*NON-CONTACT ULTRASOUND: THE LAST FRONTIER IN NON-DESTRUCTIVE TESTING AND EVALUATION

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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. A variety of ultrasound generation mechanisms has 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 100kHz to 5MHz 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

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 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

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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. Obviously, ultrasound has come a long way since the discovery of piezoelectricity by Pierre and Jacques Curie in 1876 (1) and its first application by Richardson in 1913 for sonar (2).

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 (3). 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!"*

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:

$$\textbf{T (Transmission co-efficient in the medium of propagation)} = 4Z_1Z_2/(Z_1+Z_2)^2 \qquad (1)$$

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

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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.,

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

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

$$\mathbf{T = 20 \log V / V_0, [dB]} \qquad (3)$$

$$\textbf{Energy transferred in the medium of propagation} = \mathbf{20 \log T, [dB]} \qquad (4)$$

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. (4).

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. 1. 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 4, 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.

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 NON-CONTACT ULTRASONIC 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 (5) 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. (6). It was used to characterize the Rayleigh waves in metals (7) and for subsurface materials evaluation (8). 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

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metals, pharmaceutical and food products, tissue, etc. Ultrasound generated by electromagnetic acoustic transducers has been used in the NCU mode for non-destructive testing (9). This method is only applicable to ferromagnetic materials.

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 (10). 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 (11,12,13). 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 (14). 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 (15,16). Researchers at Strathclyde University (17) 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 (18)[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 11MHz frequency (19,20). 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 (21).

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

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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 chapter we describe the successful development of piezoelectric transducers which are characterized by extraordinarily high sensitivities in a frequency range from 100kHz to 5MHz. The evidence of the high sensitivity of these new transducers can be seen from the fact that even very high frequencies such as, 2MHz to 5MHz can be propagated through a number of solids in the NCU mode.

4 PIEZOELECTRIC TRANSDUCERS FOR UNLIMITED NON-CONTACT ULTRASONIC TESTING

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. 2. To understand this, we examine the effect of the final acoustic impedance matching layer on the piezoelectric material with respect to transmission of ultrasound from it (piezoelectric element) to air, as per equations 1 and 4. 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 14, 15, 16, and 17 and this author's 1983 design (commercially available as air/gas propagation transducers from Ultran Laboratories), the best final piezoelectric matching layer for maximum ultrasound transmission in air is composed of soft polymers. 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.

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 (18) a transducer with compressed fiber as the final matching layer. 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 (18). 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 ~8MHz. However, from a practical standpoint they have been shown to propagate up to 5MHz ultrasound in nearly all material types in the NCU mode under ambient air environment. Leaving aside transmission in plastics and composites, the sensitivity of NC

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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 Transducer Characterization Scheme

NC transducers, like their contact or water-coupled counterparts, can also be characterized in the transmission or in the reflection (pulse echo) modes. Fig. 3 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.

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

Where V_n is the amplitude of the noise in volts.

Sensitivity (insertion loss) is determined by,

$$\mathbf{S = 20 \log V_x/V_0, [dB]} \qquad (6)$$

By utilizing this characterization scheme, several NC transducers were analyzed under ambient air environment. Figures 4, 5, 6, and 7 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. 3. 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. 3, 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 6, 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.

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 8 and 9 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 8 and 9, 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 Fig. 8 was obtained by AC transducers, and Fig. 9 by NC

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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 non-contact transducer design over the other air-coupled transducers described in references (14,15,16,17), including this author's air/gas propagation transducers commercially available from Ultran Laboratories since 1983.

In order to further demonstrate the exceptionally high sensitivity of NC transducers, we decided to conduct an experiment which would normally be considered impossible! An experiment analogous to the one described above was performed, except in this 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. 10 presents the observation from this, showing a 3.26mV signal transmitted through a 20 mm aluminum in non-contact mode. AC transducers (based upon soft polymer matching layers, i.e., without or with porosity or with hollow spheres) were unsuccessful in generating ultrasound transmission through 20mm aluminum by 16 volt excitation, despite high signal averaging! It is also interesting to note that by low energy excitation, with NC transducers we have been able to propagate MHz frequencies even in steel, the acoustic impedance of which is 51Mrayl, i.e., six orders of magnitude higher than air! We show an example of this startling conclusion in Fig. 11. It is important to note that the purpose of observations shown in figures 8 to 11 is to demonstrate the high sensitivity of NC transducers relative to any other similar device. The purpose of these experiments is not to recommend or suggest the usage of low energy transducer excitation for the testing of materials.

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. In 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. 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 ambient air conditions and better than ±1ns under closed conditions. The NCA 1000, Fig. 12, 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.

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)

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

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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. 13 shows pulse echo reflection signals from a 9mm thick silicone rubber sample. This observation was generated by using 1MHz focused NC transducer. Similar results have also been observed for other plastic materials. However, at the time of this writing, we have no concrete proof of generating these observations from high acoustic impedance materials, such as metals, ceramics, etc. 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.

