such as defects, texture, microstructure, and roughness.

APPLICATIONS OF NONCONTACT ULTRASOUND

Noncontact transducers have now been successfully produced in the frequency range of 100 kHz to >5 MHz.

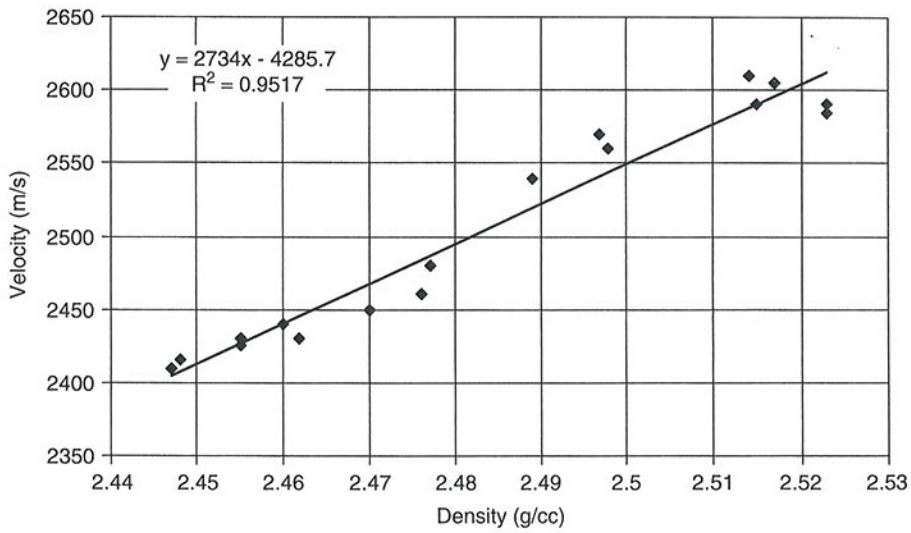


Figure 33. Relationship between velocity and density for isostatically pressed, high-density green alumina. Transducers: 1-MHz, 12.5-mm active area diameter.

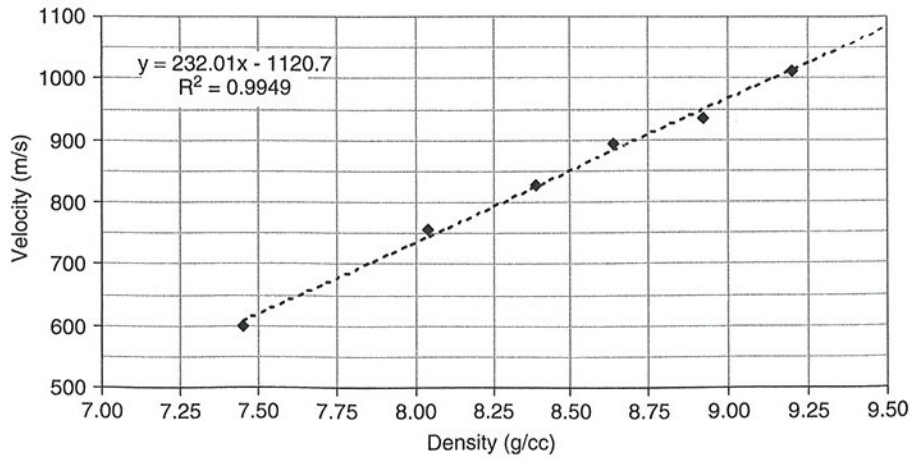


Figure 34. Relationship between velocity and density for pressed green tungsten carbide. Transducers: 500-kHz, 12.5-mm active area diameter.

Applications of noncontact transducers greater than 3MHz in ambient air are limited, but transducers between 200 kHz and 3 MHz have been extensively used for several industrial and medical applications (22–29). In this section, we present selected examples of NCU applications for materials testing and other objectives.

Materials Characterization and Defect Detection

Figures 30 and 31, respectively, show the relationships between densities of green and sintered alumina and the noncontact velocities in these materials. Figure 32 shows a correlation between ultrasonically (from reference samples) and physically determined densities of green alumina. The noncontact ultrasonic technique has been successfully applied to characterize density and defects in a variety of green materials such as ceramics tiles, multilayer electronic packages, powder metals, cements, and concrete. Figures 33 and 34, respectively, show the velocity–density relationships for isostatically pressed high-density green alumina and tungsten carbide. Examples of defect detection in green and sintered ceramics are shown in Figs. 35 and 36, and similar observations for aluminum are shown in Fig. 37. Figures 38 and 39, respectively, show trend plots of direct transmission and same side reflection in graphite fiber-reinforced plastic (GFRP) composites bonded to a honeycomb structure. The same side observations (Fig. 39)

