NON-CONTACT ULTRASOUND:
The Final Frontier in Non-destructive Analysis

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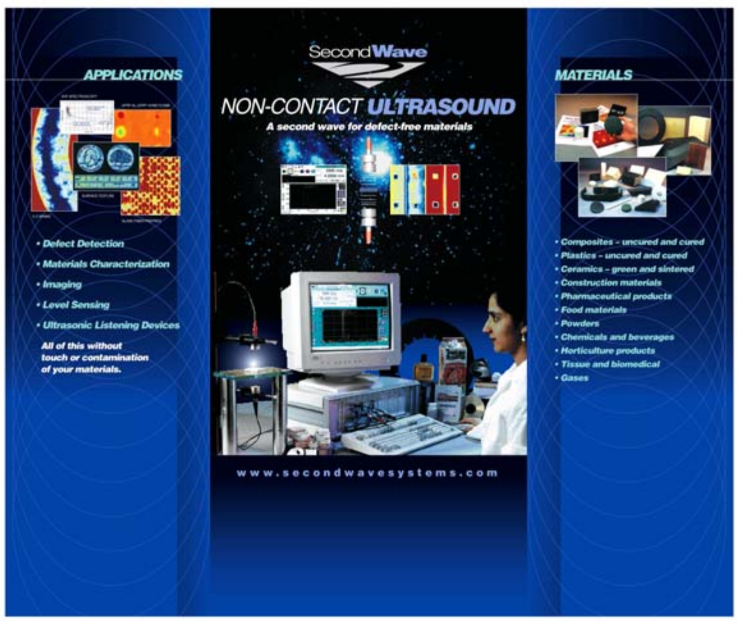

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A word about this publication

The work presented in this publication began in 1973 when I first got involved with ultrasound at the Glass Research Center of PPG Industries. We needed to ultrasonically characterize multi-layer porous ceramic structures at very high temperatures. This required dry coupling, high frequency, and extremely broadband high temperature resistant transducers. Regrettably, neither these transducers, nor the analytical *modus operandi* existed back in 1973. At that time ultrasound was preoccupied with overt flaw detection in metals. Despite the enormity of knowledge and developments in other wave-based characterization methods, ultrasound appeared virtually absent from the materials characterization scene.

In 1978 I started an *ad hoc* R&D program at Ultran Laboratories with the ultimate aim of developing ultrasound analogous to other wave-based methods. Since then we have advanced this subject substantially by creating unusually large bandwidth, high frequency, longitudinal and shear wave transducers, some dry coupling and non-coupling types. We demonstrated ultrasonic characterization of green, consolidated particles, porous, and liquid-sensitive materials in time (velocity-density) and frequency (attenuation as a function of microstructure/texture) domains. Ultimately this work also produced a scheme for the ultrasonic classification of materials, transducer selection guide, and transducer libraries.

However, our attention was focused on **eliminating all types of contact with the test media** and to **analyzing and presenting ultrasonic information in materials terms.** The former was achieved in 1995 through the development of phenomenally high transduction piezoelectric transducers. The latter was accomplished in 1998 by the creation of a dedicated non-contact ultrasonic analyzer. Both of these advancements have now earned the U.S. and international patents. A new company – SecondWave Systems -- was formed to underscore the significance of these developments.

This publication provides a detailed introduction to Non-Contact Ultrasonic (NCU) transducers and the NCU analyzer as well as a number of applications of relevance to materials industry, food, pharmaceutical, construction, forensic, and medical fields. Readers will find these advancements ready for many on and off–line applications in materials processing, quality control, reliability, and safety, besides developing their own ideas for the betterment of our increasingly complex world.

The author gratefully acknowledges the assistance of M. Langron, Ultran Laboratories, in producing the transducers used for this paper. Enthusiastic support and the valuable suggestions of I. Neeson -- VN Instruments, Canada; E. Blomme, Katholieke Hogeschool -- Belgium, M. Landa -- Academy of Sciences, Czech Republic, and B. Hosten, Universite Bordeaux -- France are acknowledged with much gratitude. The work presented in this paper was supported by the continuing efforts of SecondWave for the advancement of industry and medical science through innovative developments in ultrasound.

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We challenge the business community, entrepreneurs, engineers, and scientists to imagine what can be accomplished with modern ultrasound -- which once was difficult, or even impossible!

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*NON-CONTACT ULTRASOUND: The Final Frontier in Non-destructive Analysis

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ABSTRACT

Nondestructive and Non-invasive ultrasound is commonly used to test materials for defects and properties and to examine the human body for diagnostic evaluations. Though the value of ultrasound in industry and medical fields is obvious, its modus operandi is severely limited by the physical coupling of ultrasonic transducers with the test medium by applying liquids gels, grease, glycerin water, etc. For the past 20 years, few attempts have been made to change this mode of coupling to non-contact mode. Variety of ultrasound generation mechanisms have been developed by utilizing piezoelectric, capacitive, laser, and electromagnetic phenomena. In this chapter we describe the development of phenomenally high air/gas transduction piezoelectric transducers in the 80kHz to 10MHz frequency range. We also introduce a dedicated ultrasonic non-contact analyzer system which is characterized by >150dB dynamic range and ±1ns time-of-flight accuracy. Based on the combination of the new transducers and the analytical system, a number of industrial and medical applications in time, frequency, and image domains are also delineated.

1 INTRODUCTION

1.1 Significance of Materials Characterization

In order to develop and manufacture applications specific materials, they must be characterized to insure producibility and reliable performance under the intended applications conditions. "Characterization describes those features of the composition and structure (including defects) of a material that are significant for a particular preparation, study of properties, or use, and suffice for the reproduction of the material (1)".

Characterized information is of value in materials processing, including process variables (composition, temperature, pressure, and times), and materials applications and uses, Fig. 1. Summarily, it is important to know that all materials processing conditions are right in generating the right properties and features of the material. In order to obtain this information a number of methods of materials characterization – for chemical composition, texture/microstructure, defects, and properties -- are required. *Mr. Spock's tricorder and Dr. McCoy's medical scanner captivate our imagination for an all encompassing analytical gadget.* Nevertheless, it is highly desired to get maximum information about the material during various stages of its manufacture and applications without destroying or altering it during the process of characterization. Since the early 1970s much attention has been focused on developing Non-Destructive Characterization (NDC) methods by utilizing electro-magnetic, thermal, and mechanical waves as the characterizing vehicles. This paper deals with ultrasonic method that underscores the recent advances in non-contact and analytical methodologies.

1.2 Ultrasonic Characterization of Materials

Ultrasound is widely used in health care for non-invasive diagnostics and in industry for non-destructive 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 materials

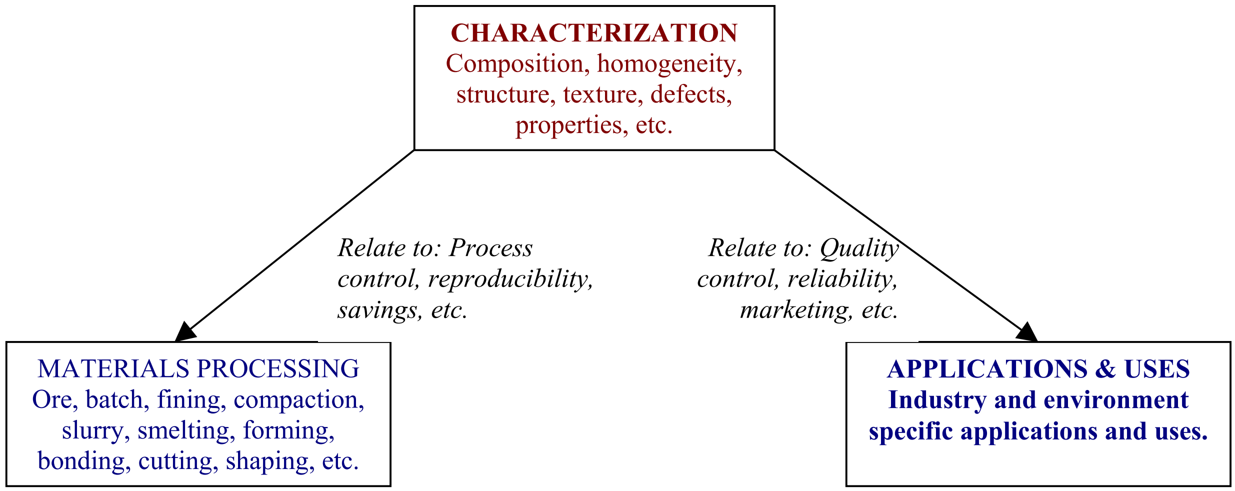

Fig. 1. Characterization of materials and its significance (1.)

characteristics such as density, thickness, mechanical properties, and level sensing, among others. 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 upon wave-material interaction phenomena. These are: optical, x-ray, infra-red, Raman spectroscopy, nuclear magnetic resonance, neutron, γ-ray, mass spectrometry, etc. 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 non-hazardous, and provides the means to determine mechanical properties, microstructure, imaging, & microscopy. Ultrasonic equipment is also portable and cost-effective. Most significantly, ultrasound is applicable to all states of matter, with the exception of plasma and vacuum. Furthermore, propagation of ultrasound in a material is not affected by its transparency or opacity. Table I 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 multi-layered, 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; robotics, artificial intelligence, and so on. 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 the industry, it can replace harmful x-rays in many critical instances. Ultrasound is useful for visualization of the fetus, measurement of 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 with advanced electronics and signal processing to the point that we can measure resolution and detectability in the micrometer range.

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Apparently, ultrasound has come a long way since the discovery of piezoelectricity by Pierre and Jacques Curie in 1876 (2) and its first application by Richardson in 1913 for sonar (3).

Table I. 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 & 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 or texture, 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, thickness, and attenuation mapping as functions of discrete point analysis by raster C-scanning, linear, 2D, or phased array, by synthetic aperture techniques or by the integration of other methods.	Surface and internal imaging of defects, microstructure, density, velocity, mechanical properties, true 2-D and 3-D imaging.

While ultrasound and its applications have grown phenomenally in the recent years, 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 is based upon the severe limitation of a physical contact between the transducer and the test medium by a liquid gel (4). If this contact could be eliminated, then we could do applications such as diagnosing burnt or malignant skin damage without discomfort to the patient. Similarly, a number of industrial materials sensitive to liquid contact could be tested for the measurements of thickness, density, mechanical properties, defect detection, etc. This is significant in assuring materials quality and process control, and for cost-effective production. The development of Non-Contact Ultrasound (NCU) mode would allow many more useful applications of ultrasound. For example, with 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 & lumber) could also be tested under manufacturing conditions. NCU can also be applied to medical problems where contact with a patient can be harmful, as in the evaluation of wounds and diagnosis of the eye.

However, for NCU to become a reality, we first need the 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 ~200kHz to >5MHz) cannot be propagated through solids or liquids without a physical contact between the transducer and the test medium. Therefore, NCU has been generally considered an impossible dream. This is understandably due to the phenomenal acoustic impedance mismatch 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, super-hard alloys and dense ceramics, cermets, diamond, and diamond-like materials. To realize the NCU mode, this acoustic impedance barrier must be broken. And for this to happen, it is imperative that ultrasonic transducers be characterized by phenomenally high sensitivity. Achieving of NCU analogous to *"throwing a helium-filled rubber balloon so that it can pierce through a stainless steel wall!"*

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2 REALITY THAT DEFIES NON-CONTACT ULTRASOUND

The exorbitant mismatch between acoustic impedance of the coupling medium air and that of the test material generates enormous resistance for 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 with 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 (Transmission co-efficient in the medium of propagation) = $4Z_1Z_2/(Z_1 + Z_2)^2$ (1)

where Z_1 is the acoustic impedance of ultrasound carrier medium (for example, air in the case of NCU mode)), and Z_2 is the acoustic impedance of the test medium. The transmission co-efficient 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 with 0° incidence on the interface between the two media, i.e.,

$T \propto V^2 / V_0^2$ (2)

This relation can also be described in decibel scale, i.e.,

Energy transferred in the medium of propagation = 20 log T, [dB] (3)

For more description and significance of plane wave transmission and reflection at a number of interfaces in terms of acoustical pressure and intensity, see ref. (5).

In the case of non-contact transmission ultrasound 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. 2. Therefore, the high loss of energy at air-material interface is doubled by further loss at the material-air interface. By utilizing equations 1 and 3,

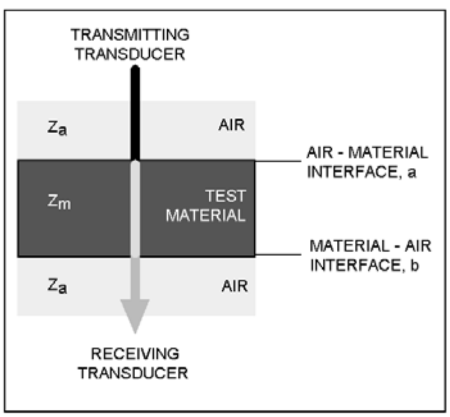

Fig. 2. Interfaces to be crossed by ultrasound (shown by arrow) in non-contact transmission mode in order to propagate ultrasound through a test material. Interface 'a' corresponds to air-material (from acoustic impedance Z_a to Z_m) transmission. Interface 'b' corresponds to material-air (from acoustic impedance Z_m to Z_a) transmission.

Table II provides the transmission co-efficients and energy losses in selected test materials in the non-contact ultrasound mode. As a reference, similar losses for water immersion (contact technique) are also provided. From this data the following conclusions can be drawn:

i. Transmission losses decrease as the acoustic impedance of the test material comes within the vicinity of the coupling medium, whether it is air or water.

ii. Total energy loss at various interfaces in the non-contact transmission mode can run as high as six orders of magnitude when compared to similar losses by using water as the coupling medium.

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TABLE II. Transmission co-efficients and energy transfer in selected materials at various interfaces in the non-contact mode, per Fig. 1. As a reference, similar data for water is also shown. Z (air) = 415Rayl. Z (water) = 1.5Mrayl. 1 Rayl = kg/m^{2}s.

MATERIAL Z_m (Mrayl)	INTERFACE Fig. 1	TRANSMISSION CO-EFFICIENT, T equation 1		ENERGY TRANSFER equation 3 (dB)		TOTAL ENERGY LOSS AT INTERFACES a + b (dB)	
		In Air	In Water	In Air	In Water	In Air	In Water
Steel 51.0	Air – Steel, a Steel – Air, b	0.000034 0.000034	0.11 0.11	-89 -89	-19 -19	178	38
Aluminum 17.0	Air – Aluminum, a Aluminum – Air, b	0.0001 0.0001	0.3 0.3	-80 -80	-10 -10	160	20
Acrylic 3.5	Air – Acrylic, a Acrylic – Air, b	0.0005 0.0005	0.84 0.84	-66 -66	-1.5 -1.5	132	3
Silicone Rubber 1.0	Air – Rubber, a Rubber – Air, b	0.018 0.018	0.96 0.96	-35 -35	-0.35 -0.35	70	<1

While conducting this exercise, we did not address the issues of 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 non-contact 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 since attenuation in a medium increases as a function of the fourth power of the frequency, transmission of MHz frequencies in air becomes almost incomprehensible. To overcome these NCU-defying realities, we need to first create ultrasonic transducers that are characterized by high sensitivity (or very low insertion loss). Sensitivity is needed not only to overcome interfacial transmission losses, Table II, but also to facilitate transducer excitation by relatively low power voltages. This will help avoid the 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 of this task has captivated the imagination of materials and transducer researchers.

3 PURSUIT OF NCU TRANSDUCERS

A few researchers have tried to develop non-contact means for materials characterization by utilizing the wave phenomena, which includes optics, thermal, infrared, X-ray, and nuclear magnetic resonance. In pursuit of bulk ultrasonic wave propagation in 1963, White (6) reported the generation of elastic waves in solid materials by the momentary heating of 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 process of testing.

Next came laser-induced ultrasound, Bondarenko, et al. (7). It was used to characterize the Rayleigh waves in metals (8) and for subsurface materials evaluation (9). The laser-based method has been applied to those materials which could withstand the impact of a high power laser beam. Laser-based ultrasound has become acceptable for high melting point metals and ceramics. The non-destructiveness 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, tissue, etc. Ultrasound generated by electromagnetic acoustic transducers has been used in the NCU mode for non-destructive testing (10). This method is only applicable to ferromagnetic materials.

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The various non-contact analytical methods outlined above 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 the test media by the non-contact mode -- as shown in Table II -- presents us with 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 non-contact ultrasound was the testing of styrofoam blocks by utilizing a 25 kHz frequency (11). A precursor to high frequency non-contact transducers was the 1982 development of piezoelectric dry coupling longitudinal and shear wave transducers up to 25MHz frequency. Since 1983, these transducers have been commercially available for characterizing thickness, velocity, elastic and mechanical properties of green, porous, and dense materials (12,13,14). Dry coupling transducers feature a solid compliant and acoustically transparent transitional layer in front of the piezoelectric materials such as lead meta-niobates and lead zirconate-lead titanate. These devices, which eliminate the use of liquid couplant, do require contact with the material.

An important by-product of dry coupling devices was the development of air/gas propagation transducers, which utilize less than a 1 Mrayl acoustic impedance matching layer of a non-rubber 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 ~5MHz frequency and receiving up to 20MHz. Air/gas propagation transducers, between 250kHz to ~5MHz, 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 1MHz and 2MHz frequency were also produced at Stanford University by utilizing silicone rubber as the front acoustic impedance matching layer (15). By using such a transducer at 1MHz, the distance in air could be measured from 20mm to 400mm with an accuracy of 0.5mm. 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 (16,17). Researchers at Strathclyde University (18) have reported air-coupling transducers based upon piezoelectric composites between 250kHz to 1.5MHz frequencies. By utilizing tone burst transducer excitation, they have been successful in producing millivolt level transmitted signals through a composite laminated honeycomb structure at 500kHz.

More recently, piezoelectric transducers featuring perfect acoustic impedance matched layers for optimum transduction in air have been successfully developed from <100kHz to 5MHz (19)[1]. The sensitivity of these new transducers in air is merely 30dB lower than their conventional contact counterparts. As a result, ultrasound in the MHz region can be easily propagated through practically any medium, including even the very high acoustic impedance materials such as steel, cermets, and dense ceramics. This advancement, the major focus of this paper, will be discussed in detail along with the various medical and industrial applications in non-contact 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 micro-machined capacitance air transducers with the latter claiming a high 11 MHz frequency (20,21). These transducers -- characterized by high bandwidths -- have been used to evaluate composites and other materials. At the University of Bordeaux, ultrasound experts have reported the generation and detection of Lamb waves in non-contact mode in anisotropic viscoelastic materials by utilizing capacitive transducers (22).

[1] *U.S. and international patents granted. US Patent #6,311,573.*

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Though much progress has been made in enhancing the transduction efficiency of transducers based upon piezoelectric and capacitive phenomena, from a practical standpoint these advancements have by no means reached a saturation point. In the subsequent sections of this paper we describe the successful development of piezoelectric transducers which are characterized by extraordinarily high sensitivities in a frequency range from 80 kHz to 10 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 MHz to 5 MHz can be propagated through a number of solids in the NCU mode.

4 PIEZOELECTRIC TRANSDUCERS FOR UNLIMITED NCU

The efficiency of an ultrasonic transducer is dependent on the coupling co-efficients and other electro-mechanical properties of the piezoelectric material. It also depends upon the mechanism by which ultrasound is transferred from the piezoelectric material to the medium in which ultrasound needs to be propagated. In the non-contact mode, this medium is air. Since 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 it is the characteristics of the final layer that determine the transduction efficiency of a transducer device. In the case of non-contact transducers, the significance of the final acoustic impedance matching layer cannot be over-emphasized. Since 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. 3. To understand this, we examine the effect of the final acoustic impedance matching layer on the piezoelectric

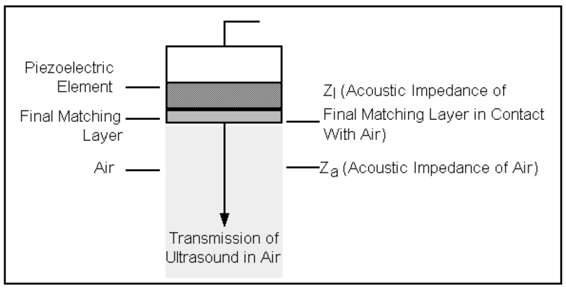

Fig. 3. Schematic of an ultrasonic transducer showing the critical final acoustic impedance matching layer relative to the piezoelectric element and coupling medium air.

material with respect to transmission of ultrasound from it (piezoelectric element) to air, as per equations 1 and 3. Table III shows transmission co-efficients and 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. From this data, the following conclusions can be drawn:

i. The transmission co-efficient in air increases as the acoustic impedance of the front layer on the piezoelectric material is reduced.