6.2 Separate Transmitter and Receiver 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. 14, 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,

$$\mathbf{Sin_i / Sin_r = V_a / V_m} \qquad (7)$$

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

By manipulating the incident angle in air a variety of wave types can be produced in a test material. Fig. 15 shows the far side thickness reflection of longitudinal wave from 12mm thick aluminum. Fig. 16 shows the far side thickness reflection of longitudinal and shear waves from 32mm thick transparent polystyrene. Fig. 17 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. 18 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.

6.3 Direct Transmission

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 shown in figures 19 and 20. 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.

7 VERY HIGH FREQUENCY NCU PROPAGATION IN MATERIALS

By utilizing the NC transducers under ambient air environment we have amply demonstrated that frequencies as high as 2MHz can be easily propagated through a variety of materials, including fibrous and particulate, plastics, ceramics, metals, and composites. However, frequencies even higher than 2MHz have been successfully

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investigated for propagation through solids. Fig. 21 shows an example of 4MHz propagation through 4.5mm thick multi-layer graphite fiber reinforced plastic composite under ambient air environment. Similar observations have also been made for soft polymers, thin metals and fibrous and particulate materials. As expected, the magnitude of transmitted signals through solids increases substantially when examined under high gas pressures. Fig. 22 exhibits propagation of 4MHz transmission through 8mm thick steel under 60 bars nitrogen by using a single transducer in pulse-echo technique, section 6.1.

8 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.

8.1 Velocity 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. 23, 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,

$$V_m = 2d_m / t_m \qquad (8)$$

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.

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.

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 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:

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$$\mathbf{V_m = d_m/t_m} \tag{9}$$
$$\mathbf{d_m = V_a \times t_{am}} \tag{10}$$
$$\mathbf{t_{am} = t_a - (t_1 + t_2)/2} \tag{11}$$
$$\mathbf{t_m = t_{am} - (t_a - t_c)} \tag{12}$$

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,

$$\mathbf{d_m = V_a \times [t_a - (t_1 + t_2)/2]} \tag{13}$$
$$\mathbf{V_m = d_m / t_{am} - (t_a - t_c)} \tag{14}$$

As an example, Fig.20 shows actual transmitted and reflected signals when a test material is examined in the non-contact transmission mode. Identification and location of these signals with respect to the test material are shown in figures 19 and 20. As can be seen from equations 13 and 14, 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. These parameters are measured and calculated by the NCA 1000 computer and are displayed with velocity and thickness of the test material on the monitor screen, Fig. 25.

8.2 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,

$$\mathbf{IR_m = IR_c - IR_a} \tag{15}$$

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. 26 shows the IR_c (-21.72dB) of the transmitted peak of ultrasound from air into the specimen and Fig. 27 shows a similar peak, but 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:

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

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 4) 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.,

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

$$\rho_m = Z_m / V_m \quad (18)$$

Measurement of IR_m and solution of equations 17 and 18 provide approximate ideas about the acoustic impedance and density of the test material. For accurate determination of these characteristics, factors -- such as ultrasound attenuation (analogous to absorption co-efficient in x-ray absorption) and material thickness -- must also be considered, i.e.,

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

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 (21).

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.

8.3 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 shown in Fig. 28. In order to generate frequency dependence of ultrasonic attenuation, the sample spectrum is subtracted from that of the reference air spectrum, Fig. 29. By performing a similar analysis, the surfaces of materials can also be analyzed in the frequency domain. Frequency dependent attenuation can be related to the test material's internal and surface characteristics, such as defects, texture, microstructure, roughness, etc.

9 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 (22, 23, 24, 25, 26, 27, 28,29). In this section we present selected examples of NCU applications with respect to materials testing and other objectives.

9.1 Materials Characterization and Defect Detection

Figures 30 and 31, respectively, show the relationships between densities of green and sintered alumina with non-contact velocities of these materials. Fig. 32 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 33 and 34, respectively, show the velocity

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density relationships for isostatically pressed high density green alumina and tungsten carbide. Examples of defect detection in green and sintered ceramics are shown in figures 35 and 36, and similar observations for aluminum in Fig. 37. Figures 38 and 39 respectively, show direct transmission and same side reflection trend plots in Graphite Fiber Reinforced Plastic (GFRP) composites bonded to a honeycomb structure. The same side observations, Fig. 39, correspond to the bond between GFRP and honeycomb material.

By performing the non-contact ultrasonic spectroscopy, the examples of texture and microstructure analysis are shown in figures 40 and 41. Fig. 40 shows the frequency dependence of ultrasound attenuation by three specimens of extremely porous ceramics (in the present case, space shuttle tiles), and Fig. 41 shows similar observations from two samples of packaging foam varying in cell dimensions. Fig. 42 shows very high frequency non-contact transmission spectroscopy of two samples of paper towels. Similar observations have also been made for the detection of bubbles and pores in liquids and other materials.