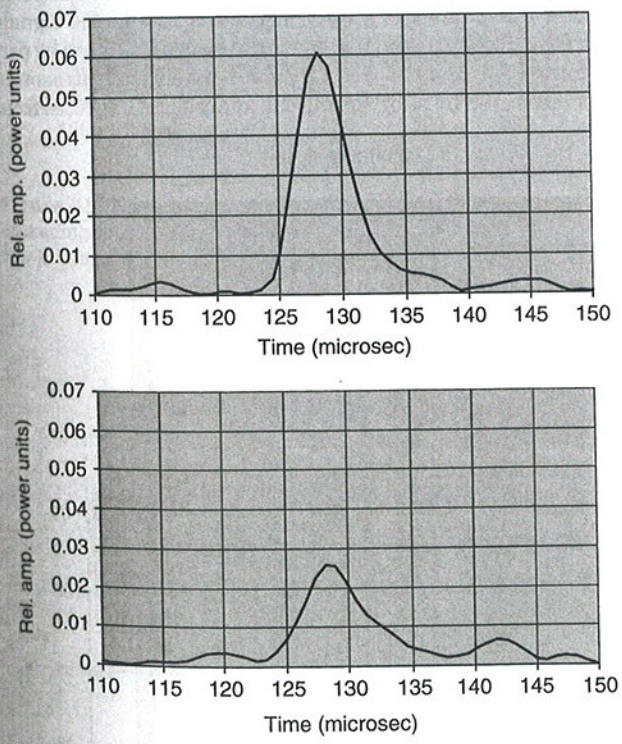


Figure 35. Defect detection in a sample of 14-mm thick green porcelain. Top: ultrasound transmission through a defect-free region. Bottom: ultrasound transmission through a region that has 1.5-mm diameter side-drilled cylindrical hole. Compare the amplitudes of the transmitted ultrasound intensity of the two regions. Transducers: 1-MHz and 12.5-mm active area diameter.

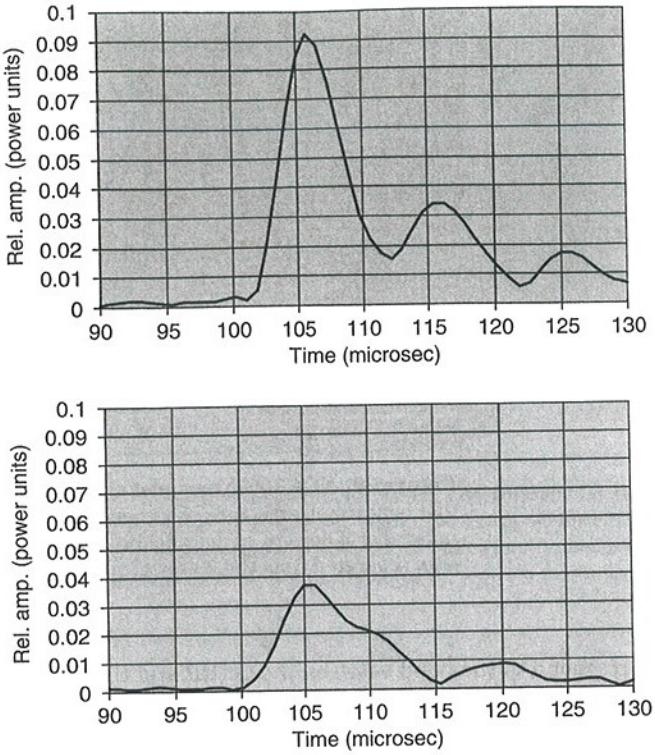


Figure 36. Defect detection in a sample of 20-mm thick, 20% porous, low thermal expansion sintered ceramic. Top: ultrasound transmission through a defect-free region. Bottom: ultrasound transmission through a region that has 1.5-mm diameter side-drilled cylindrical hole. Compare the amplitudes of the transmitted ultrasound intensity of the two regions. Transducers: 1-MHz and 12.5-mm active area diameter.

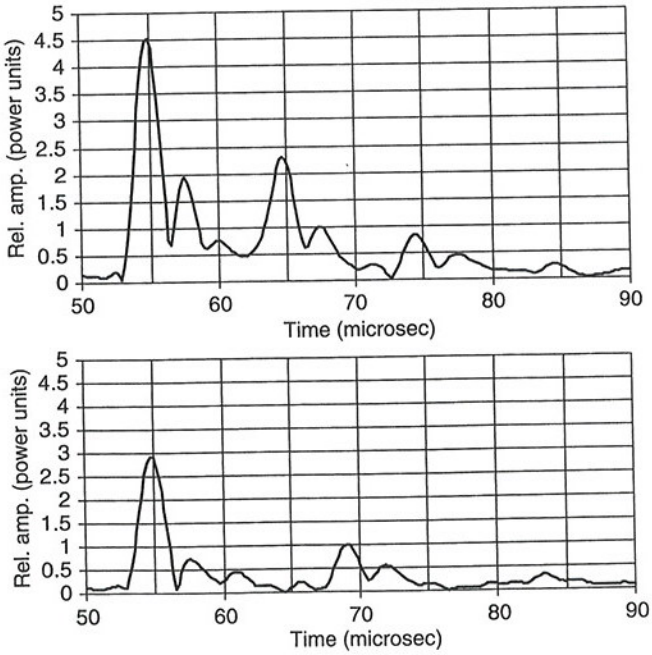


Figure 37. Detection of defects in an 8-mm thick sheet of aluminum by noncontact transmission mode. Top: defect-free region. Bottom: region that has a 1.5-mm cylindrical hole. Transducers: 2-MHz and 12.5-mm active area diameter.