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

In light of references 15, 16, 17, and 18 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. In these transducer designs the polymer layer can be with or without porosity or with 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 –58 dB to –54 dB transfer of ultrasonic energy in air, which is significant for the propagation of ultrasound in some solids up to ~2 MHz ultrasound in the non-contact mode. For example, by using a suitable transducer excitation mechanism with 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 in materials >3 Mrayl by such transducers is arduous, if not impossible.

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TABLE III. Transmission co-efficients and energy transferred in air as a function of the final acoustic impedance matching layer on the piezoelectric element. As a reference, similar data is also shown with water as the coupling medium. Z (air): 415 Rayl. Z (water): 1.5 MRayl.

FINAL LAYER ON PIEZOELECTRIC ELEMENT Z (Mrayl)	TRANSMISSION CO-EFFICIENT, T equation 1		ENERGY TRANSFERRED equation 3 (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
*Pressed Fiber, 0.1	0.018	--	-35	---

While the AC transducers based upon polymer matching layers transducers do demonstrate the feasibility of non-contact ultrasound, but are far from being the most efficient. In order to enhance the 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 a transducer with compressed fiber as the final matching layer (19.) For the sake of simplicity and comparison, we will identify them as Non Contact (NC) transducers. This transducer design exhibited unprecedented and phenomenal transduction in air which was found to be sufficient for NCU transmission in practically all material types. Perfected in 1997, the NC transducers are able to increase ultrasonic energy transfer from the transducer to air from –54 dB (AC transducers) to –35 dB, Table II. Increment of sensitivity by an order of magnitude is extremely significant and warrants special attention. After initial trials of 200kHz, 500kHz, 1MHz, and 2MHz, NC transducers have been produced up to ~10 MHz within a dimensional range of <1 mm to >75 mm, Fig. 4. However, from a practical standpoint they have been shown to propagate up to 5MHz ultrasound in most material types in the NCU mode under ambient air environment. Leaving aside transmission in plastics and composites, the sensitivity of NC transducers is also high enough for transmission in materials with extremely high acoustic impedance such as, steel, dense ceramics, and cermets. In the following sections we provide detailed observations of the NC transducers and their sensitivity compared to the AC types.

4.1 Characteristics of NCU Transducers

NC transducers, like their contact or water-coupled counterparts, can also be characterized in the transmission or in the reflection (pulse echo) modes. Fig. 5 shows the setup for characterizing transducers in the transmission mode which is used to analyze the NC and AC transducers. Here, the transmitting and receiving transducers are aligned and separated by a 10mm (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 with a mechanism to measure the frequency domain characteristics. Frequency and bandwidth are measured directly from the frequency domain envelope, while V_x, the received signal amplitude in volts, and the pulse width are measured from the time domain rf trace. Signal-to-Noise-Ratio (SNR) is determined by the following relation when measurements are made without signal averaging. It is understood that while doing so the instrument and cable noise also factor into the measurement.

$$\mathbf{SNR = 20 \log V_x/V_n, [dB]} \qquad \mathbf{(4)}$$

Where V_n is the amplitude of the noise in volts.

Sensitivity (insertion loss) is determined by,

$$\mathbf{S = 20 \log V_x/V_0, [dB]} \qquad \mathbf{(5)}$$

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Fig. 4. Non-contact ultrasonic transducers.

Frequency range: <80 kHz to ~10 MHz.
Dimensional range: <1 mm to >75 mm.

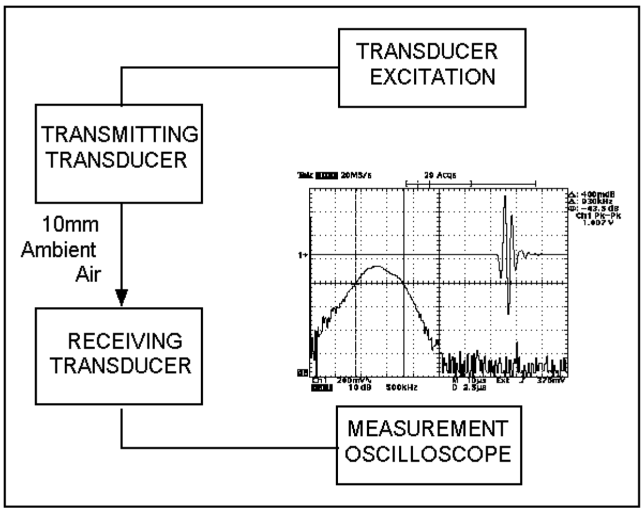

Fig. 5. Non-contact ultrasonic transducer characterization scheme in transmission mode.

Frequency, Bandwidth, Pulse Width, and Signal-To-Noise Ratio: Directly read from the oscilloscope.

Sensitivity = 20Log (V_x/V_0). V_0 = Excitation in volts. V_x = Received signal amplitude in volts

By utilizing this characterization scheme, several NC transducers were analyzed under ambient air environment. Figures 6, 7, 8, and 9 show typical time and frequency domains for 200kHz, 1.5MHz, 3.0MHz and 5.0MHz NC transducers with their salient acoustic characteristics.

4.2 Sensitivity Comparison of NC and AC Transducers with Conventional Contact Transducers

Since sensitivity is the most critical requirement for NC or AC transducers, it is important that some kind of a comparison scheme be developed. To this effect we have chosen conventional contact, water immersion transducers as a reference. A number of NC transducers were characterized for sensitivity in the transmission mode according to Fig. 5. Similar transducers, suitable for conventional contact water immersion operation with acoustic impedance matching to water, were characterized in water for sensitivity measurements. The setup for such transducer characterization is the same as in Fig. 5, except that in this case the 10mm air column was replaced by a 10mm column of water. Sensitivities for both transducer types were calculated according to equation 5, shown in Table IV.

From this comparison it is quite clear that the new non-contact transducers are approximately 30dB below their contact counterparts. AC transducers were found to be approximately 50 dB below their conventional contact water immersion counterparts.

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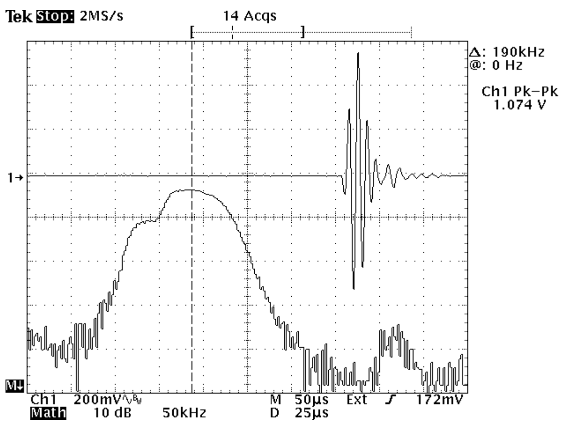

Fig. 6. 200 kHz, 50 mm diameter NC transducers. BCF: 200 kHz. Bandwidth @ -6dB: 100 kHz (50%). Sensitivity: -46 dB. SNR: 50 dB.

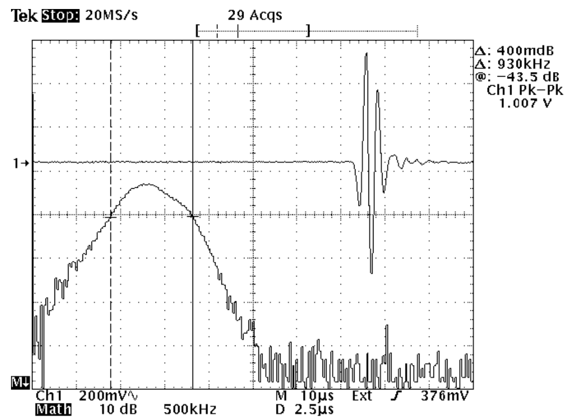

Fig. 7. 1.5 MHz, 25 mm diameter NC transducers. BCF: 1.4 MHz. Bandwidth @ -6dB: 0.92 MHz (65%). Sensitivity: -58 dB. SNR: 46 dB.

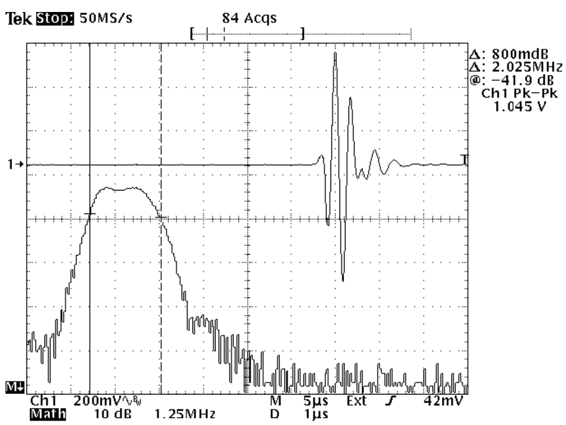

Fig. 8. 3 MHz, 12.5 mm diameter NC transducers. BCF: 2.6 MHz. Bandwidth @ -6dB: 2 MHz (75%). Sensitivity: -62 dB. SNR: 40 dB.

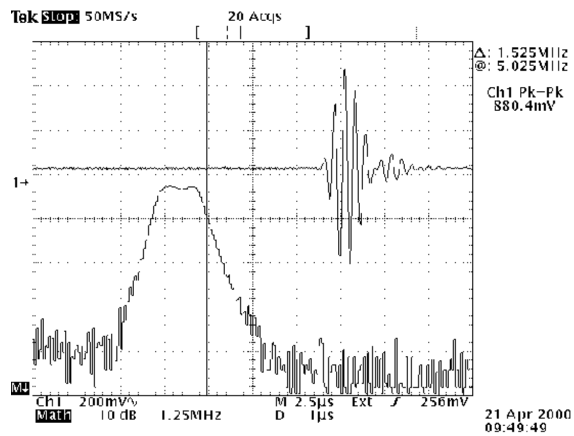

Fig. 9. 5 MHz, 12.5 mm diameter NC transducers. BCF: 4.5 MHz. Bandwidth @ -6dB: 1.5 MHz (33%). Sensitivity: -68 dB. SNR: 40 dB.

4.3 Applications Related Experiments and Sensitivity Comparison

In the previous section we demonstrated high sensitivity of new NC and AC transducers by analyzing them according to a transducer characterization scheme and by comparing them to similar observations from 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 applications-related experiments aimed at propagating ultrasound in an NCU mode through a solid material by utilizing AC and NC transducers. Figures 10 and 11 present observations in support of this. Both observations correspond to NCU transmission through 20mm thick aluminum by 1MHz and 20mm active area diameter transducers in direct transmission mode. In both cases transducers are separated by ~5mm air column from the test material surfaces. Furthermore, in figures 10 and 11, the transmitting transducer was excited by a high energy 400 volt (into 4Ω input impedance) pulser, while the received signal from the receiving transducer was amplified by 64dB gain. The key difference is that observation in Fig. 10 was obtained by AC

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Table IV. Sensitivity Comparison of Non-Contact and Conventional Contact Transducers.* Mode of Testing: Transmission. Medium of Testing: 10mm Ambient Air for Non-Contact and 10mm Water for Contact Transducers

FREQUENCY (MHz)	ACTIVE DIAMETER (mm)	SENSITIVITY IN AMBIENT AIR (dB)	SENSITIVITY IN WATER (dB)
0.25	50 25	-38 -46	-18 -26
0.5	50 25	-44 -50	-20 -24
1.0	25 19 12.5 3.2	-52 -54 -56 -62	-32 -34 -36 -38
1.5	12.5	-58	-38
2.0	12.5 1.5	-58 -66	-38 -40
3.0	12.5	-62	-38
5.0	12.5	-68	-40

*Sensitivities reported here were obtained by exciting a damped transmitting transducer with a broadband and ~15ns pulse. Tone burst excitation sensitivities were found to be generally 12dB to 20 dB higher than those reported here.

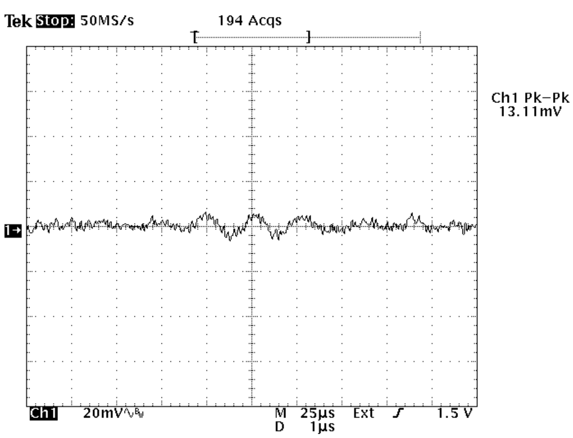

Fig. 10. A 1 MHz non-contact transmitted signal through 20 mm aluminum by using transducers based upon soft porous polymer matching layer. Excitation: 400 V into 4 Ω input impedance. Amplification: 64 dB. Signal amplitude: 13.1 mV.

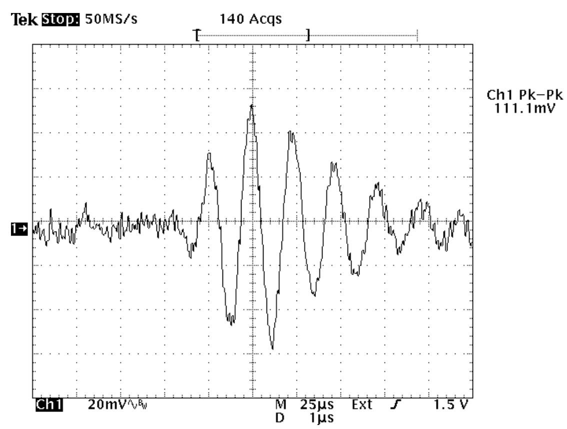

Fig. 11. A 1 MHz non-contact transmitted signal through 20 mm aluminum by using transducers based upon compressed fiber matching layer. Excitation: 400 V into 4 Ω input impedance. Amplification: 64 dB. Signal amplitude: 111.1 mV.

transducers and in Fig. 11 by NC transducers. Under these conditions, the amplitude of the transmitted signal through 20mm aluminum by AC transducers is 13.1mV, while with NC transducers it is 111.1mV. This clearly establishes the superiority of the new by AC transducers is 13.1mV, while with NC transducers it is 111.1mV. This clearly establishes the superiority of the new non-contact transducer design over the other air-coupled transducers described in references (15,16,17,18), including this author's air/gas propagation transducers commercially available from Ultran Laboratories since 1983.

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In order to further demonstrate the exceptionally high sensitivity of NC transducers, we decided to conduct a few experiments, which would normally be considered impossible! A setup analogous to the one described above was used, except in the present case the NC transmitter was excited by merely a single burst of 16 volt sine wave and 64 dB amplification of the received signal. Fig. 12 shows 1 MHz transmitted signals through aluminum, Graphite Fiber Re-enforced Plastic (GFRP) composite, and acrylic. Fig. 13 shows observations through these materials at 3 MHz.

It is fair to exclaim that without the exceptional nature of new non-contact transducers, such observations would merely be a figment of wild imagination!

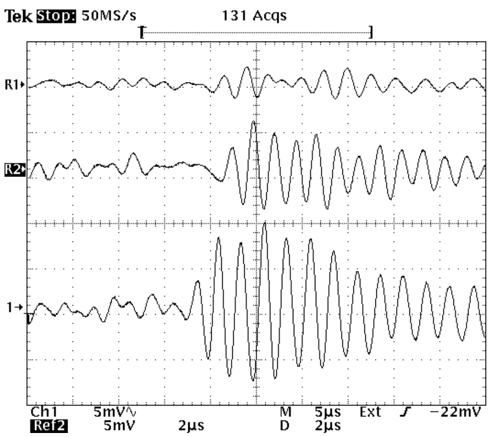

Fig. 12. 1 MHz NCU transmission with 16 V excitation and 64 dB amplification.
Top: 3.2 mm aluminum – 4 mV recd. amp.
Middle: 4.5 mm GFRP – 10 mV recd. amp.
Bottom: 3.2 mm Acrylic – 18 mV recd. amp.

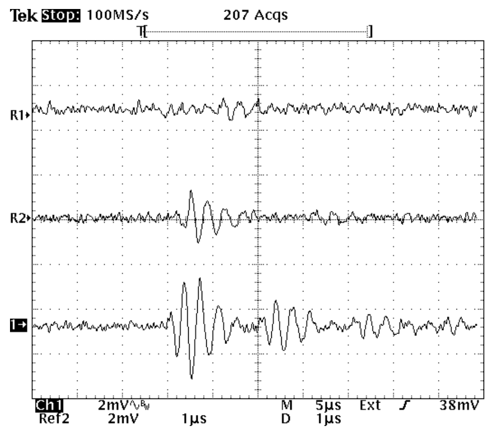

Fig. 13. 3 MHz NCU transmission with 16 V excitation and 64 dB amplification.
Top: 3.2 mm aluminum -- > 1mV recd. amp.
Middle: 4.5 mm GFRP -- >2 mV recd. amp.
Bottom: 3.2 mm Acrylic – 5 mV recd. amp.

The purpose of this exercise is focused on exhibiting the phenomenally high transduction efficiency of non-contact transducers. For practical usage of NCU such low energy transducer excitation, is apparently not enough, thus not recommended.

5 NON-CONTACT ULTRASONIC ANALYZER

As is evident from the foregoing 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 of conventional contact or immersion ultrasound. In order to accomplish this task the high transduction of NC transducers is not enough. For example, we still need to overcome the natural barrier of acoustic impedance mismatch between the coupling air and the test medium. From Table II we see that losses due to this mismatch are formidable. In order to circumvent this and without jeopardizing 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. Between 1997-98 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 (23.) It is based on the synthesis of a computer-generated chirp combined with the best attributes of the non-contact transducers. Signal processing in the NCA 1000 is done by synthetic aperture imaging techniques. The NCA 1000 is characterized by >150dB dynamic range and a Time-of-Flight (ToF) measurement accuracy of ±10ns under

[2] *U.S. patent #6,343,510.*

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ambient air conditions and better than ±1ns under closed conditions. The absolute accuracy of ToF under stable conditions of this system is 80 ps.

The NCA 1000, Fig. 14, measures ToF, thickness, velocity, and integrated response (area underneath transmitted or reflected signals in dB) of materials in time domain. By using the FFT mechanism of this system it is also possible to conduct non-contact 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. For further significance of these ultrasonic measurements, see Table V.

Fig. 14. Ultrasonic Non-Contact Analysis system, the NCA 1000, shown here with non-contact transducers and monitor screen displaying the thickness and velocity of the test material.

Table V. NCA 1000 Measurements and their Significance.

MEASUREMENT/ FUNCTION	SIGNIFICANCE OF MEASUREMENT
Longitudinal velocity	Density, open porosity, bulk & mechanical properties.
Surface velocities	Surface density, texture, elastic & mechanical properties.
Time of flight	For constant thickness materials, relate to velocity, open porosity, density, etc.
Thickness	Off-line and on-line thickness control
Transmissivity	Texture, microstructure, defects, and subtle variations.
Reflectivity	Surface texture, profile, particle size, etc.
Amplitude attenuation	Overt defects and subtle variations.
Frequency attenuation	Texture, microstructure, and subtle changes.
Transducer scanning	Internal and surface imaging of defects, velocity (density), thickness, time of flight, transmissivity, and reflectivity.