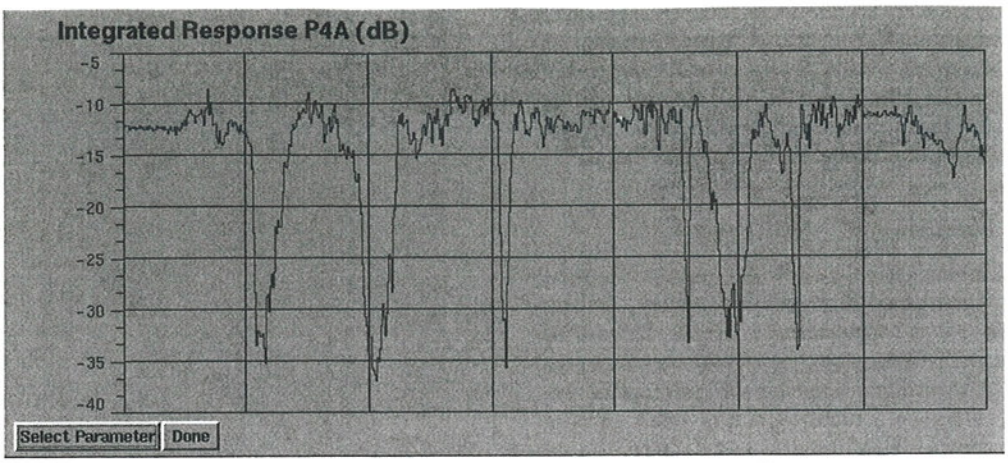


Figure 38. NCA 1000 trend plot showing direct transmission through a GFRP composite bonded to a honeycomb structure at various points. Regions showing the sharp drop in transmission are indicative of defects, such as delaminations. Transducers: 500-kHz and 12.5-mm active area diameter, separated from the material surfaces by ~40 mm ambient air.

correspond to the bond between the GFRP and the honeycomb.

Examples of textural and microstructural analysis by noncontact ultrasonic spectroscopy are shown in Figs. 40 and 41. Figure 40 shows the frequency dependence of ultrasound attenuation by three specimens of extremely porous ceramics (in this case, space shuttle tiles), and Fig. 41 shows similar observations from two samples of packaging foam whose cell dimensions vary. Figure 42 shows very high frequency noncontact transmission spectroscopy of two samples of paper towels. Similar observations have also been made to detect bubbles and pores in liquids and other materials.

To evaluate surface characteristics by noncontact ultrasonic spectroscopy, several grinding discs of SiC varying in particle size were chosen. These discs were placed at a fixed air distance of 10 mm from a 2-MHz, 12.5-mm active area diameter transducer. Reflection from a polished sample of steel was assumed as a reference signal. Reflected signals from the reference and test materials were analyzed by performing FFT, and the frequency dependence of ultrasound was measured by subtracting the sample FFT spectra from

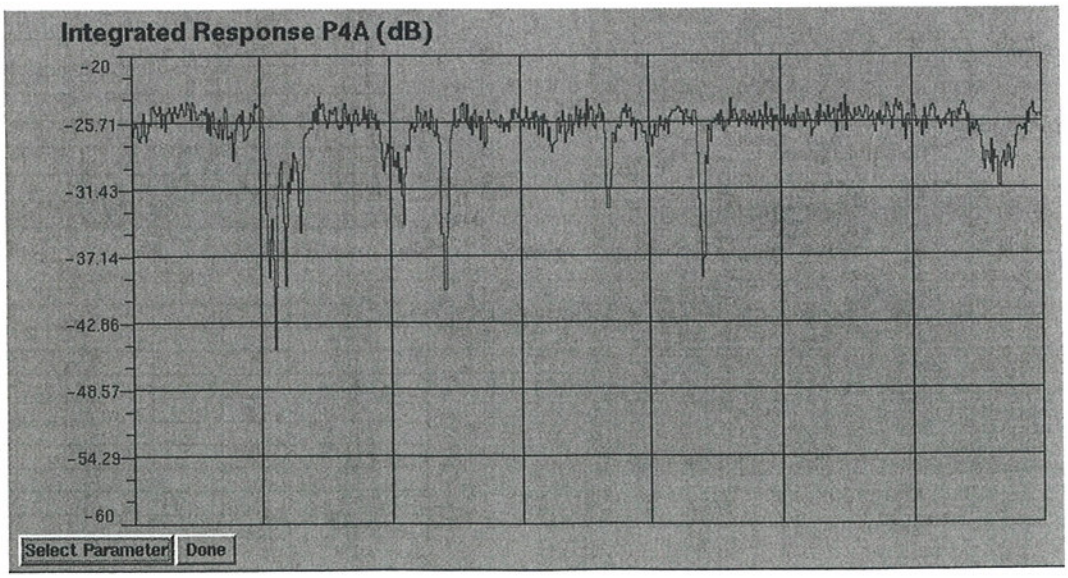


Figure 39. NCA 1000 trend plot showing the T–R reflection from same side in a GFRP composite bonded to a honeycomb structure at various points. Regions showing the sharp drop in reflected ultrasound from composite to honeycomb bond are indicative of defects, such as delaminations. Transducers: 500-kHz and 12.5-mm active area diameter, separated from the test material surface by ~10 mm ambient air.

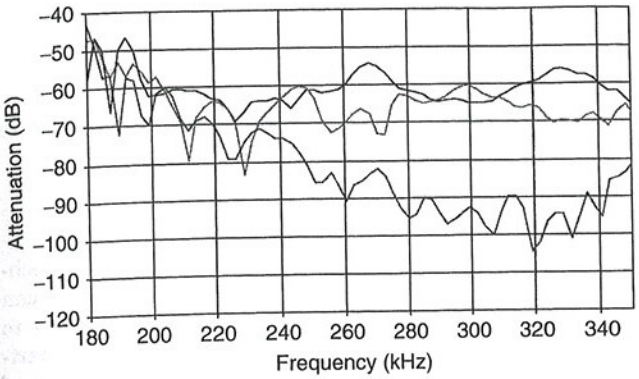


Figure 40. Noncontact transmission ultrasonic spectroscopy of extremely porous ceramics (space shuttle tiles) for microstructural characterization. Top: 0.38 g/cc. Middle: 0.28 g/cc. Bottom: 0.1 g/cc. Transducers: 250-kHz, 25-mm active area diameter.