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6 REFLECTION AND TRANSMISSION IN NON-CONTACT MODE

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

6.1 Single Transducer Operation (Pulse Echo)

By operating one transducer simultaneously as transmitter and receiver (analogous to pulse echo technique), it is very easy to generate reflection from air-material interface due to the extremely high reflection co-efficient at this interface. However, in this mode it is nearly impossible to produce a far side reflection corresponding to the test material thickness under ambient air environment. This difficulty stems from several factors, such as extremely small transmission of ultrasound in the test material, extremely high beam spread on the surface of the material, and inherent initial pulse electrical noise associated with single transducer operation. 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. Fig. 15 shows pulse echo reflection signals from a 9mm thick silicone rubber sample. This observation was generated by using 1MHz focused NC transducer. Similar

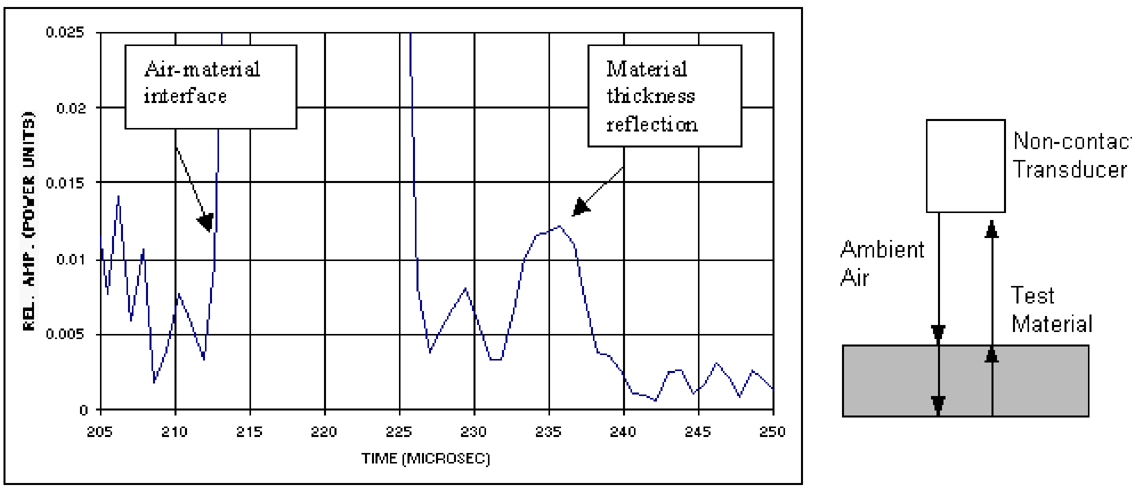

Fig. 15. Non-contact ultrasound pulse echo reflection from a 9mm thick silicone rubber. Transducer: 1MHz, 12.5mm active area diameter, and 76mm point focused. Transducer to material distance in air: 40mm. It is important to note that the material thickness reflection is ~40dB lower than that of the air-material interface.

results have also been observed for other plastic materials, though with considerable amount of difficulty. At the time of this writing, we have no concrete proof of generating pulse-echo observations under ambient environment from high acoustic impedance materials, such as metals, ceramics, etc. At the risk of sounding pessimistic, we believe that NCU pulse-echo technique will, at best, remain a distant possibility. On the other hand, if a material can be examined under high gas pressure, then the pulse-echo technique becomes more practical. For example, Fig. 16 demonstrates thickness reflections through a 8 mm plate of steel by using 4 MHz NCU transducer at 60 bar nitrogen.

Since the reflection from air-material interface is extremely strong with 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 non-contact ultrasound.

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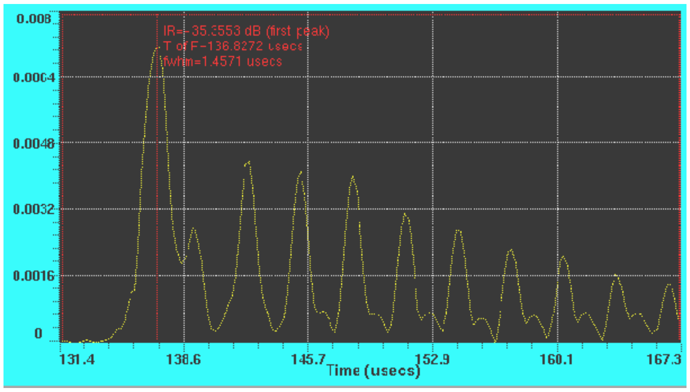

Fig. 16. Pulse echo thickness reflections from 8 mm thick steel plate by using 4 MHz NCU transducer at 60 bar nitrogen.
First peak: Material-gas interface.
Subsequent peaks: Material thickness multiples.

6.2 Separate T and R Operation on the Same Side (Pitch-Catch)

By using two non-contact transducers, one Transmitter (T) and the other Receiver (R), on the same side of the test material, Fig. 17, it is possible to launch and measure the characteristics of longitudinal, shear, and surface waves in practically all material types. Generation of these waves is determined by the Snell's law,

$$\mathbf{Sin_i / Sin_r = V_a / V_m} \tag{6}$$

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.

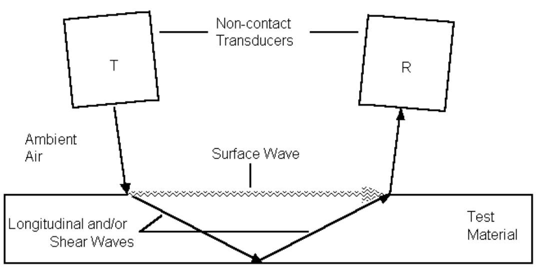

Fig. 17. Schematic of a setup for same side operation of separate Transmitting (T) and Receiving (R) transducers, also showing various types of wave propagation in the test material.

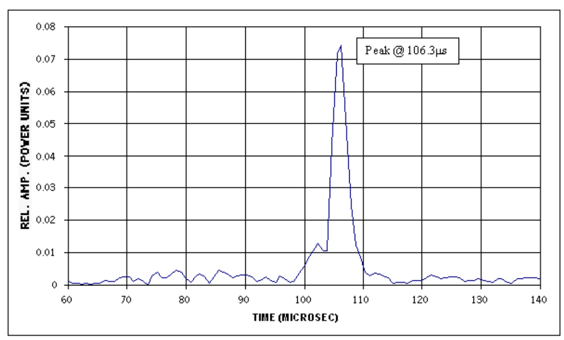

Fig. 18. Thickness reflection of longitudinal wave propagation in 12 mm thick aluminum, per Fig. 17 setup.

By manipulating the incident angle in air a variety of wave types can be produced in a test material. Fig. 18 shows the far side thickness reflection of longitudinal wave from 12mm thick aluminum. Fig. 19 shows the far side thickness reflection of longitudinal and shear waves from 32mm thick transparent polystyrene. Fig. 20 is a longitudinal wave refracted surface wave in aluminum produced with the incident angle equal to the first critical angle (i.e., total reflection of longitudinal wave) which for aluminum is 3.16°. Fig. 20 shows a shear wave refracted surface wave in aluminum, generated by the incident angle equal to the second critical angle (i.e., total reflection of shear wave), which for aluminum is 6.3°. 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 exhibit the feasibility of various types of bulk and surface wave generation by non-contact ultrasound. Applications of such measurements include: NCU evaluation of materials from one side, defect detection, anisotropy measurements, relationships of ultrasonic velocities to test material elastic and mechanical properties, etc.

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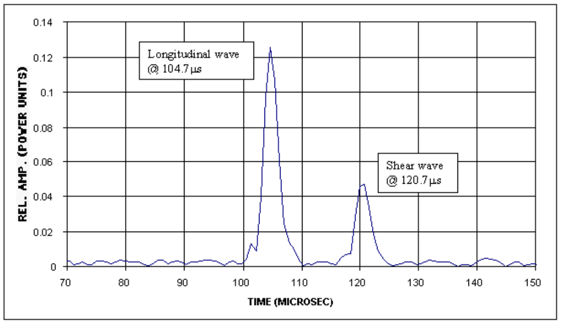

Fig. 19. Thickness reflections of longitudinal and shear waves in 32mm thick transparent polystyrene per Fig. 17 setup.

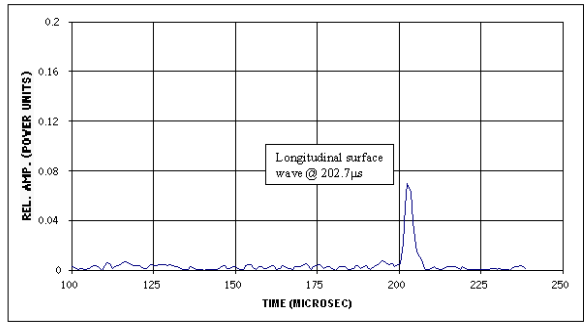

Fig. 20. Surface wave in aluminum produced by total reflection of longitudinal wave, i.e., when the incident angle is equal to the first critical angle.

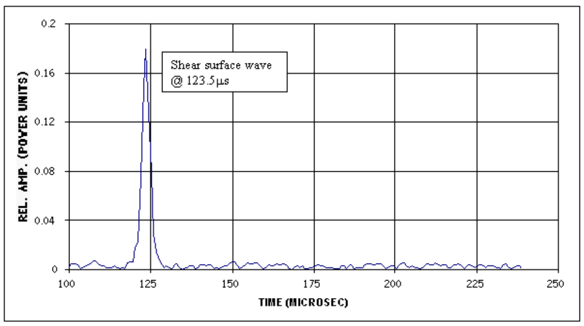

Fig. 21. Surface wave in aluminum produced by total reflection of shear wave when the incident angle is equal to the second critical angle.

6.3 Direct Transmission Operation

When a test material is inserted between two non-contact 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

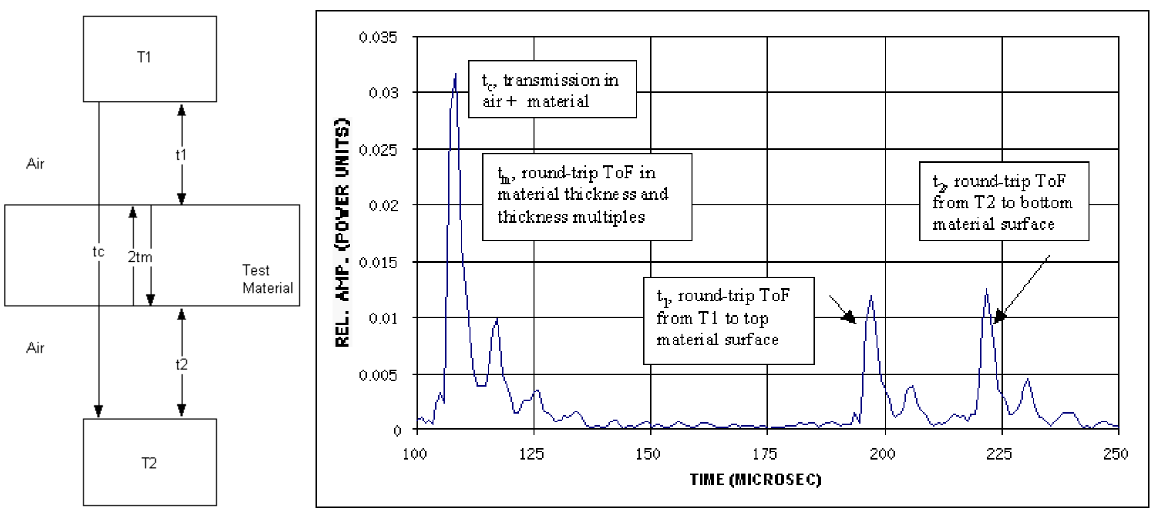

Fig. 22. Propagation of ultrasound in direct transmission non-contact mode. Left (schematic): tc is the complete Time of Flight (ToF) corresponding to propagation of ultrasound in air and the test material, 2tm is the round-trip ToF through the test material thickness, t1 and t2 are, respectively, ToFs from transducer T1 to the top surface of the materials, and transducer T2 to the bottom surface of the material. Right hand figure shows transmitted and reflected signals through a test material, corresponding to left hand setup.

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shown in Fig. 22. Direct transmission is relatively the easiest technique to apply in non-contact ultrasound. Therefore, it has been quite extensively studied and developed. Applications of this technique are numerous: thickness and velocity measurements, defect detection, texture and microstructure evaluation, transmission, velocity, thickness, and ToF imaging, detection of presence or absence of liquids in containers and many more.

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7 NON-CONTACT ULTRASONIC MEASUREMENTS

Since ultrasound can be reflected and transmitted through the test material and its surfaces, one can utilize their respective signals to make significant measurements in 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.

7.1 Velocity, Time of Flight, Density, and Thickness Measurements

There are several ways by which longitudinal wave velocity in the test materials can be determined by non-contact ultrasound. For example, if multiple reflections corresponding to the thickness of the test material are observed, Fig. 22, then one can measure the ToF, t_m, between the two successive peaks to determine the velocity of a known thickness material. The ToF measured this way corresponds to round trip ToF in the test material therefore,

$$\mathbf{V_m = 2d_m / t_m} \quad \mathbf{(7)}$$

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

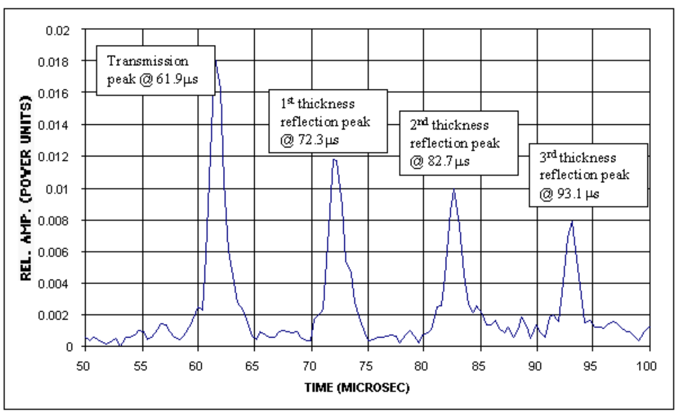

Fig. 23. Material velocity determination by direct transmission NCU propagation in a test material (in this case, 13.5mm thick isotropic graphite) characterized by multiple thickness reflections. Note that the ToF (round trip ToF through the material) between any two successive peaks is 10.4µs, thus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

It is important to note that the appearance of multiple thickness reflections in NCU mode is dependent upon 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 with thickness greater than one wave length in the test material, material thickness reflections are then 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 in a manner similar to 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.

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As seen in the aforementioned technique, in order 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 materials thickness and its velocity in the NCU mode, we must examine all paths of ultrasound transmission and reflection, i.e., to and from the test material. These paths relate to propagation of ultrasound relative to transmitting and receiving transducers "talking to each other" in the air column, ultrasound transmitted

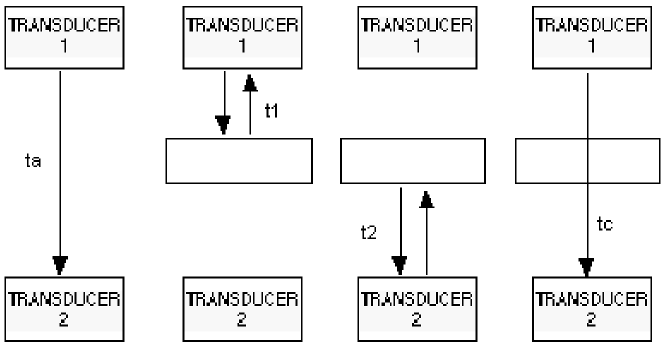

Fig. 24. Propagation of ultrasound with respect to test material in non-contact transmission mode. The NCA 1000 measures and calculates all times of flight shown in this figure, then displays them on the monitor screen, Fig. 25. See text for details.

through the test material, and ultrasound reflections from the test material surfaces in air. These paths of ultrasound propagation in 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 following:

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 will be 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 with the test material in between – measures ToF, t_c. If ultrasound is propagated from transducer 2 to transducer 1, the same ToF will be measured.

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

$$\mathbf{V_m = d_m/t_m} \quad \textbf{(8)}$$
$$\mathbf{d_m = V_a \times t_{am}} \quad \textbf{(9)}$$
$$\mathbf{t_{am} = t_a - (t_1 + t_2)/2} \quad \textbf{(10)}$$
$$\mathbf{t_m = t_{am} - (t_a - t_c)} \quad \textbf{(11)}$$

In these equations, d_m is the test material's thickness, V_m, the test material velocity, 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,
$$\mathbf{d_m = V_a \times [t_a - (t_1 + t_2)/2]} \quad \textbf{(12)}$$
$$\mathbf{V_m = d_m / t_{am} - (t_a - t_c)} \quad \textbf{(13)}$$

As an example, Fig.22 shows actual transmitted and reflected signals when a test material is examined in the non-contact transmission mode. As can be seen from equations 12 and 13, in order 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.

The initial calibration for velocity, thickness, and time of flight measurements are accomplished by using a simple procedure with a calibration reference material, the time of flight, thickness, and velocity of which are known. Since NCA 1000 also measures the absolute attenuation, it can be used to determine the absolute material density.

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Measurements necessary for these characteristics are automatically recorded and calculated by the NCA 1000 computer and are displayed on the monitor screen, Fig. 25.

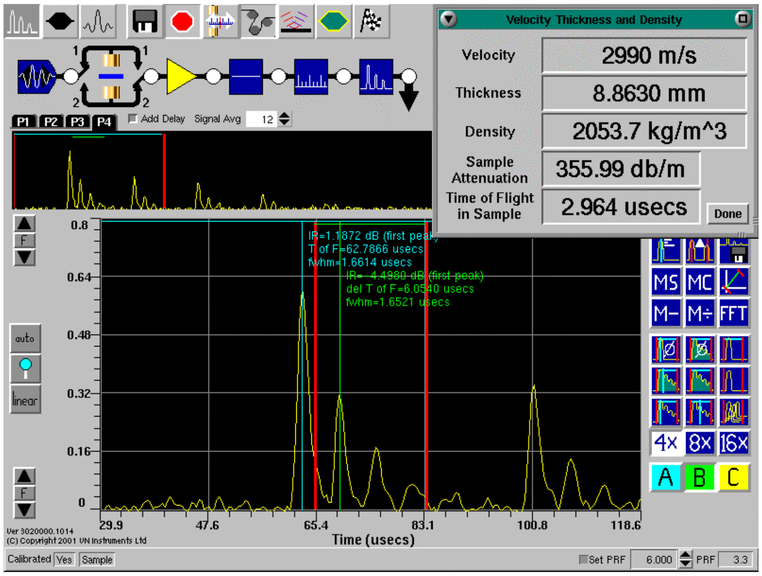

Fig. 25. The NCA 1000 screen displaying velocity, thickness, density, attenuation, and time of flight of a material. The test material in this case is a 8.86 mm non-porous graphite fiber re-enforced plastic composite.

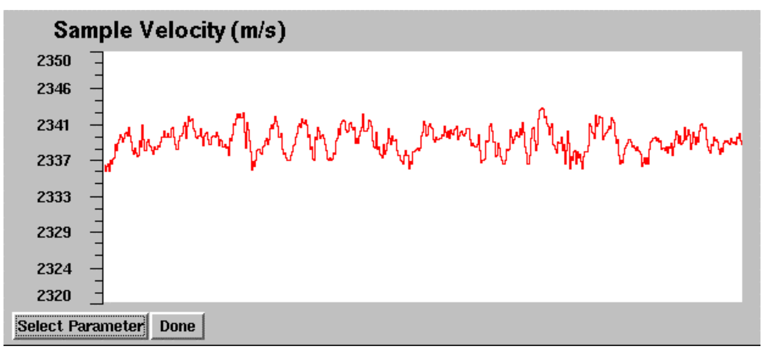

Fig. 26. NCA 1000 trend plot showing the measured velocity variations at a given point for an example material, polystyrene. Based upon the repeatability of measurements the accuracy of velocity is within +/- 2 m/s.