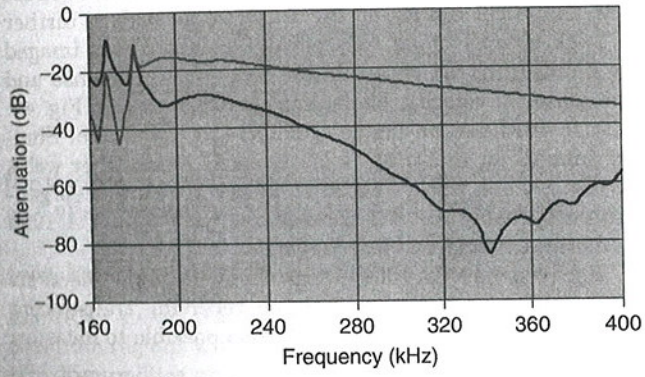


Figure 41. Noncontact transmission ultrasonic spectroscopy of packaging foam. Top: small cell. Bottom: large cell. Transducer: 250-kHz and 25-mm active area diameter.

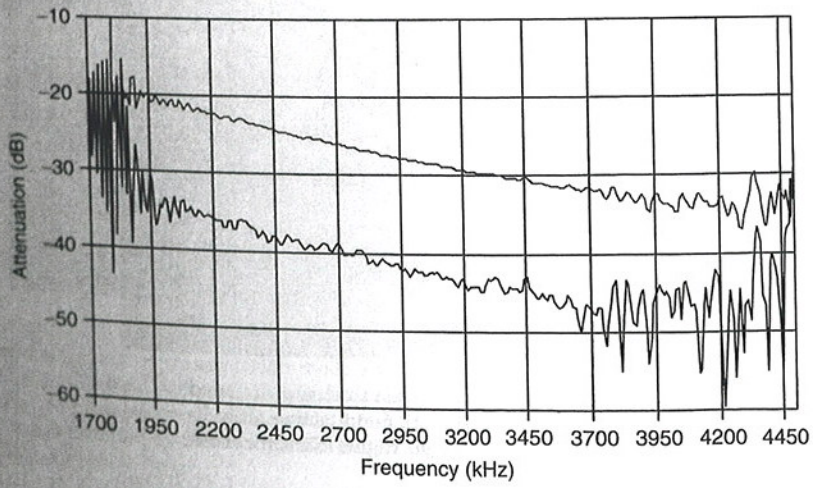


Figure 42. Very high frequency noncontact transmission ultrasonic spectroscopy of two different paper towels. Top: 0.2-mm thick, relatively hard, shallow dimpled texture. Bottom: 0.4-mm thick, relatively soft and deeply dimpled texture.

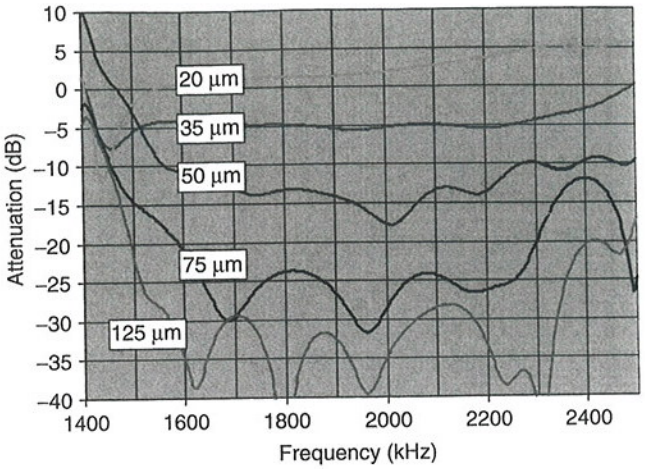


Figure 43. Noncontact reflection ultrasonic spectroscopy for surface characterization of materials. Note that as the surfaces become rough, the attenuation of ultrasound increases. Transducer: 2-MHz and 12.5-mm active area diameter.

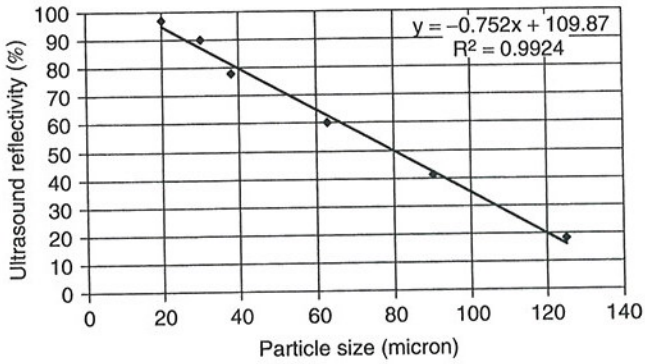


Figure 44. Noncontact reflectivity measurement for surface characterization of materials. Compare the reduction in reflectivity and high ultrasound attenuation (Fig. 36) as functions of increasing particle size. Transducer: 2-MHz and 12.5-mm active area diameter.

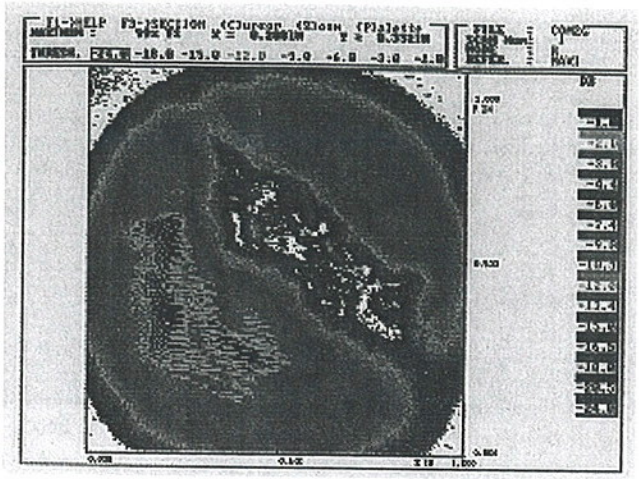


Figure 45. Partial contact ultrasonic image of an impact-damaged eight ply graphite-fiber-reinforced plastic composite 1.5 mm thick. Area scanned: 25 × 25 mm. This image was generated by using a 2-MHz and 25-mm active area diameter transmitter in contact with the material surface, and a 2-MHz, 3-mm diameter receiver was raster scanned in noncontact mode across the other surface of the material. A conventional pulser that sent 400 V into a 4-Ω input impedance square wave and 64-dB receiver gain was used.