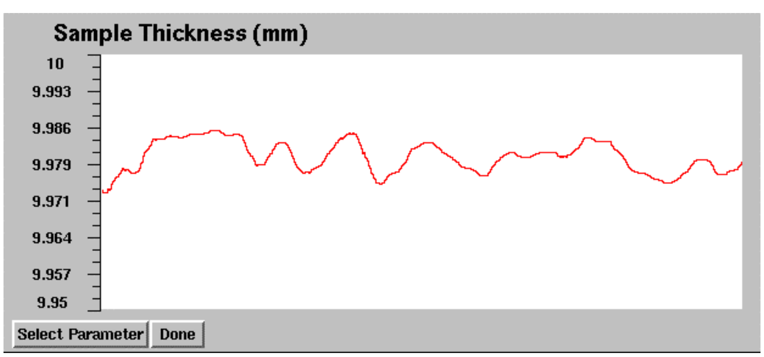

Fig. 27. NCA 1000 trend plot showing the measured thickness variations at a given point for an example material, polystyrene. Based upon the repeatability of measurements the accuracy of thickness is within +/- 0.005 mm.

It should be pointed out that absolute density measurement is only possible if the test material shows at least one thickness reflection, besides the directly transmitted signal. By utilizing air velocity (due to fluctuations in temperature, altitude, and humidity) compensation transducers, accuracy of test material velocity, time of flight, and thickness can be greatly improved. For example, for some materials velocity and thickness can be measured within better than +/-0.1% of the mean value. Based upon the repeatability of observations at a given point, figures 26 and

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27 show the measurement accuracy of velocity and thickness of an example material, polystyrene under ambient environment.

7.2 Integrated Response, Transmissivity and Reflectivity Measurements

In the time domain display, the NCA 1000 -- besides measuring and displaying the times of flight of the signals -- 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, >150dB, 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, besides relating it (IR) to subtle changes in the material. For example,

$$\mathbf{IR_m = IR_c - IR_a} \qquad \mathbf{(14)}$$

where, IR_m is the amount of ultrasonic energy transmitted in the test material, IR_c, the ultrasound transmission through air and the material (between the transmitting and receiving transducers), and IR_a is the amount of ultrasound energy transmitted only through air. IR_c and IR_a are directly measured by the NCA 1000. If a given test material is homogeneous, then the measurement of IR_m has been found to be related to the transmission co-efficient (eq. 1). To illustrate this, we evaluated a flat and polished specimen of polystyrene. Fig. 28 shows the IR_c (-21.72dB) of the transmitted peak of ultrasound from air into the specimen and Fig. 29 shows a similar peak, but

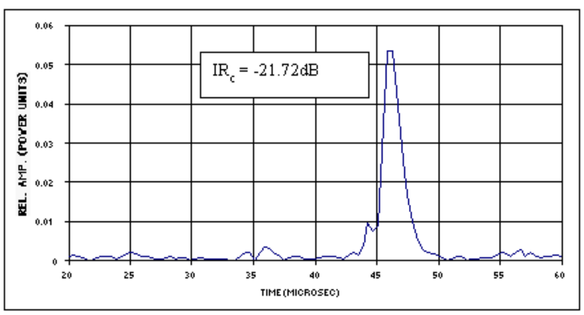

Fig. 28. Non-contact transmission through a 20mm thick flat and polished polystyrene showing the Integrated Response, IR_c of the transmitted peak.

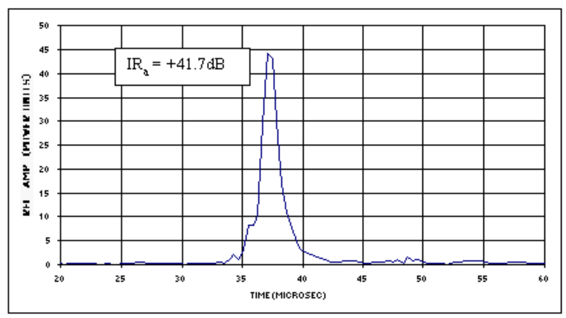

Fig. 29. Non-contact transmission through air column showing IR_a of the transmitted peak.

only through air, corresponding to IR_a (+41.7dB), thus yielding IR_m –63.42dB for the specimen. It is important to note that this measurement corresponds very closely to:

$$\mathbf{IR_m = 20 \log T} \qquad \mathbf{(15)}$$

where T, the transmission co-efficient is defined by eq. 1.

For example, the calculated value of amount of ultrasonic energy transmitted in polystyrene (equations 1 and 3) is –63.34dB, which is very close to –63.42dB determined by measuring integrated response peaks. It should be pointed out that, as such the transmission co-efficient is assumed to be independent of ultrasonic attenuation and thickness of the test medium. In reality this is not absolutely true. For example, varying thickness of polystyrene samples at different frequencies yield different values of T. Though these variations are very small, yet they are measurable. On the other hand, if the transmission co-efficient 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, i.e.,

$$\mathbf{Z_m = \frac{Z_1}{T} \left[(2-T) \pm 2\,(1 - T)^{1/2}\right]} \qquad \mathbf{(16)}$$

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$$\rho_m = Z_m / V_m \quad (17)$$

Measurement of IR_m and solution of equations 16 and 17 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 co-efficient in x-ray absorption) and material thickness -- must also be considered, i.e.,

$$T = I_2/I_0 = Z_1 Z_2 /(Z_1 + Z_2)^2 = \exp^{(-\mu\rho x)} \quad (18)$$

Where T is the transmission co-efficient, I_2, the ultrasound energy transmitted into the material (acoustic impedance Z_2) from air (acoustic impedance Z_1), I_0, the input ultrasound energy, μ, the material ultrasound attenuation co-efficient, ρ, the material density, and x, the material thickness. At the time of this writing, the development of these relationships and techniques for measurements of T, Z, μ, and ρ by non-contact ultrasound are in progress (24.)

Since the validity of the transmission co-efficient measurement still needs to be determined, it is best to refer to IR_m as transmissivity (when propagating ultrasound through the material in direct transmission mode), or reflectivity (when ultrasound is reflected from the surface of the material). Such measurements are useful in evaluating the test material internal and surface characteristics, such as defects, texture, microstructure, roughness, etc.

7.3 Non-Contact Ultrasonic Spectroscopy

By performing the Fast Fourier Transformation (FFT) of transmitted or reflected time domain signals, test materials can also be characterized to investigate 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 frequency-dependence of ultrasonic characterization is the acquisition of a reference frequency magnitude spectrum of a transmitted signal in air, i.e., without the test material. The next step is to do the same with the test material inserted between the transducers. As an example, the FFT magnitude spectra for air and the test material are, respectively, shown in figures 30 and 31. In order to generate frequency dependence of ultrasonic attenuation, the reference air spectrum is subtracted from that of the sample+air spectrum, Fig. 32. This information is directly displayed on the NCA 1000 screen, Fig. 33. 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, roughness, etc.

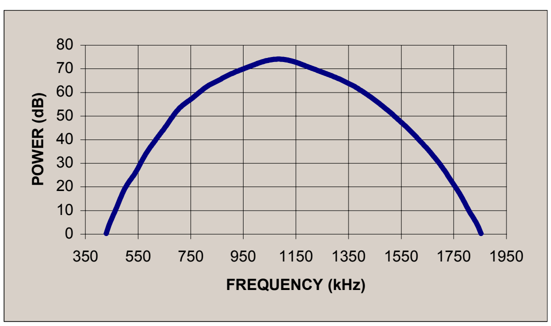

Fig. 30. Magnitude spectrum in air with 1 MHz Transducers in transmission mode.

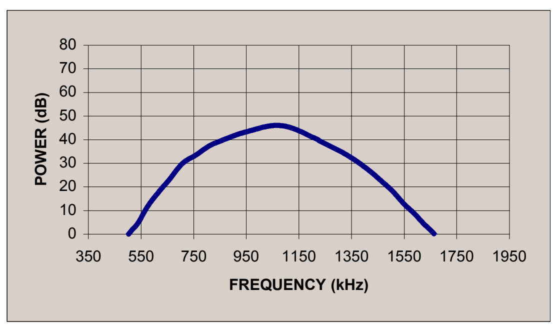

Fig. 31. Magnitude spectrum with sample (in this case a polyurethane foam) between the transducers.

8 APPLICATIONS OF NON-CONTACT ULTRASOUND

Non-contact transducers have now been successfully produced in the frequency range of 100kHz to >5MHz. While the applications of non-contact transducers greater than 3MHz in ambient air environment are limited, transducers between 200kHz to 3MHz have been extensively used for several industrial and medical applications (25, 26, 27, 28, 29, 30, 31, 32, 33 and 34.) In this section we present selected examples of NCU applications with respect to materials testing and other objectives.

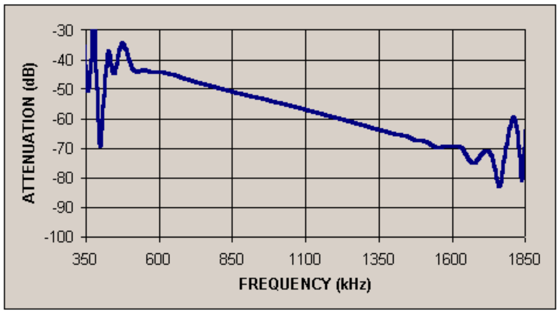

Fig. 32. Frequency dependence of ultrasound Attenuation by subtracting reference air spectrum (Fig. 30) from that of sample+air spectrum (Fig. 31).

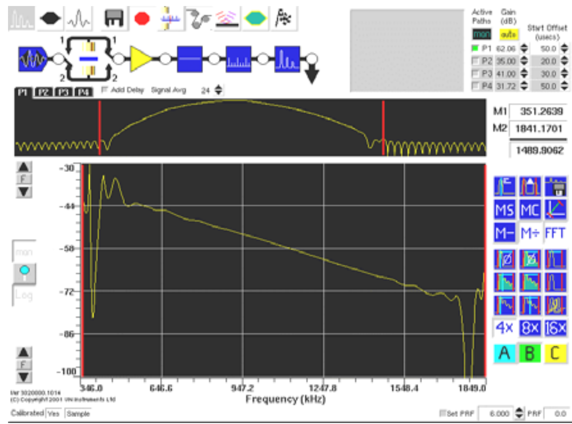

Fig. 33. NCA 1000 screen showing the frequency-dependence of ultrasound attenuation obtained by performing the routine shown in figures 30, 31, and 32.

8.1 Materials Characterization and Defect Detection

Figures 34 and 35, respectively, show the relationships between densities of green and sintered alumina with non-contact velocities of these materials. Fig. 36 shows a correlation between ultrasonically (from reference samples) and physically determined densities of green alumina. The non-contact ultrasonic technique has been successfully applied to characterize density and defects in a variety of green materials such as ceramics tiles, multi-layer electronic packages, powder metals, cements, concretes, etc. Figures 37 and 38, respectively, show the velocity density relationships for isostatically pressed high density green alumina and tungsten carbide.

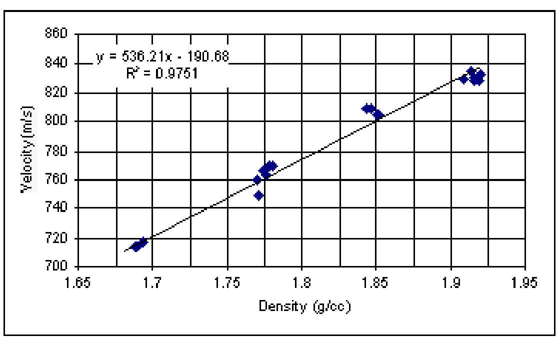

Fig. 34. Relationship between density and non-contact ultrasound velocity for low density green

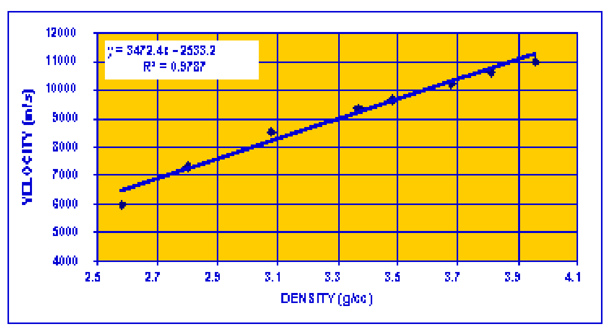

Fig. 35. Relationship between density and non-contact ultrasound velocity for sintered alumina.

When reliable NCU velocity measurement is not possible, then one can relate transmissivity – section 7.2 – to materials density or porosity. An example of this for green alumina is shown in Fig. 39. It has been further found that materials transmissivity and velocity are also related to each other, Fig. 40. As a general rule, NCU velocity for dense and fully sintered oxides, carbides, nitrides, and borides of metals and non-metals is even more difficult to measure. However, in order to estimate the density of such materials, transmissivity can be used, Fig. 41. Detailed description of these measurements and their further significance in materials processing and characterization is beyond the scope of this paper.

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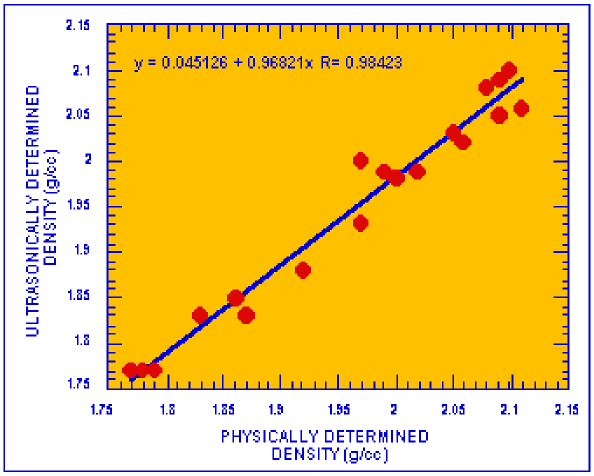

Fig. 36. Correlation between physically and non-contact ultrasound measured densities of green alumina.

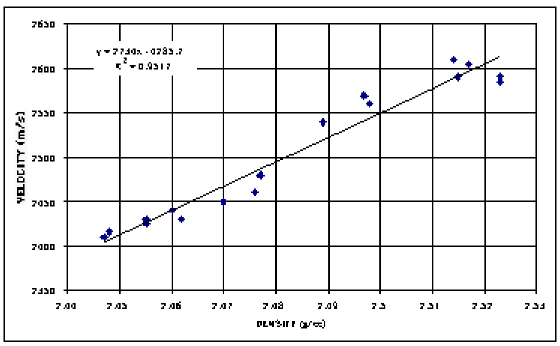

Fig. 37. Density-velocity relationship for green dense isostatically pressed alumina.

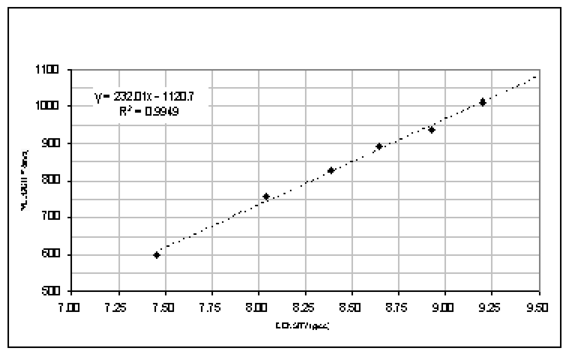

Fig. 38. Density-velocity relationship for green tungsten carbide.

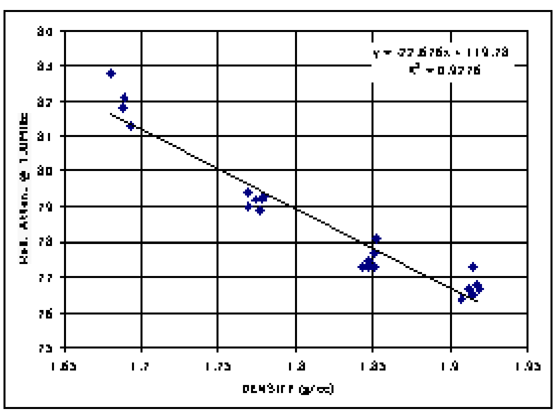

Fig. 39. Ultrasonic transmissivity as a function of green alumina density.

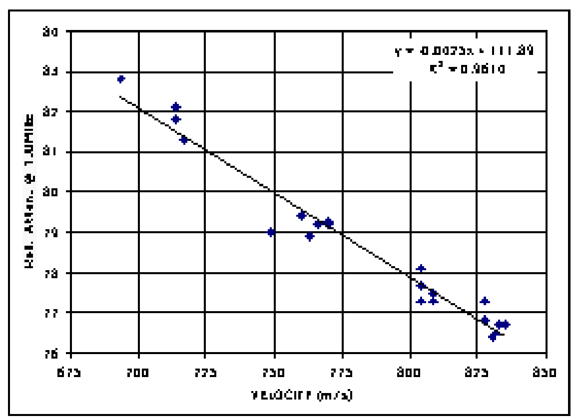

Fig. 40. Relationship between velocity and transmissivity.

Examples of defect detection in green and sintered ceramics are shown in figures 42 and 43. Fig. 44 is quantitative NCU imaging of a number of side-drilled holes in a 10 mm thick sample of acrylic. Here detectability has been described as a function of interrogating NCU frequency.

Observations given in figures 34 to 43 were generated in direct transmission mode.

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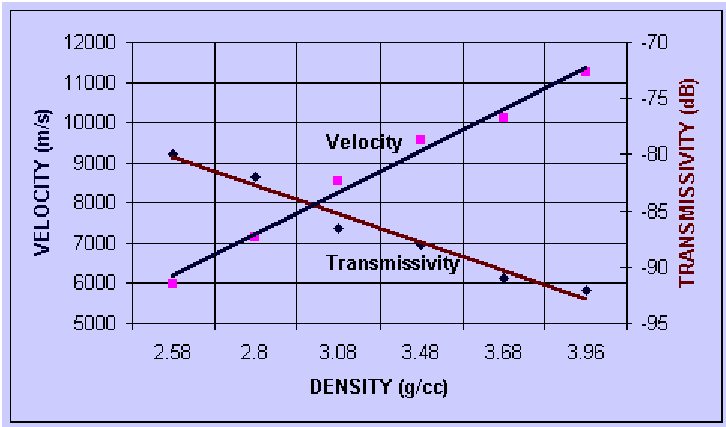

Fig. 41. Relationship of transmissivity and velocity with density of sintered alumina.

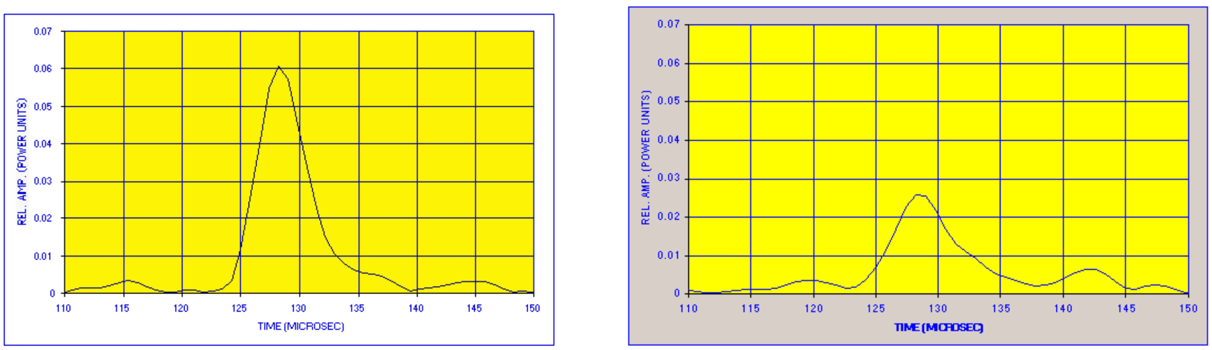

Fig. 42. Defect detection in 14 mm thick green porcelain. Left: transmission through a non-defective region. Right: Transmission through a region with 1.5 mm side drilled cylindrical hole.