that of the steel reference (Fig. 43). It is quite evident that as the particle size increases, the frequency-dependent attenuation also increases. A similar experiment was performed in which the integrated response (IR) of reflected ultrasound from the test and reference materials surfaces was measured. The reflectivity of ultrasound (as a function of particle size) was determined by comparing the sample IR with that of a steel reference specimen (Fig. 44). Once again, it is quite clear that as the particle size increases, the ultrasound reflectivity decreases (due to the scattering of ultrasound). By performing these simple experiments, it is relatively easy to characterize the material's surface texture or its roughness.

Noncontact Ultrasonic Imaging

Analogous to the conventional water immersion technique, ultrasonic transducers in the noncontact mode can be raster scanned to generate images corresponding to the internal and surface characteristics of test materials. Figure 45 shows a partial contact ultrasonic image of an impact-damaged 1.5-mm thick multilayered graphite-reinforced plastic composite. The test material in this case was placed on a large stationary transmitting transducer, and a small receiver in the noncontact mode was scanned across the other surface of the material. Figure 46 shows noncontact transmission images of a thick, mild-impact-damaged glass-fiber-reinforced plastic composite by monitoring signals corresponding to transmission and thickness reflection through the material. To demonstrate the analytical ability of the NCA 1000 system further a thick sample of an iron powder compact was imaged by monitoring the transmission integrated response and the material velocity. These images are shown in Fig. 47. Figure 48 shows an image of defects in aluminum. Similar images for materials, such as steel welds, fiber webs, cheese, meats, wood, and other materials have been generated by using the NC transducers with the NCA 1000 and other commercial instruments.

Because the NCA 1000 interprets ultrasound reflections of both the transmitting and the receiving transducers from material surfaces, it is now also possible to measure

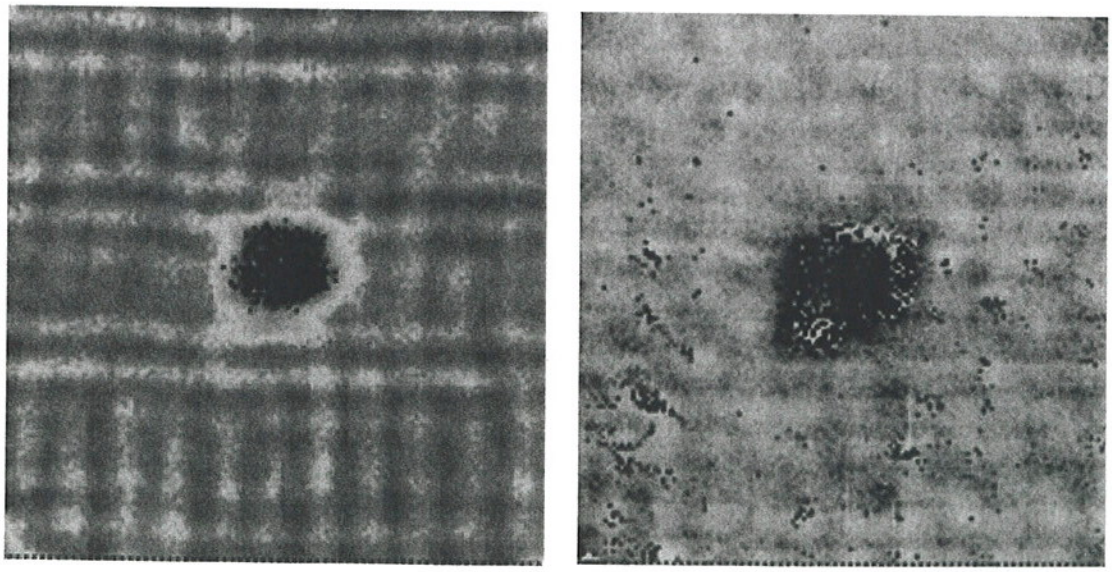


Figure 46. Noncontact ultrasonic imaging of a mild-impact-damaged 6.4-mm thick multilayered glass-fiber-reinforced plastic composite by using NCA 1000 and 1-MHz, 12.5-mm active area diameter transducers with a 1-mm aperture. Left: Direct transmission image. Right: First thickness reflection image.

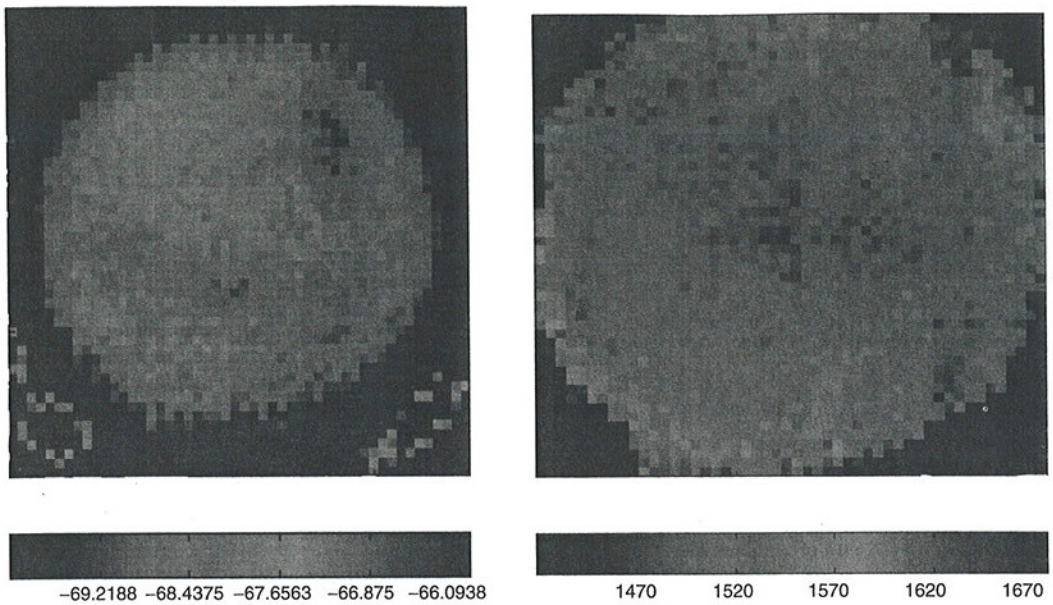


Figure 47. Noncontact imaging of a green 14-mm thick iron powder compact by using the NCA 1000 and 500-kHz, 12.5-mm active area diameter transducers with a 3-mm aperture in direct transmission mode. Left: Relative attenuation of integrated response (dB). Right: Velocity (m/s). Area scanned: 50 × 50 mm. Note that the outer high velocity region is also characterized by high attenuation (low IR) and the inner region of low velocity by lower attenuation.

the thicknesses of materials that are continuously rolled on a production line and are too wide for micrometers.

Food, Beverage, and Pharmaceutical

Figure 49 shows transmitted noncontact ultrasound signals from regions with and without almonds in milk chocolate. Figure 50 is an example of fat content measurement in milk and milk products. Similarly, Fig. 51 shows the measurement of sugar content in water. We have also applied noncontact ultrasound to detect beverages and other liquids in plastic, metal, and cardboard containers. The quality of heat and vacuum seals in pharmaceutical

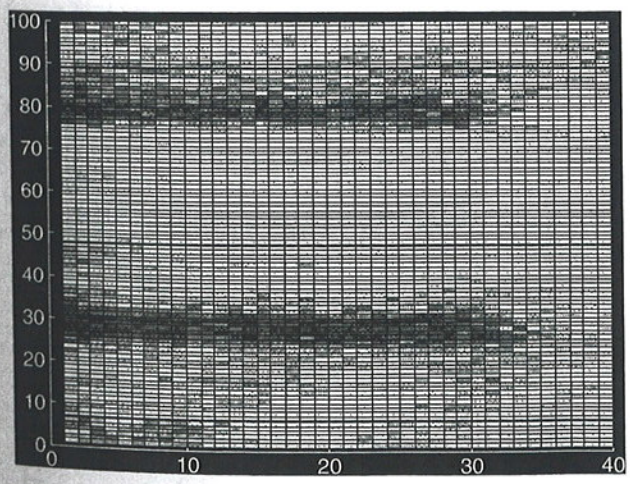


Figure 48. Noncontact ultrasonic image of a 8-mm thick aluminum sheet in transmission mode showing 1.5-mm (top) and 2.0-mm (bottom) side-drilled cylindrical holes. Also compare with Fig. 37. Transducers: 2-MHz and 12.5-mm active area diameter. Image provided by E. Blomme, Katholiieke Hogeschool, Kortrijk, Belgium.

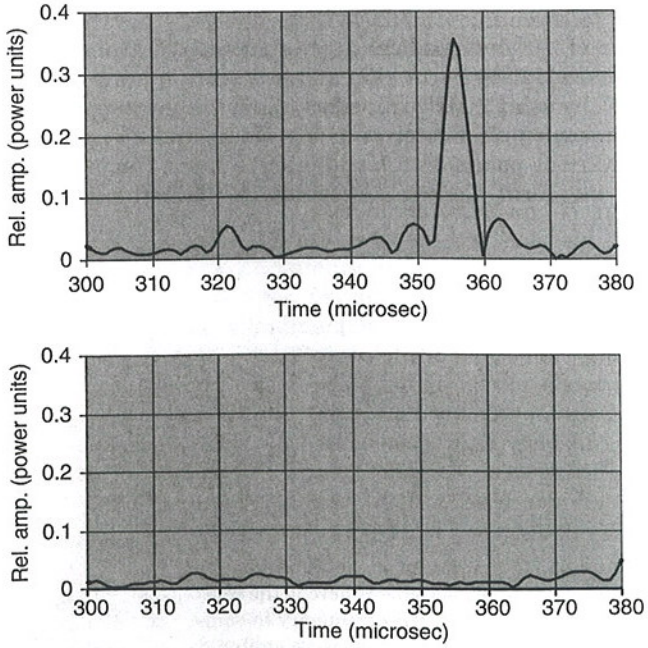


Figure 49. Detection of absence or presence of almonds in milk chocolate. Top: region without almonds. Bottom: region that has almonds. Transducer: 1-MHz, 12.5-mm active area diameter.