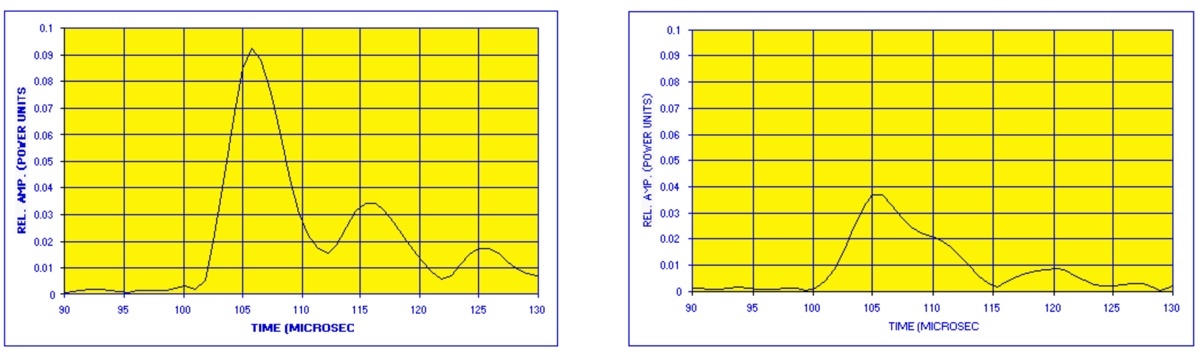

Fig. 43. Defect detection in 20 mm thick porous sintered low thermal expansion ceramic. Left: transmission through a non-defective region. Right: Transmission through a region with 1.5 mm side drilled cylindrical hole

By performing the non-contact ultrasonic spectroscopy – section #7.3 -- the examples of texture and microstructure analysis are shown in figures 45 and 46. Fig. 45 shows the frequency dependence of ultrasound attenuation by three specimens of extremely porous ceramics (in the present case, space shuttle tiles), and Fig. 46 shows similar observations from two samples of packaging foam varying in cell dimensions.

By virtue of very high frequency NCU transducers, it has also been possible to characterize materials within a relatively broad frequency range. Fig. 47 shows very high frequency non-contact transmission spectroscopy of two

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samples of paper towels. Similar observations have also been made for the detection of bubbles and pores in liquids and other materials.

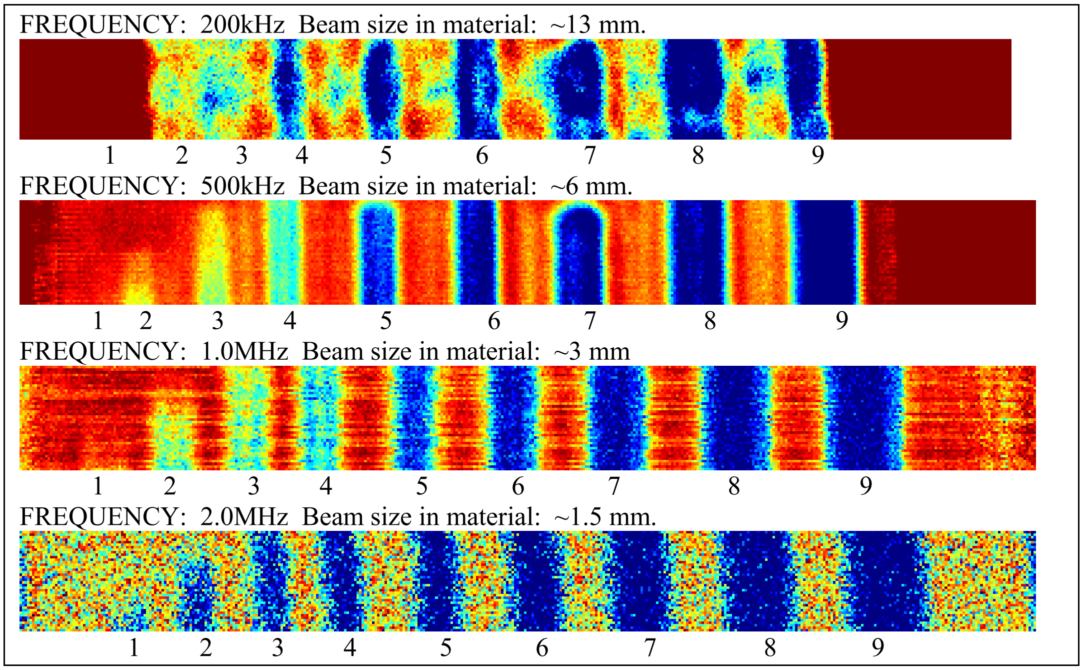

Fig. 44: Non-contact ultrasound transmission images of nine side-drilled cylindrical holes in a 10 mm thick sample of acrylic, as a function of frequency. Indicated by numerals 1 to 9, respectively, the hole diameters are: 0.5, 0.8, 1.5, 2.3, 3.2, 4.0, 5.5, and 6.3 mm.

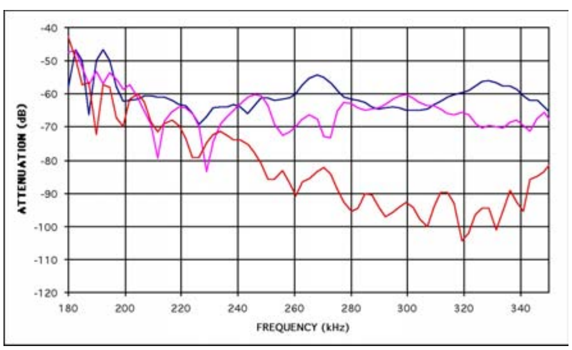

Fig. 45. Non-contact transmission ultrasonic spectroscopy of extremely porous ceramics (space shuttle tiles) for texture characterization.Top: 0.38g/cc. Middle: 0.28g/cc. Bottom: 0.1g/cc.

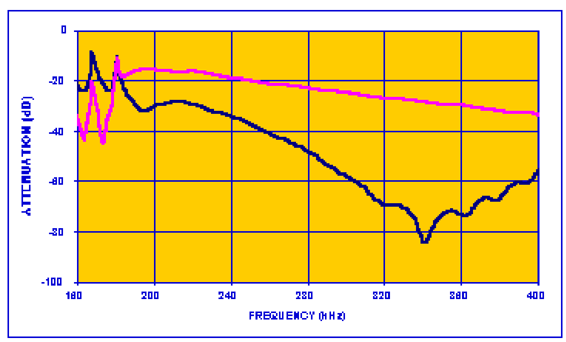

Fig. 46. Non-contact transmission ultrasonic spectroscopy of polyurethane foams varying in cell size. Top: small cell. Bottom: large cell.

In order to evaluate the surface characteristics by non-contact ultrasonic spectroscopy, several grinding discs of SiC varying in particle size were chosen. These discs were placed at a fixed air distance of 10mm from a 2MHz, 12.5mm 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 frequency dependence of ultrasound was measured by subtracting the sample FFT spectra from that of the steel reference. These observations are shown in Fig. 47. 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. Reflectivity of ultrasound (as a function of particle size) was determined by comparing the sample IR with that of a steel reference specimen. These observations are shown in Fig. 49. 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 surface texture or its roughness.

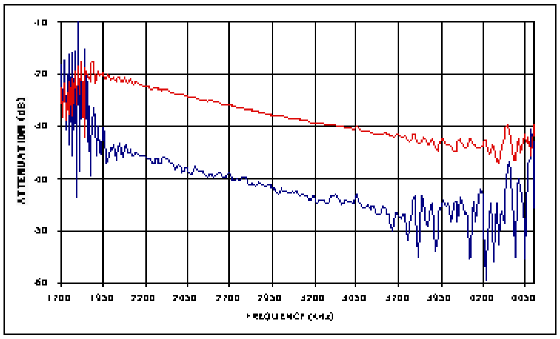

Fig. 47. Very high frequency non-contact transmission ultrasonic spectroscopy of two different paper towels. Top: 0.2mm thick, relatively hard shallow dimpled texture. Bottom: 0.4mm thick, relatively soft and deeply dimpled texture.

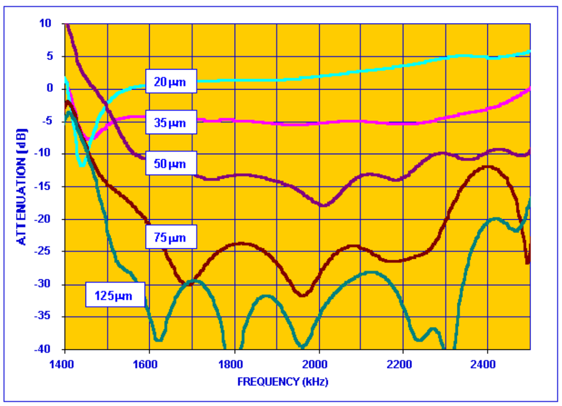

Fig. 48. Non-Contact reflection ultrasonic spectroscopy for surface characterization of materials.

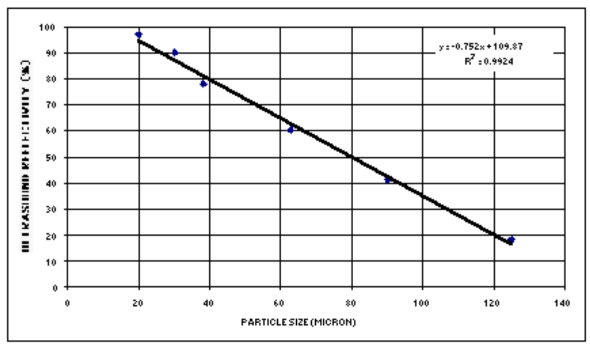

Fig. 49. Non-contact reflectivity for surface characterization.

8.2 NCU Imaging

Analogous to the conventional water immersion technique, in the non-contact mode ultrasonic transducers can be raster scanned to generate images corresponding to the internal and surface characteristics of the test materials. Fig. 50 shows non-contact 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. In order to further demonstrate analytical ability of the NCA 1000 system, a thick sample of iron-based compact was imaged by monitoring the transmission integrated response and the material velocity. These images are shown in Fig. 51. 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.

By monitoring reflectivity or time of flight surfaces of materials can be imaged to provide significant information with respect to surface texture and depth. An example of surface imaging is shown in Fig. 52. These materials, obviously do not need any introduction! Observations shown in Fig. 52 were acquired by using a 3 MHz, 6.3 mm diameter, and 6.3 mm point focus transducer, with a beam size of approximately, 0.12 mm.

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Since the NCA 1000 interprets ultrasound reflections from both the transmitting and the receiving transducers from material surfaces, it is now also possible to measure the thickness of materials that are continuously rolled on a production line and which are too wide for micrometers.

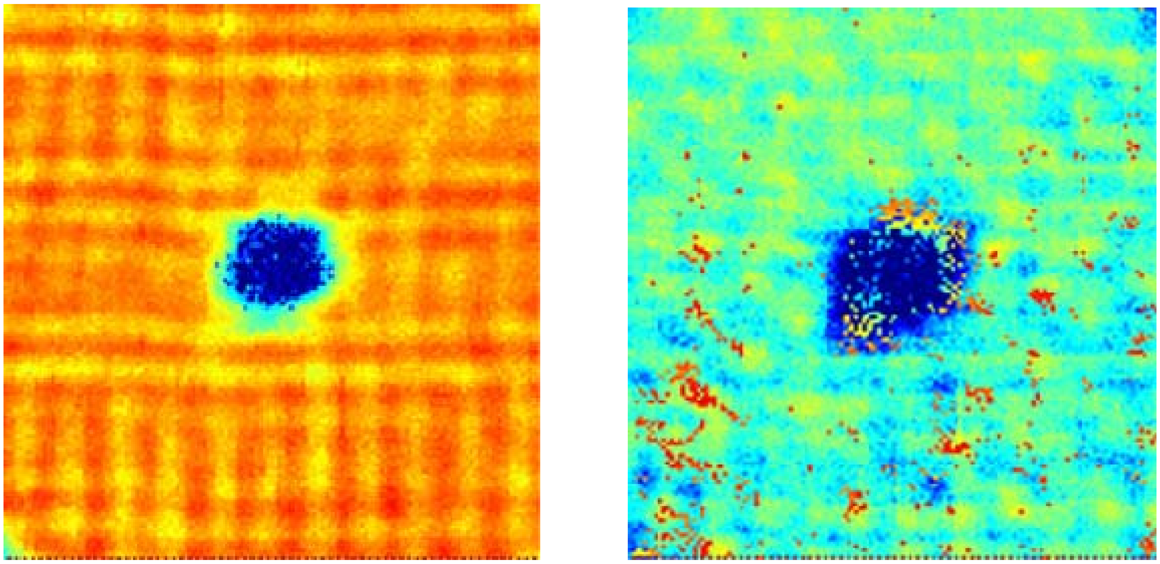

Fig. 50. Non-contact ultrasonic imaging of a mild, impact-damaged 6.4mm thick multi-layered glass fiber reinforced plastic composite by using NCA 1000 and 1MHz, 12.5mm active area diameter transducers with 1mm aperture. Left: Direct transmission image. Right: First thickness reflection image.

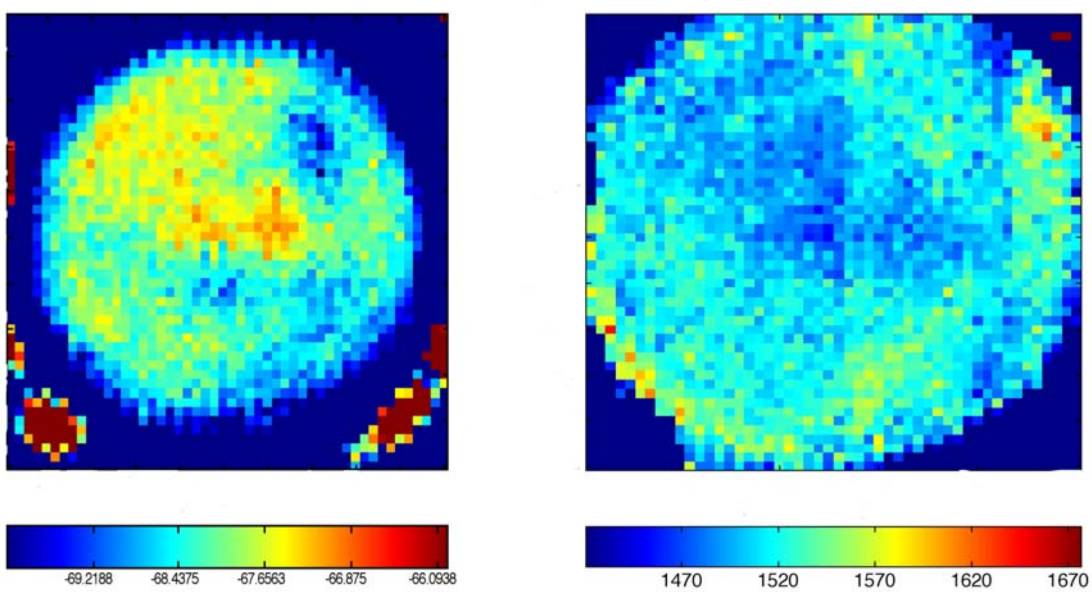

Fig. 51. Non-contact imaging of a green 14mm thick iron compact by using the NCA 1000 and 500kHz, 12.5mm active area diameter transducers with 3mm aperture in direct transmission mode. Left: Relative attenuation of Integrated Response (dB). Right: Velocity (m/s). Area scanned: 50x50mm. Note that the outer high velocity region is also characterized by high attenuation (low IR), and the inner region of low velocity with lower attenuation.

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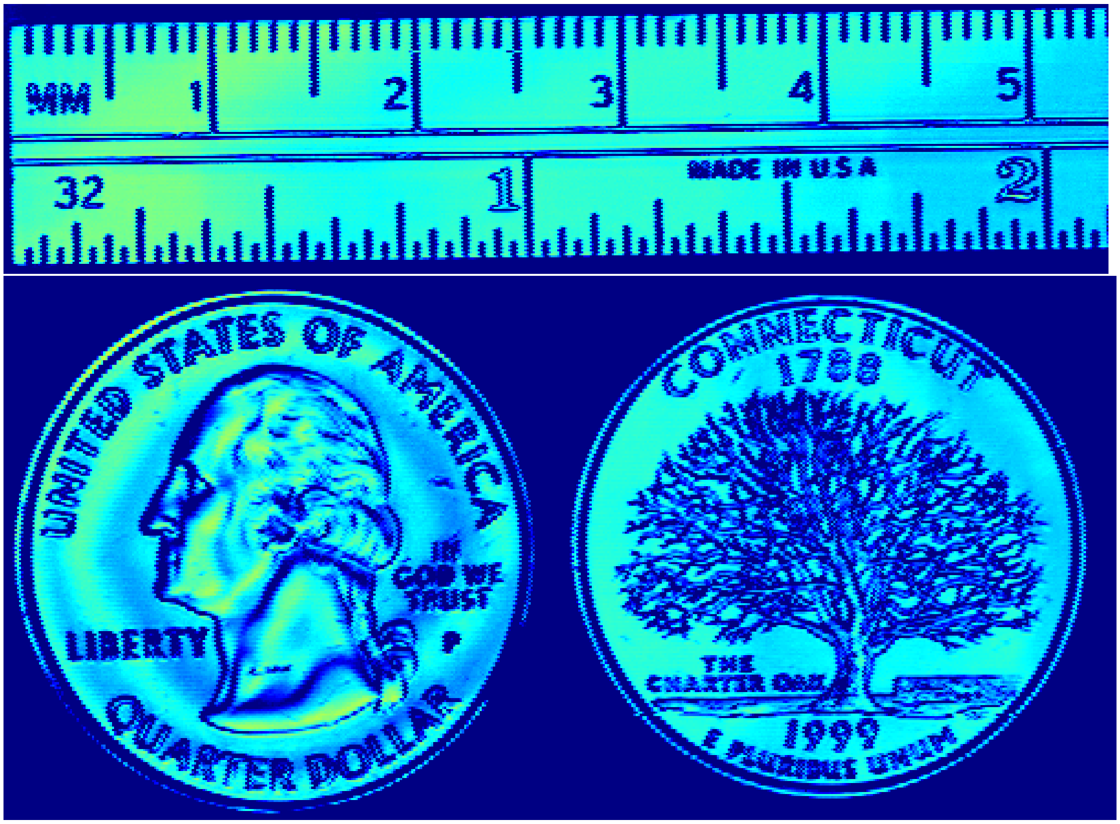

Fig. 52. NCU reflectivity as a function of surface texture.

8.3 Food, Beverage, and Pharmaceutical

Figures 53 and 54, respectively show NCU images of milk chocolate without nuts and with nuts. Figures 55 and 56, respectively show the images of reduced fat and extra sharp cheddar cheese.

Analogous to green ceramics and like material (figures 34 to 40), tablets, capsules, and other powder-based pharmaceutical products have also been characterized as functions of the velocity and frequency-dependence of ultrasound attenuation. Examples of NCU velocity as a function of production batches for pharmaceutical tablets is shown in Fig. 57.

We have also applied non-contact ultrasound for the detection of beverages and other liquids in plastic, metal, and cardboard containers. The quality of heat and vacuum seals in pharmaceutical and food packages has also been determined by this technique. . This method has also been successfully applied to detect the presence or absence of liquids (milk, beverages, chemicals, etc.) in cardboard cartons, plastic and metal containers. Feasibility of detecting the absence or presence of foreign and unwanted materials in liquid containers has also been successfully demonstrated.

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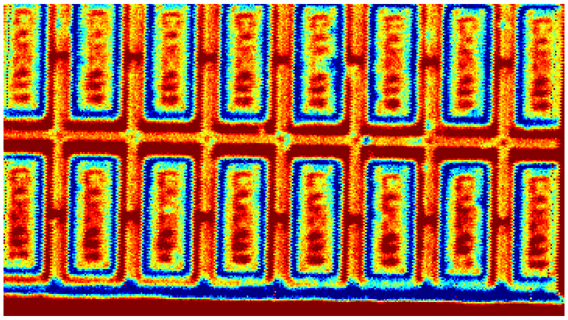

Fig. 53. Milk chocolate without nuts.

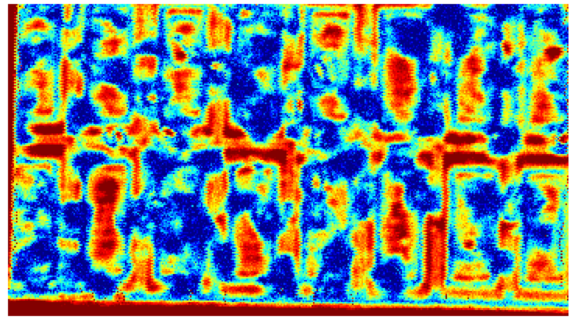

Fig. 54. Milk chocolate with nuts.

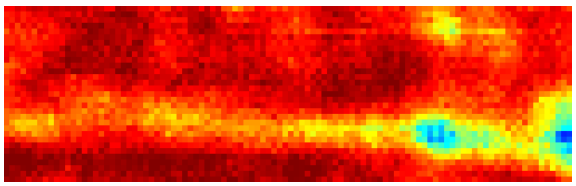

Fig. 55. Reduced fat cheddar cheese.

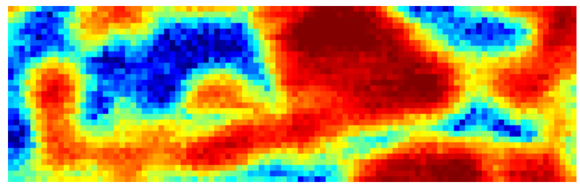

Fig. 56. Extra sharp cheddar cheese.

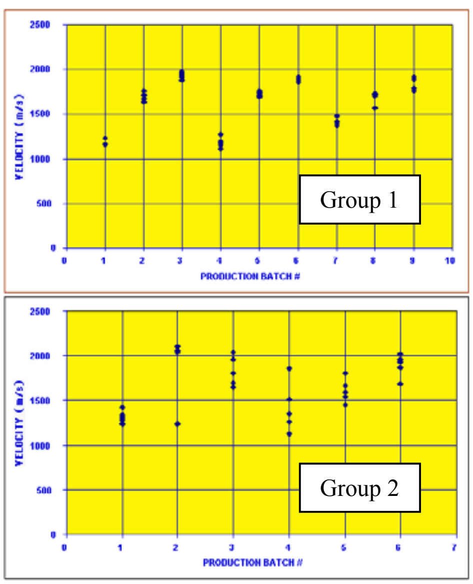

Fig. 57. Variation in ultrasonic velocities of various pharmaceutical tablets in the production batches of two groups.

We have also applied non-contact ultrasound for the detection of beverages and other liquids in plastic, metal, and cardboard containers. The quality of heat and vacuum seals in pharmaceutical and food packages has also been determined by this technique.

This method has also been successfully applied to detect the presence or absence of liquids (milk, beverages, chemicals, etc.) in cardboard cartons, plastic and metal containers.

Feasibility of detecting the absence or presence of foreign and unwanted materials in liquid containers has also been successfully demonstrated.

8.4 Medical

One of the first medical applications of NC transducers was the evaluation of burnt skin and bed sores in burn victims (26.) By utilizing 2MHz transducers with 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 was processed to create internal images of two skin conditions, Fig. 58. Detection of damage underneath the burnt skin is evident from the disruption of the interface between the epidermis and the capillary bed. Fig. 59 shows the propagation of non-contact ultrasound through a human heel paving the way for bone disease (osteoporosis) diagnostics without any contact with the patient. Fig. 60 and 61, respectively show A-scan and C-scan images of a human forearm.

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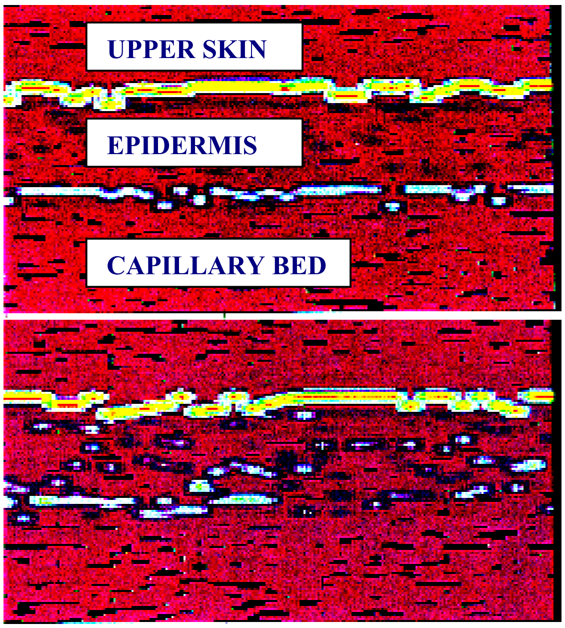


Fig. 58. Non-Contact ultrasound image cross-section of healthy (top) and burnt (bottom) human hands. Note the damaged region between the epidermis and capillary bed in the burnt hand.

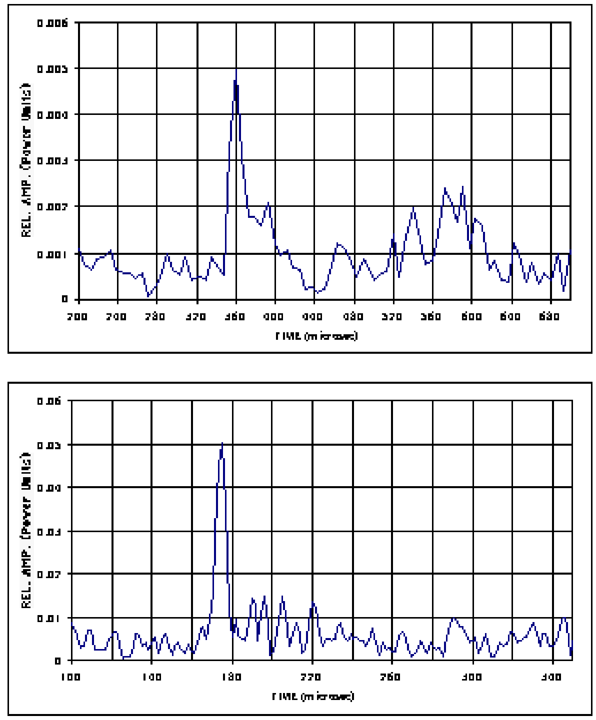


Fig. 59. NCU transmission through a human heel with 250 kHz (top) and 500 kHz (bottom) transducers.

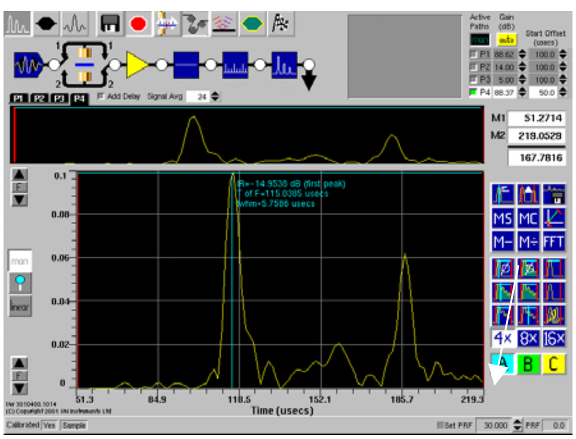


Fig. 60. NCA 1000 screen showing NCU transmission through the central portion of a human forearm. Left hand peak: Transmitted signal through tissue + bone. Rest of the signals, not identified.

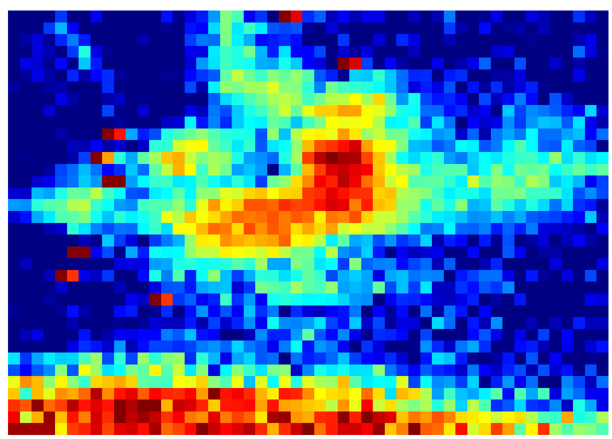


Fig. 61. NCU image of a human forearm. Data interpretation, not done, yet.

8.5 Very High Frequency Non-Contact Ultrasonic Antennas

Because the sensitivity of NC transducers is very high, it is also possible to use them in passive mode as the "listeners" of very high frequencies. In order to demonstrate this, we conducted an experiment using the setup shown in Fig. 62. Here the source of high frequency is a 25mm thick carbon steel, generated by a transducer (in contact with steel) with bandwidth at –6dB from 800kHz to 8MHz. This transducer was excited by a single burst of a 16 volt sine wave. A non-contact transducer, nominally 3.5MHz and 12.5mm active area diameter, was placed 3mm away from the material surface in ambient air. Ultrasound received by this transducer was amplified by 64dB gain. Fig. 63 shows the time and frequency domain of ultrasound detected (listened) by the NC transducer. By sweeping the frequency over 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 have successfully interrogated frequencies as high as 7MHz in ambient air. This opens the door for non-contact acoustic emission, acousto-ultrasonics, 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.

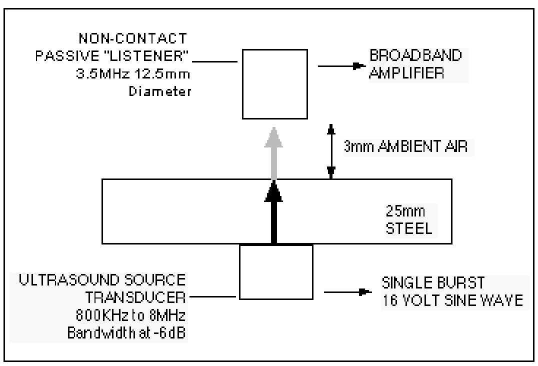


Fig. 62. Experimental setup for passive operation of non-contact transducer.

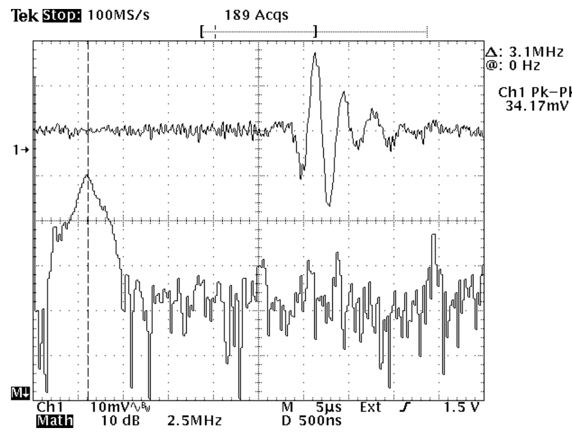


Fig. 63. Time and frequency domains of ultrasound Detected by NCU transducer, per Fig. 61 setup.

9. NON-CONTACT ULTRASONIC ANALYSIS OF COMPOSITES

Underscoring the significance of composites materials in aircraft, aerospace, automotive, and highway industries, in the following sections are provided a number of case studies and examples with respect to non-contact ultrasonic analysis of pre-pregs, cured materials, and sandwich structures. Details of observations are given in the figure captions.

9.1 NCU Transmission and Velocity as a Function of Porosity

25mm NON-POROUS AND POROUS (2-4%) EPOXY

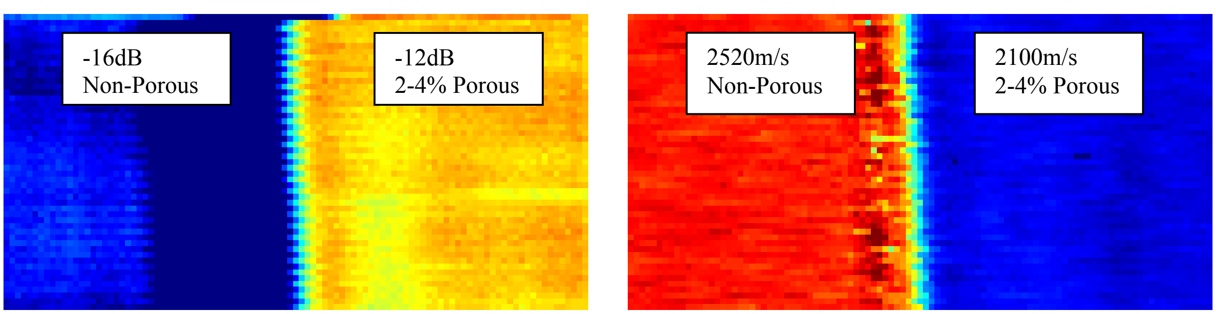


Fig. 64. NCU transmission and velocity as a function of material porosity explained by the analysis of 25 mm epoxy samples. Left: Transmission images, showing lesser (-16 dB) transmission in non-porous sample and higher (-12 dB) transmission in porous sample. Right: Velocity images, showing the velocities in two samples.

Relatively, the higher the Z, the higher the velocity and lower the transmission. This is particularly true for materials characterized by open porosity. Should the porosity be closed, it is possible that the transmission in low porosity materials might be lower than that in the non-porous materials.

By carefully understanding the interaction of NCU with materials, not only can the porosity be analyzed, but that its nature can also be deciphered. This is illustrated in Fig. 64 for Graphite Fiber Re-enforced Plastic (GFRP) samples.

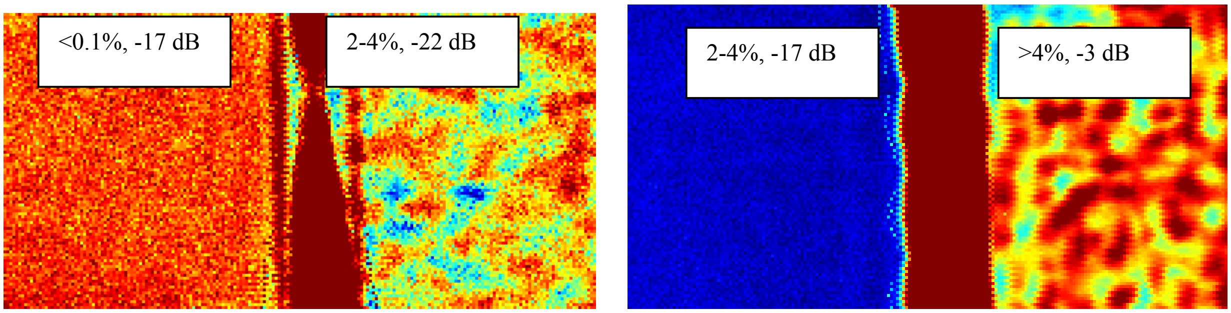
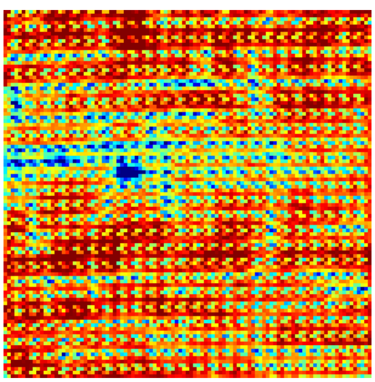
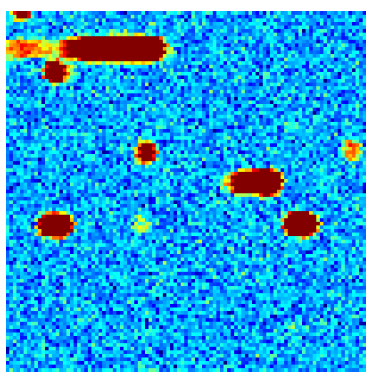


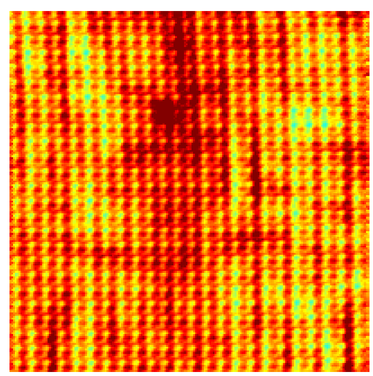
Fig. 65. NCU transmission through varying porosity GFRP. Left: 10 mm samples. Lower porosity (<0.1%) shows high transmission (-17 dB) relative to the one with higher porosity (2 – 4%) sample. Right: 2 mm samples. Here the order of transmission is reversed, relative to the left hand samples. This apparent lopsided relationship with transmission needs to be understood with respect to the nature of porosity. If the reasoning of Fig. 64 is right, then one could conclude that the 10 mm sample is characterized by closed porosity, while the 2 mm one with open porosity.

9.2 NCU of Pre-pregs

By eliminating contact with the test media, now it is possible to apply ultrasound during the early stages of materials formation such as, unpolymerized polymers, composites, powder compacts, etc. By doing so the characterized information can be directly related to material-making process. Here we provide a few examples of NCU of prepregs.







TRANSMISSION IMAGES

Fig. 66. 0.4 mm GFRP prepreg -- 4 MHz4 MHz

Fig. 67. 0.2 mm GlFRP prepreg -- 3 MHz.

Fig. 68. 0.3 mm GFRP prepreg –

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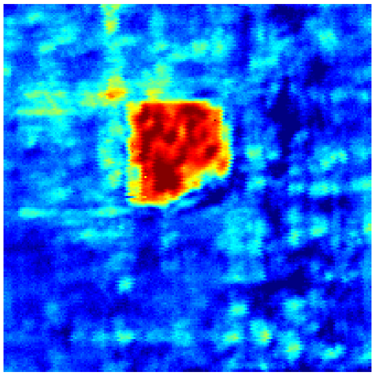

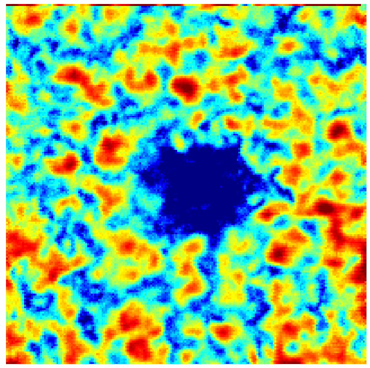

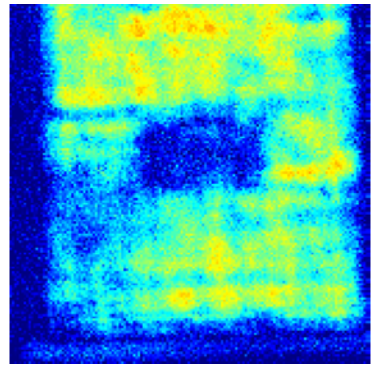

TRANSMISSION IMAGES

Fig. 69. 1.4 mm multi-layer prepreg With trapped film.

Fig. 70. 4 mm multi-layer prepreg with trapped film.

SAME SIDE T-R IMAGE

Fig. 71. 1.4 mm multi-layer prepreg with trapped film.

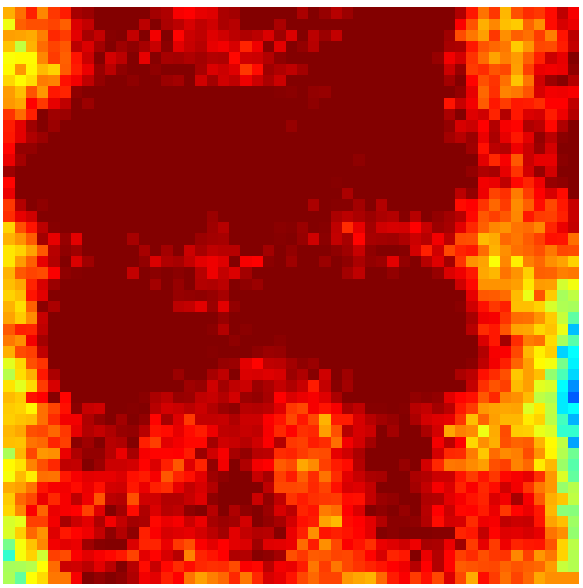

Fig. 72. 1.4 mm uncured GFRP – transmission image. Dark brown, high transmission. Lighter region, low transmission.