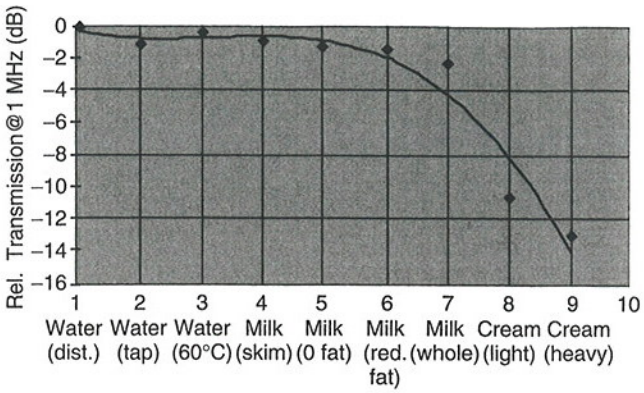


Figure 50. Estimation of fat content in various types of milk and milk products using distilled water as a reference. Ultrasound measurement here is the relative transmission of 1 MHz frequency in samples. Samples in plastic bottles were analyzed in the transmission mode and transmitting and receiving transducers were separated from the bottles by ~15 mm of ambient air.

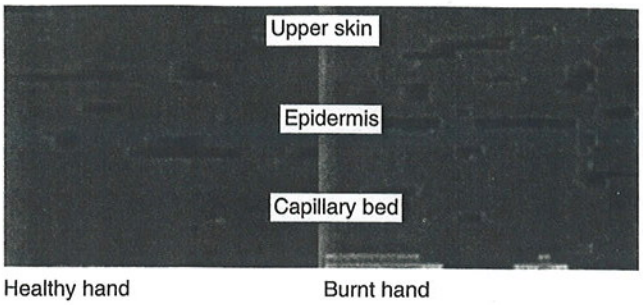


Figure 52. Noncontact ultrasound image cross section of healthy (left) and burnt (right) human hands. Note the damaged region between the epidermis and capillary bed in the burnt hand. The transducer used for this analysis was a noncontact 2-MHz in the reflection (pulse-echo) mode. These images were generated by Joie P. Jones, University of California, Irvine, and his Burn Center team.

and food packages has also been determined by this technique. Analogous to green ceramics and like material (Figs. 30, 33, and 34), tablets, capsules, and other powder-based pharmaceutical products have also been characterized as functions of the velocity and frequency dependence of ultrasound attenuation. This method has also been successfully applied to detect the presence or absence of liquids (milk, beverages, chemicals) in cardboard cartons and plastic and metal containers. The feasibility of detecting the absence or presence of foreign and unwanted materials in liquid containers has also been successfully demonstrated.

Medical

One of the first medical applications of NC transducers was evaluating burnt skin and bed sores in burn victims (24). By using 2-MHz transducers and a prototype portable ultrasonic pulser-receiver, many observations were made at various points on a healthy and a burnt human hand at the Burn Center, University of California, Irvine, under the direction of Joie P. Jones. The NC transducer was used in the reflection (pulse-echo) mode. The collected data were processed to create internal images of two skin conditions (Fig. 52). Detection of damage underneath the burnt skin is evident from the disruption of the interface between the epidermis and the capillary bed. Figure 53 shows the propagation of noncontact ultrasound through a human heel paving the way for bone disease (osteoporosis) diagnostics without any contact with the patient.

Very High Frequency Noncontact Ultrasonic Antennas

Because the sensitivity of NC transducers is very high, it is also possible to use them in a passive mode as "listeners" for very high frequencies. To demonstrate this, we conducted an experiment using the setup shown in Fig. 54. Here, the source of high frequency is 25-mm thick carbon steel, generated by a transducer (in contact with steel) that has a bandwidth at −6 dB from 800 kHz to 8 MHz. This transducer was excited by a single burst of a 16-volt sine wave. A noncontact transducer, nominally 3.5 MHz and 12.5-mm active area diameter, was placed 3 mm from

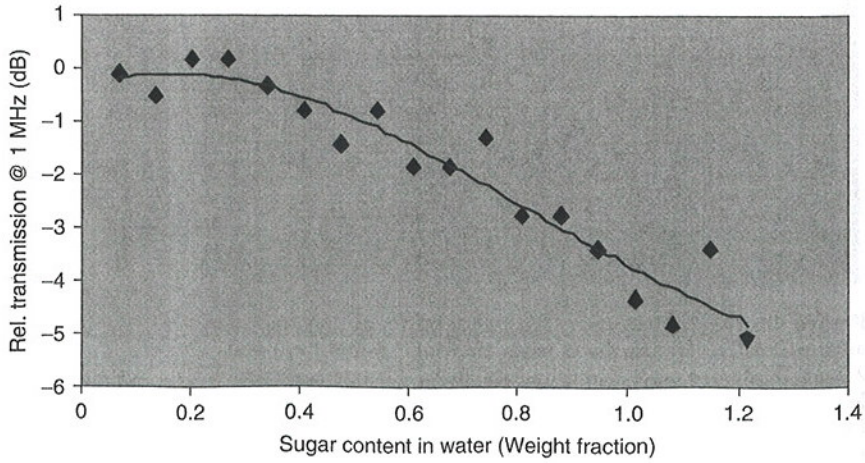


Figure 51. Estimation of sugar content in water. Ultrasound measurement here is the relative transmission of 1-MHz frequency in samples. Samples in plastic bottles were analyzed in the transmission mode, and transmitting and receiving transducers were separated from the bottles by ~15 mm of ambient air.