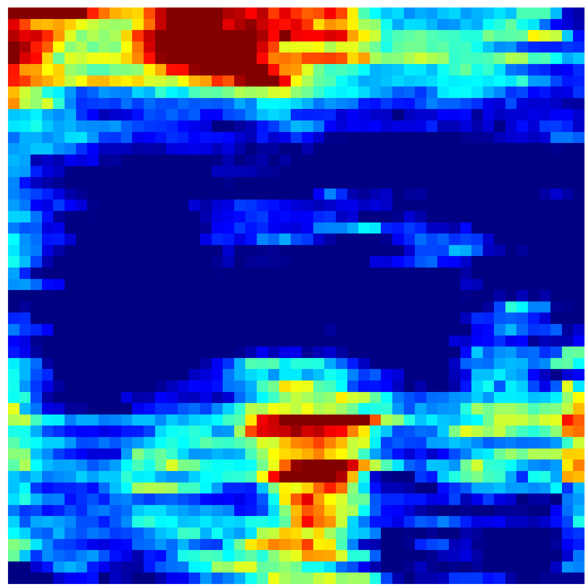

Fig. 73. 1.4 mm uncured GFRP velocity image. Dark blue, low velocity. Brown region, high velocity.* Compare with Fig. 72.

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9.3 NCU of cured composites

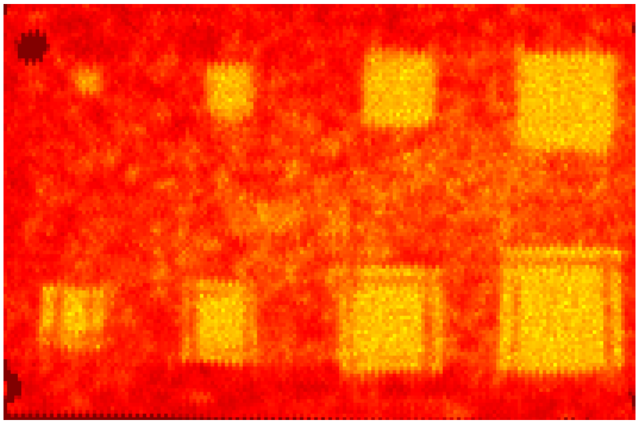

Fig. 74. Embedded defects in 5 mm GFRP composite.

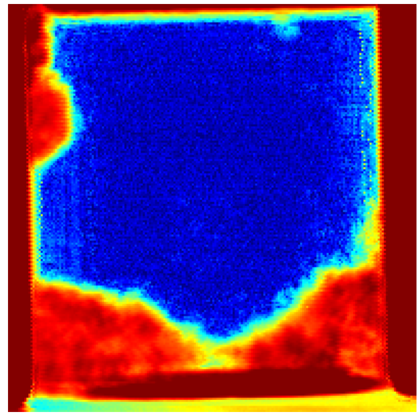

Fig. 75. Total delaminations in 4 mm Carbon-Carbon composite.

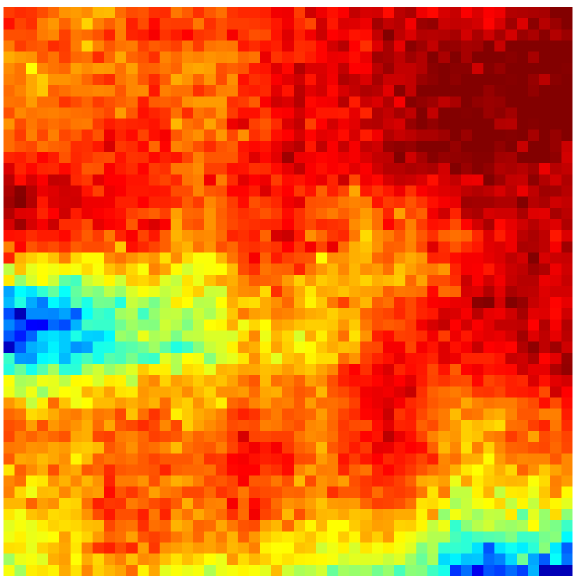

Fig. 76. 2.2 mm high temp. GFRP composite – Transmission image. Brown: High transmission. Blue: Low transmission.

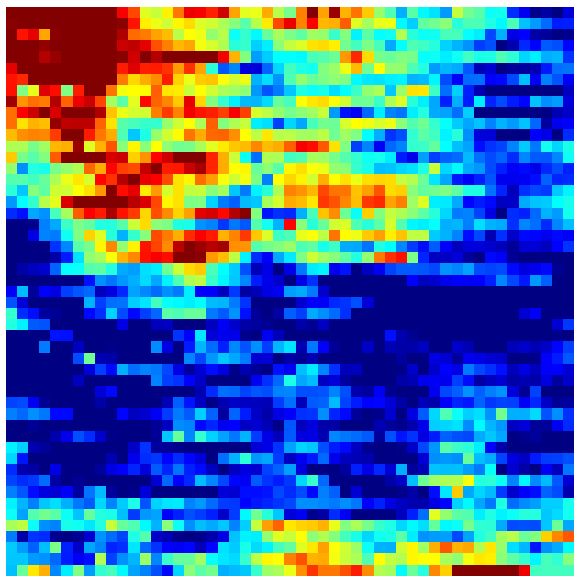

Fig. 77. 2.2 mm high temp. GFRP composite -- Velocity image. Blue: Low velocity. Brown: High velocity. Compare with Fig. 76.

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9.4 Multi-layer, Sandwich, and Honeycomb Structures

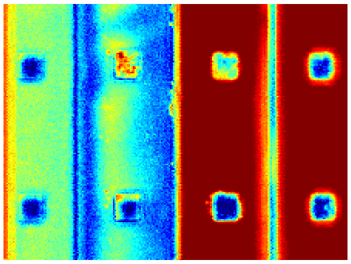
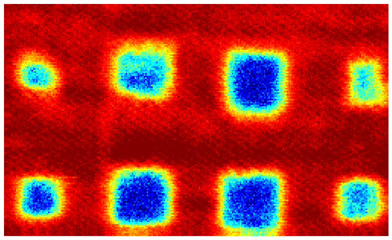


Fig. 78. Multiple sheets of bonded aluminum.



TRANSMISSION IMAGES

Fig. 79. GFRP (1 mm)-Al honeycomb (30 mm) – GFRP (1 mm).

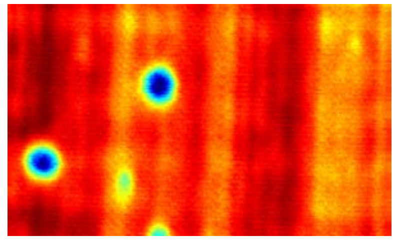


Fig. 80. Al-Al-Al honeycomb.

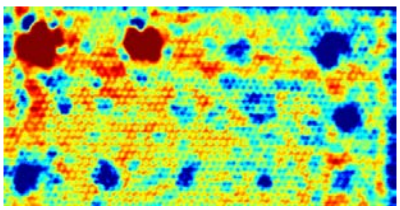
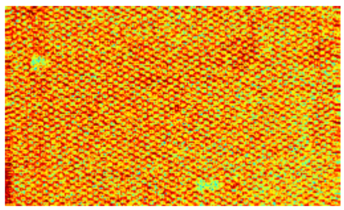


Fig. 81. Al-Nomex-Al honeycomb.



TRANSMISSION IMAGES

Fig. 82. Al-Nomex-Al Honeycomb.

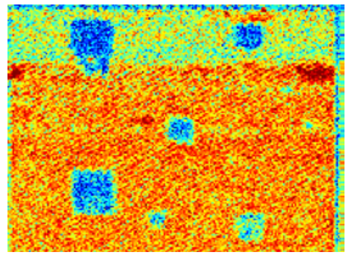
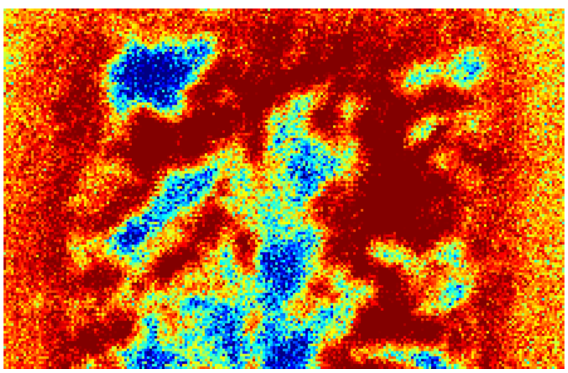


Fig. 83. Al-nomex-Al honeycomb.



TRANSMISSION IMAGES

Fig. 84. GFRP (2 mm) – Foam (12 mm) – GFRP (2 mm) sandwich.

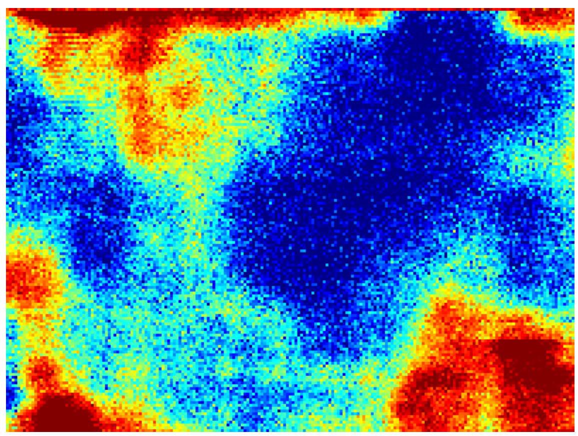


Fig. 85. 15 mm alumina armor plate.

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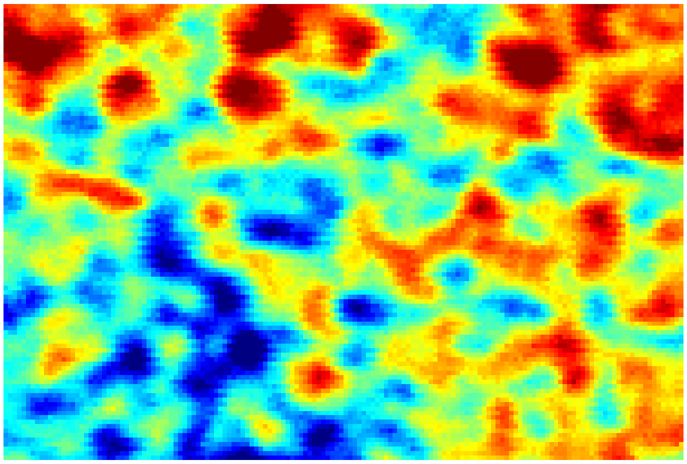
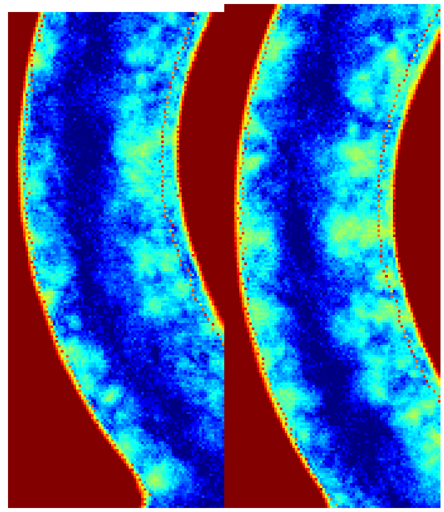


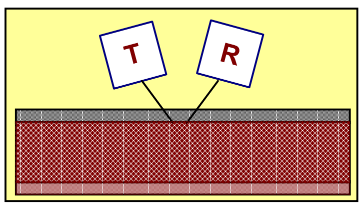


TRANSMISSION IMAGES

Fig. 86. PEI foam core.

Fig. 87. Carbon-Carbon disk brake.

9.5 Same Side NCU – T-R Reflection – (Pitch-Catch)



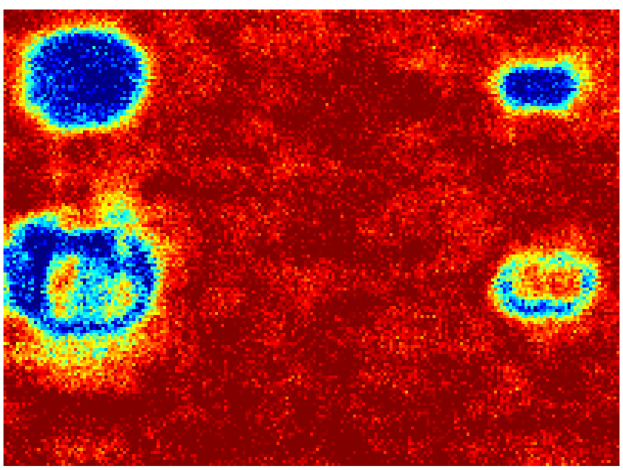


Fig. 88. 0.5 mm GFRP -- Al honeycomb interface at 500 kHz – same side.

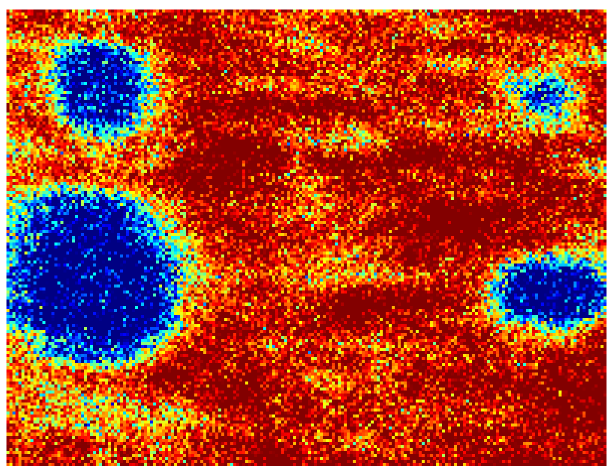


Fig. 89. 0.5 mm GFRP – Al honeycomb interface at 1.0 MHz – same side.

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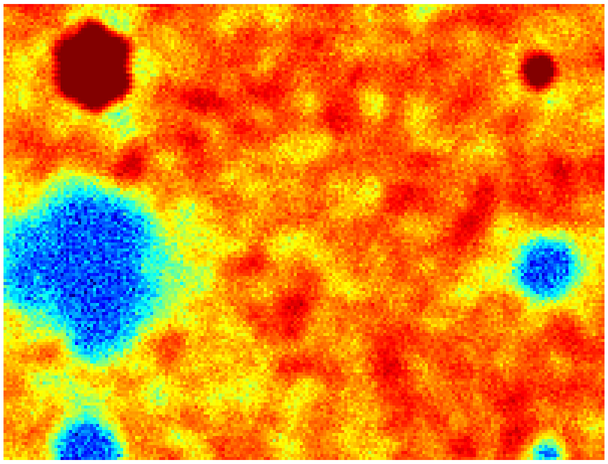

Fig. 90. 0.5 mm GFRP -- Al honeycomb – 0.5 mm GFRP – TRANSMISSION IMAGE.

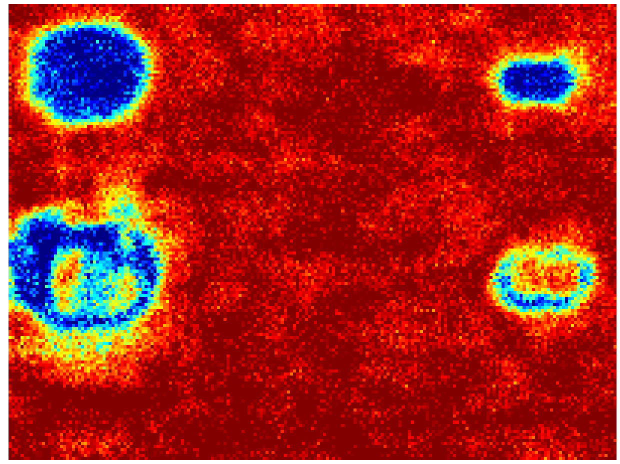

Fig. 91. 0.5 mm GFRP – Al honeycomb interface SAME SIDE IMAGE. Compare with Fig. 89.

9.6 Same Side NCU – Single Transducer – Special Case[3]

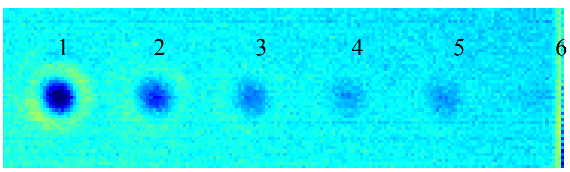

Fig. 92. Detection of 6 mm diameter flat bottom holes at varying depths in acrylic.

#1 –1 mm; #2 – 1.5 mm; #3 – 2 mm; #4 – 2.5 mm #5 – 3.0 mm; and #6 – 3.5 mm.

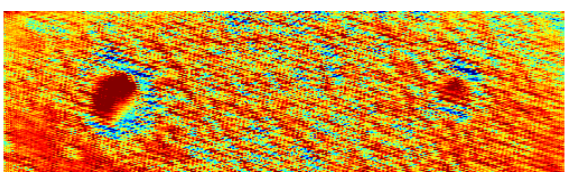

Fig. 93. 0.5 mm GFRP honeycomb interface.

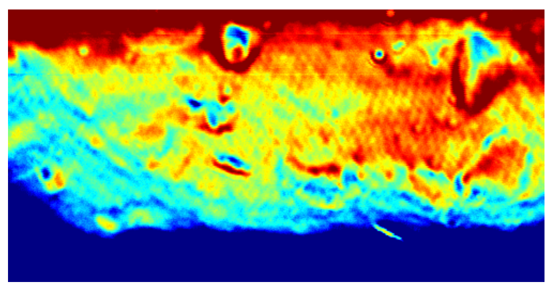

Fig. 94. Al-Al honeycomb interface in a used aircraft flap. section.

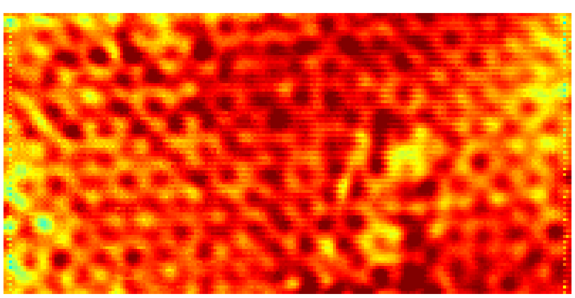

Fig. 95. NON-POROUS GFRP composite.

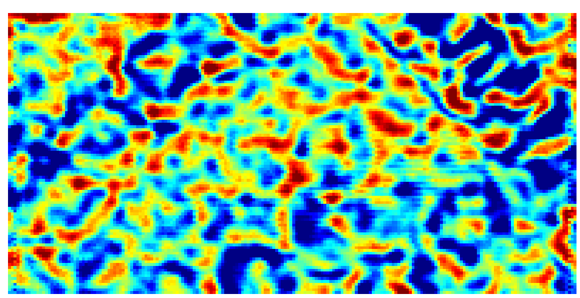

Fig. 96. POROUS GFRP composite.

[3] *Transducer and technique proprietary – Patent pending.*

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10 NCU OF ROCKS, LUMBER, CONCRETE, AND CONSTRUCTION MATERIALS

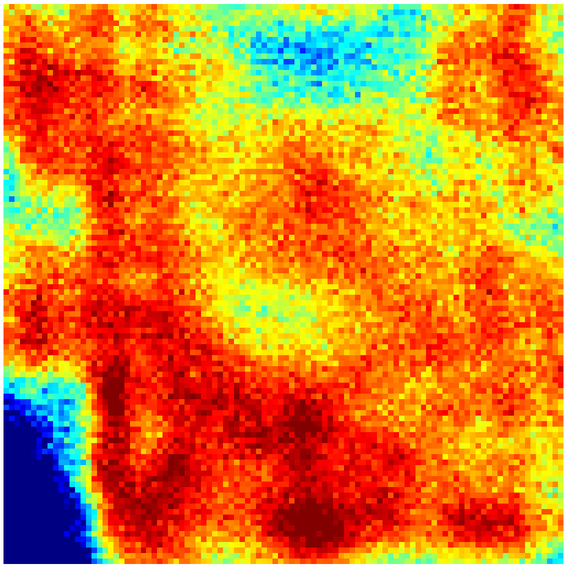

Fig. 97. 100 mm Tuff (very hard compacted volcanic ash) – image.* Darker region: High transmission. Lighter region: Low Transmission.