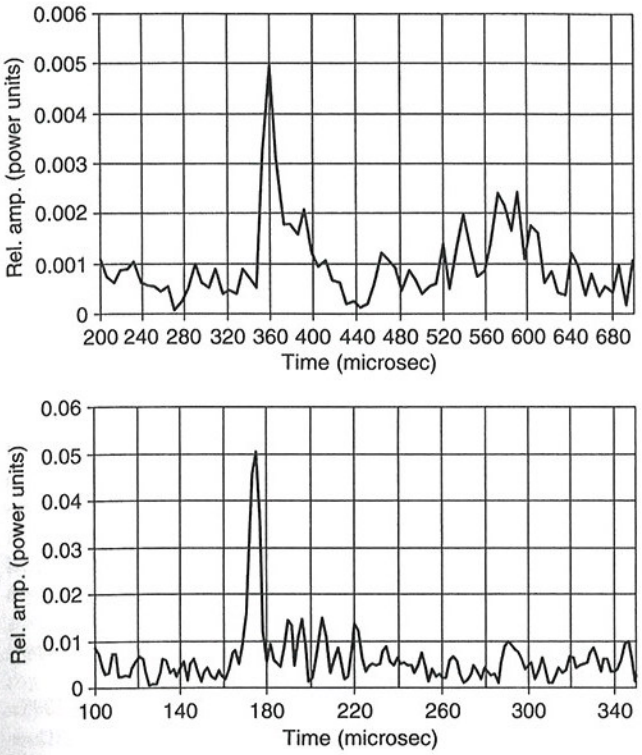


Figure 53. Noncontact ultrasound transmission through a human heel using 250-kHz (top) and 500-kHz (bottom) frequency transducers. The first peak corresponds to ultrasound transmission through air, skin, tissue, and heel bone. Other peaks are not identified.

the material surface in ambient air. The ultrasound received by this transducer was amplified by a 64-dB gain. Figure 55 shows the time and frequency domain of the ultrasound detected (heard) by the NC transducer. By sweeping the frequency across a wide range, the frequency-dependent response from the source (vibrating system) can be investigated and related to its characteristics or condition. In this mode, we successfully interrogated frequencies

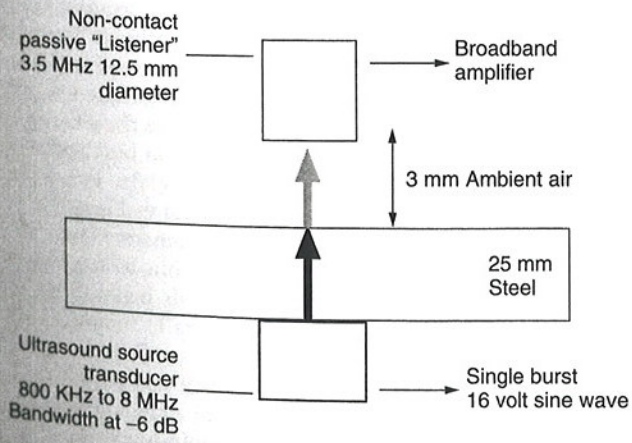


Figure 54. Experimental setup for passive operation of noncontact transducer.

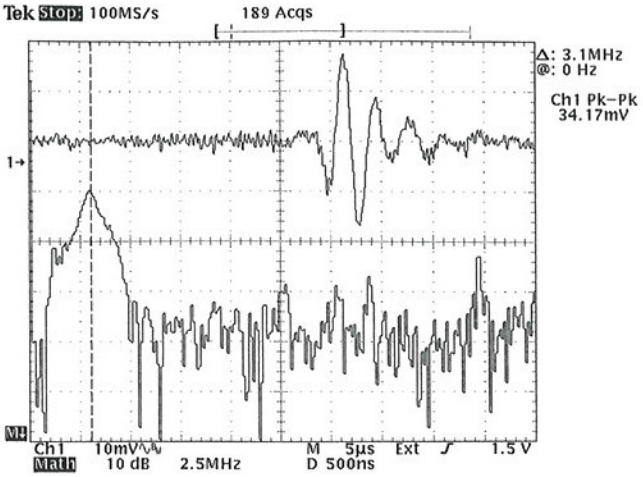


Figure 55. Time and frequency domains of ultrasound detected by noncontact transducer, per Fig. 54 setup.

as high as 7 MHz in ambient air. This opens the door to noncontact acoustic emission, acoustoultrasonics, and any other situation where detection of high frequency ultrasound is desired. Applications of the passive use of NC transducers are dynamics of vibration, materials cutting, testing of railroad, highways, bridges, runways, etc.

Other Noncontact Ultrasound Applications

Besides the applications of NCU described here, this mode can also be used for level detection; dimensional and proximity analysis; high temperature material evaluation; analysis of liquid-sensitive and hazardous material, and analysis of gases and liquids. Finally, it suffices to say that if ultrasound can be propagated through a medium or reflected from an interface, then much information about the medium and the interface can be obtained.

CONCLUSIONS

In this paper, we outlined the significance of ultrasound for nondestructive characterization of materials and for noninvasive diagnostic applications in the medical field. We have also shown the feasibility of noncontact ultrasonic measurements in the time, frequency, and image domains, analogous to other wave-based methods.

Underscoring the significance of the noncontact ultrasound mode, we presented a detailed discussion about the difficulty of achieving this mode. We have also shown that this work ultimately resulted in very high transduction noncontact transducers, thus making the noncontact ultrasound mode a reality. Applications of these transducers in industry and the medical field have been described by using documentary evidence.

We also provided an introduction to a novel ultrasonic noncontact analyzer and its applications for characterizing industrial and biomedical materials and products.

We believe that the noncontact ultrasound mode is among the most significant developments for characterizing and analyzing all states of matter. Though we have

provided selected examples of its applications, there is no doubt that the users of this technology will further enhance its use in materials quality, process control, and health care in our increasingly complex world. This advancement in the field of ultrasound and materials characterization has opened much needed and unprecedented opportunities in research and education.

ACKNOWLEDGEMENTS

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