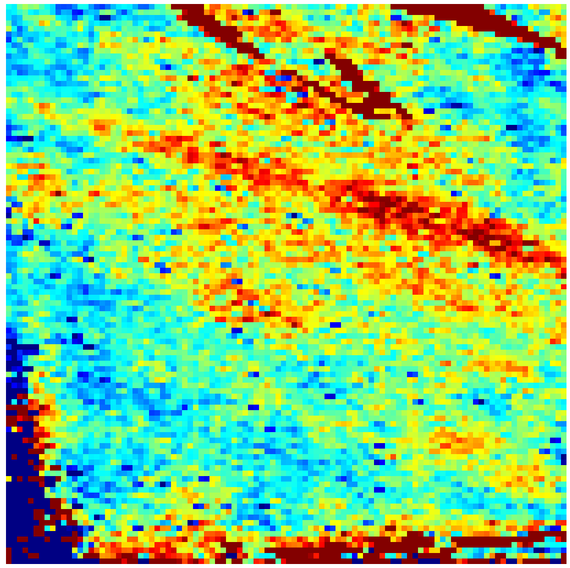

Fig. 98. Same as Fig. 97, but velocity image.* Darker region: between 5000 to 6000 m/s. Lighter region: between 4000 to 5000 m/s.

*Color images show more details.

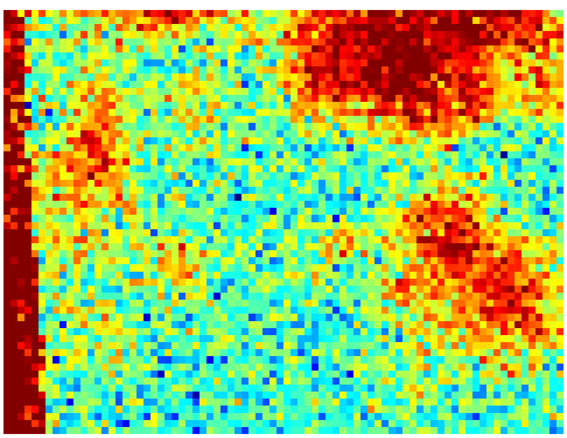

Fig. 99. 100 mm Rocky Mountain pine wood.

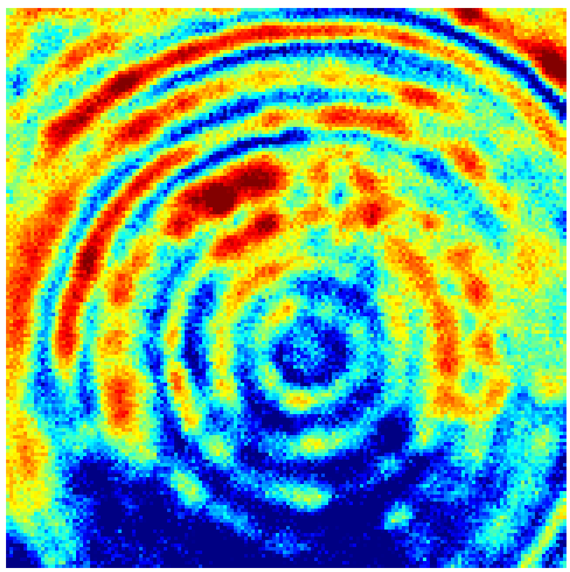

Fig. 100. 25 mm Rocky Mountain pine wood.

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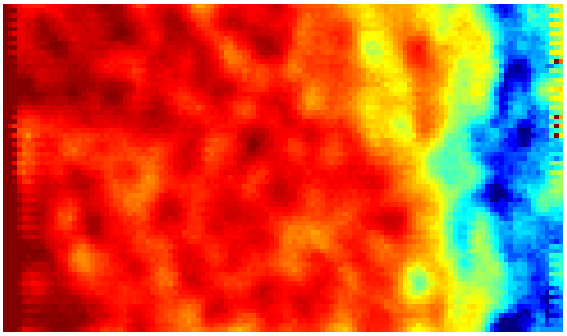

Fig. 101. 40 mm porous ceramic board.

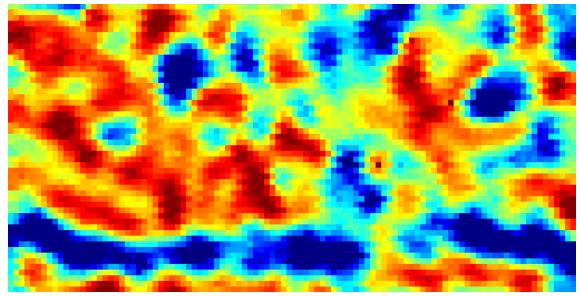

Fig. 102. 16 mm gypsum-filled dry wall.

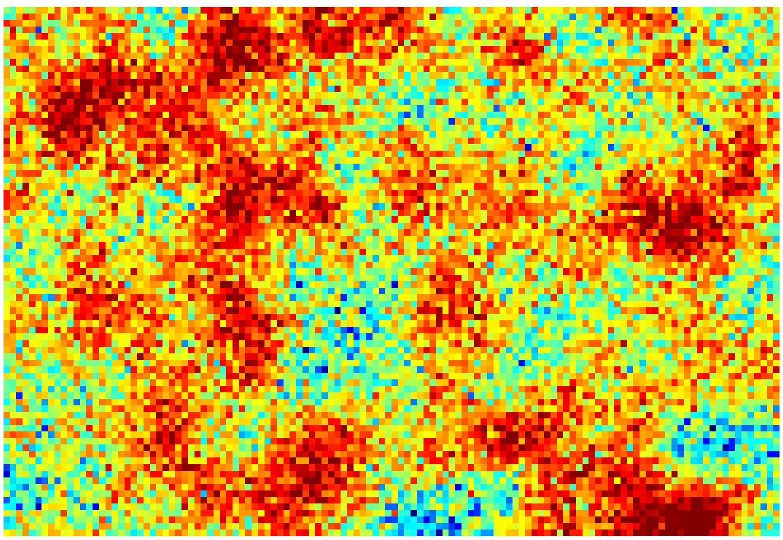

Fig. 103. 100 mm NCU transmission image of 100 mm thick section of concrete by using 200 kHz transducers.

Some evidence exists for same side NCU transmission in concrete and like materials.

11. OTHER NCU APPLICATIONS.

Besides the applications of NCU described here, this mode can also be used for level detection; dimensional and proximity analysis, high temperature materials evaluation, analysis of liquid-sensitive and hazardous materials, analysis of gases, liquids, etc. 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.

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LIMITATIONS OF NCU

1. Analogous to conventional ultrasound, NCU is also limited by the complexity of material shape and size. These complexities are overcome by manipulating the transducer geometrical-acoustics and electro-mechanical means.

2. Normally, extremely high acoustic impedance materials – heavy metals and super dense oxides, carbides, nitrides, and borides of metals and non-metals – are not suitable for NCU. However, if it is necessary, special NCU mechanism for such materials is possible.

3. Single transducer (pulse-echo) NCU at the present moment is not practical, though there is evidence for its possibility. Under high gas pressure pulse-echo is relatively easily applicable. On the other hand, two transducers can be used to interrogate from the same side under ambient environments.

4. Without special considerations, it is nearly impossible to transmit ultrasound through materials at temperatures >250C.

CONCLUSIONS

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

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

We have also provided an introduction to a novel ultrasonic non-contact analyzer and its applications for characterization of industrial and bio-medical materials and products. It is also important to note that the NCU transducers and the analyzer, NCA 1000 have been successfully integrated in laboratories and materials factories world-wide.

We believe that the non-contact ultrasound mode is among the most significant developments for characterization and analysis of 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 the causes of 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.

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ULTRASOUND REFLECTIONS AND RECOMMENDATIONS

Despite the wealth of information provided by ultrasound, this age-old method is still not as popular as other wave-based characterization methods are. Let alone NCU, even conventional ultrasound has not earned the serious attention of materials institutes and R&D laboratories. In order for ultrasound to rival other well-known methods, it is imperative to initiate inter-disciplinary materials research and education in this subject of great importance.

We need to raise the core question, "What material features and properties (micro and macro) are responsible for its ultrasonic characteristics." This crystallo-chemical question must be resolved in a practical manner in order to determine the depth of ultrasound in materials characterization.

As an example, we can learn a great deal from the ultrasound-biomedical model. 25 years ago ultrasound in medical diagnostics was barely known. And today, it is, perhaps, the most widely used method. Why and how? Because of the obvious value of ultrasound (over hazardous x-rays) the medical community and related industry gave ultrasound a respectable place in both education and research.

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2 Our personnel are highly experienced and dedicated ultrasound and materials scientists. We are electrical engineers and signal processing experts. Therefore, besides providing the technological training, we also provide scientific know-how vis-à-vis your needs. These services are integral part of our offer.

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4 Our approach is direct and no-nonsense! It is always focused on your questions and needs.

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APPENDIX I

ACOUSTIC PRESSURE AND SENSITIVITY MEASUREMENTS

In order to determine the efficiency of non-contact transducers, first a number of selected transducers (to be used as calibrated transducers) were characterized for acoustic pressure measurements by Laser interferometric technique at Laboratorie de Mecanique Physique, Universite Bordeaux, France.[4]

Same transducers were also analyzed by monitoring the amplitude (in volts) of the reflection of ultrasound from a flat reflector in air at a specified distance. Receiver gain was varied for each transducer in order to obtain one volt reflected signal amplitude.

Acoustic pressure and receiver gain are shown in Table VI for the characterized transducers.

Table VI. Acoustic Pressure and Receiver Gain to obtain one Volt Reflected Signal Amplitude of Characterized Non-Contact Transducers.

TRANSDUCER	FREQUENCY	ACTIVE DIAMETER (mm)	DISTANCE FROM MEMBRANE/ TARGET (mm)	ACOUSTIC PRESSURE (Pa/V)	RECEIVER GAIN FOR 1 V REFLECTED AMPLITUDE (dB)
NCT101	100 kHz	25	50	3.5	39
NCT52	200 kHz	12.5	36	2.8	38
NCT55	500 kHz	12.5	30	4.5	26
NCT210	1.0 MHz	6.3	12	10	28

By using transducers in Table VI as reference transducers, a few other non-contact transducers were characterized for efficiency by measuring their acoustic pressures as a function of distance from flat reflector. These observations are shown in figures 104, 105, and 106.

Sensitivity: By monitoring the amplitude of reflected signal from a flat target, figures 107, 108, and 109 show relationships between sensitivity and transducer to reflecting target distance in ambient air.

[4] Christine Biateau and Prof. Bernard Hosten, January 2002.

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Acoustic Pressure as a Function of Transducer to Flat Target Distance in Ambient air

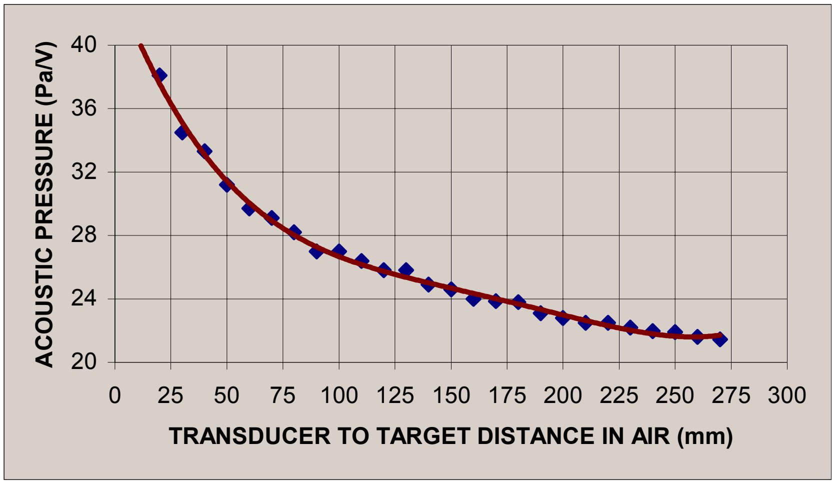

Fig. 104. Acoustic pressure of NCT202 transducer

200 kHz
50 mm Diameter

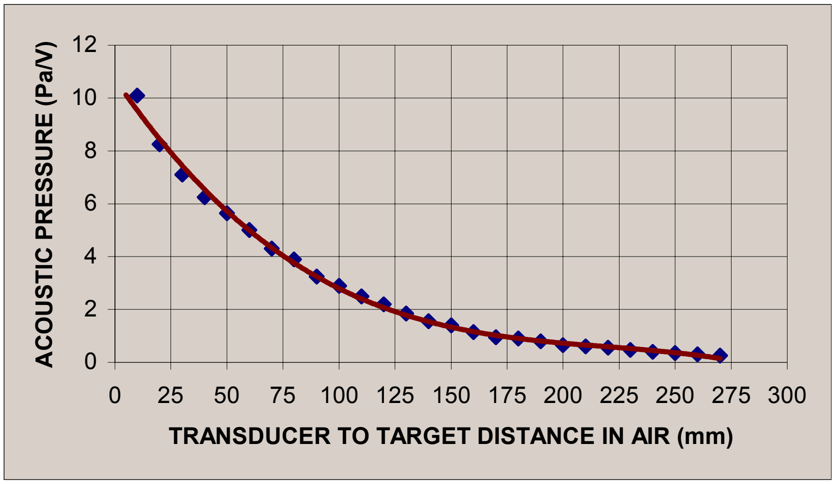

Fig. 105. Acoustic pressure of NCT55 transducer

500 kHz
12.5 mm Diameter

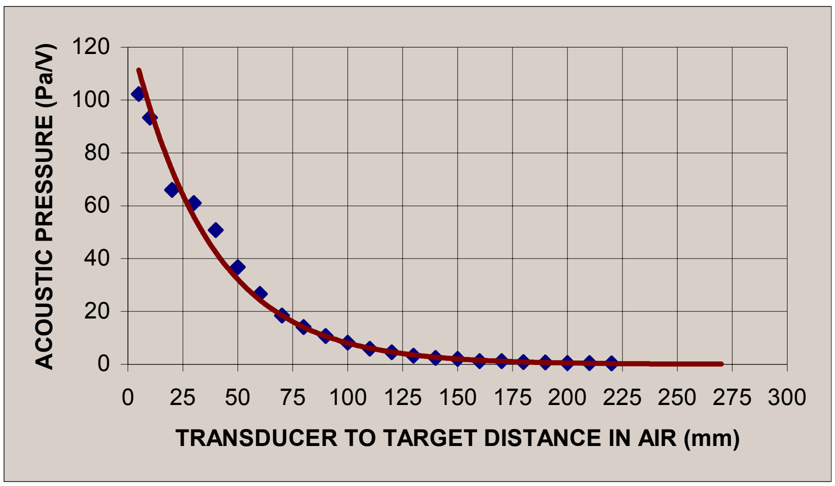

Fig. 106. Acoustic pressure of NCT510 transducer

1.0 MHz
12.5 mm Diameter

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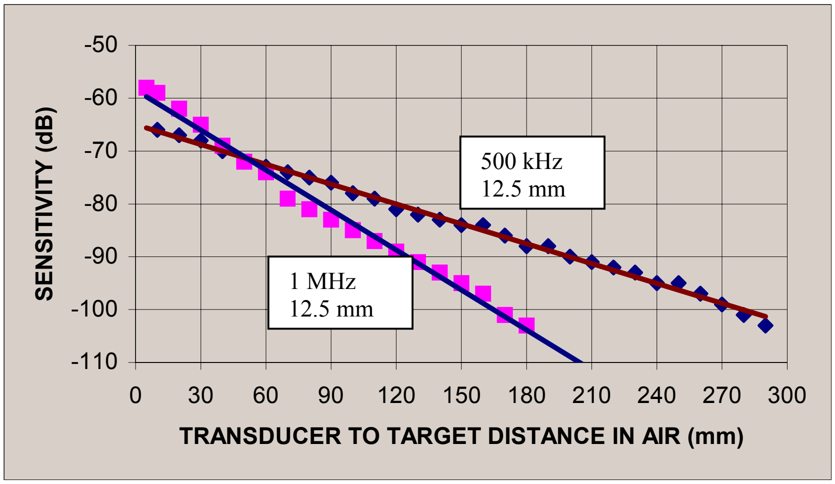

Fig. 107. Reflected sensitivity as a function of distance for:

NCT55: 500 kHz 12.5 mm diameter
NCT510: 1 MHz 12.5 mm diameter
Transducers.

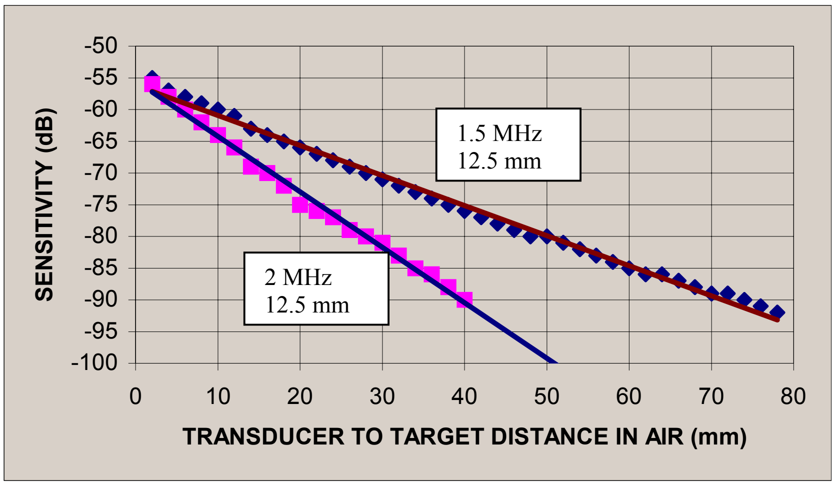

Fig. 108. Reflected sensitivity as a function of distance for:

NCT515: 1.5 MHz 12.5 mm diameter
NCT520: 2 MHz 12.5 mm diameter
Transducers.

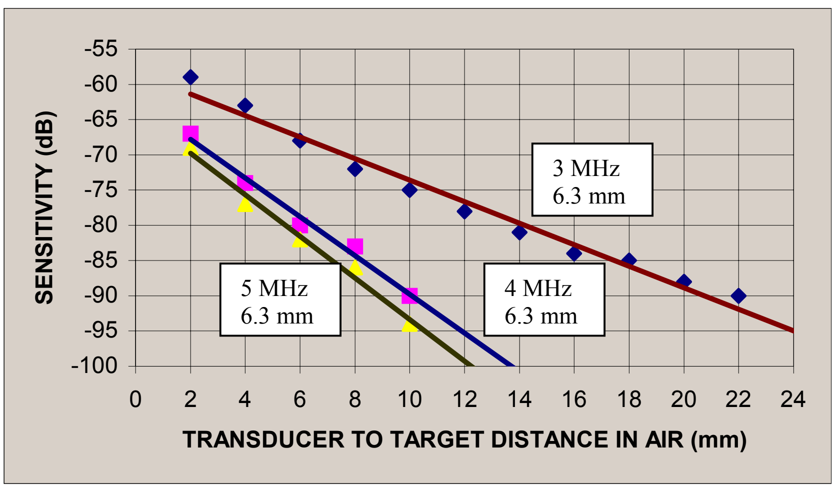

Fig. 109. Reflected sensitivity as a function of distance for:

NCT230: 3 MHz 6.3 mm diameter
NCT240: 4 MHz 6.3 mm diameter
NCT250: 5 MHz 6.3 mm diameter
Transducers.

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