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. 43. It is quite evident that as the particle size increases, the frequency-dependent attenuation also increases. A similar experiment was performed in which the Integrated Response (IR) of reflected ultrasound from the test and reference materials surfaces was measured. 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. 44. Once again, it is quite clear that as the particle size increases, the ultrasound reflectivity decreases (due to the scattering of ultrasound). By performing these simple experiments it is relatively easy to characterize the material surface texture or its roughness.

9.2 Non-Contact Ultrasonic 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. 45 shows a partial contact ultrasonic image of an impact damaged 1.5mm thick multi-layered graphite reinforced plastic composite. The test material in this case was placed on a large stationary transmitting transducer, while a small receiver in non-contact mode was scanned over the other surface of the material. Fig. 46 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. 47. Fig. 48 shows an image of defects in aluminum. Similar images for materials, such as steel welds, fiber webs, cheese, meats, wood, and other materials have been generated by using the NC transducers with the NCA 1000 and other commercial instruments.

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.

9.3 Food, Beverage, and Pharmaceutical

Fig. 49 shows transmitted non-contact ultrasound signals from regions with and without nuts in milk chocolate, almonds in this case. Fig. 50 is an example of the fat content measurement in milk and milk products. Similarly, Fig. 51 shows the measurement of sugar content in water. 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. Analogous to green ceramics and like material (figures 30, 33, and 34), tablets, capsules, and other powder-based pharmaceutical products have also been characterized as functions of the velocity and frequency-dependence of ultrasound attenuation. This method has also been successfully applied to detect the presence or absence of liquids (milk,

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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 demosntrated.

9.4 Medical

One of the first medical applications of NC transducers was the evaluation of burnt skin and bed sores in burn victims (24). 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. 52. Detection of damage underneath the burnt skin is evident from the disruption of the interface between the epidermis and the capillary bed. Fig. 53 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.

9.5 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. 54. 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. 55 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.

9.6 Other Non-Contact Ultrasound 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.

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.

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

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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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REFERENCES

1 Curie, J and Curie, P., "Development par compression de l'electricite pollaire dans les cristaux hemledres a faces inclinees, "Bulletin no. 4 de la Societee Mineralogique de France, 3 90 (1880) and C.R. Acad. Sc. Paris, 91, 294 (1880).

2 Richardson, R.L., "Apparatus for Warning a Ship at Sea of its Nearness to Large Objects wholly or partially under Water," : British Patent Specification, 11,125, March 27, 1913.

3 Green, R.E., "Ultrasonic Non-destructive Materials Characterization," in Alex Vary, ed., Materials Analysis by Ultrasonics, Noyes Data Corporation, New Jersey, 1987, p. 6.

4 Cho, Z., Jones, J.P., and Singh, M, Foundations of Medical Imaging, Wiley, New York, 1993, pp. 477-486

5 White, R.M., "Generation of Elastic Waves by Transient Surface Heating," J. App. Phys., v. 34, pp. 3559-3567 (1963).

6 Bondarenko, A.A., Drobat, Y.B., and Kruglov, S.V., "Optical Excitation and Detection of Nanosecond Acoustic Pulses in Non-destructive Testing, " Soviet J. NDT, v. 12, pp. 655-658 (1976).

7 Ledbetter, H.M. and Moulder, J.C., "Laser-Induced Rayleigh Waves in Aluminum, J. Acoust. Soc. Amer. V. 65, pp 840-842 (1979).

8 Aindow, A.M., Dewhurst, R.J., Palmer, S.B., and Scruby, C.B., "Laser-Based Non-Destructive Testing Techniques for Ultrasonic Characterization of Subsurface Flaws," NDT International, v. 17, pp. 329-335 (1984).

9 Allers, G.A., "Monitoring Pipe and Tube Wall Properties During Fabrication in a Steel Mill," in Intelligent Processing of Materials and Advanced Sensors, H.N.G. Wadley, P.A. Parish, B.B. Rath, and S.M. Wolf, editors, Metallurgical Society, Pennsylvania, (1986), pp. 17-27.

10 Brunk, J.A., Allied Signal, Private communication, (1999).

11 Brunk, J.A., Valenza, C.J., and Bhardwaj, M.C., "Applications and Advantages of Dry Coupling Ultrasonic Transducers for Materials Characterization and Inspection," in Acousto-Ultrasonics, Theory and Applications, John C. Duke, Jr., Editor, Plenum Press, New York (1988), pp. 231-238.

12 Bhardwaj, M.C. and Bhalla, A., "Ultrasonic Characterization of Ceramic Superconductors," J. Mat. Sci. Lett., v. 10 (1991).

13. Kulkarni, N., Moudgil, B. and Bhardwaj, M., "Ultrasonic Characterization of Green and Sintered Ceramics: I, Time Domain," Am. Cer. Soc., Cer. Bull, Vol. 73, No. 6, (1994).

14. Fox, J.D., Khuri-Yakub, B.T., and Kino, G.S., "High Frequency Wave Measurements in Air," 1983 IEEE Ultrasonics Symposium, pp. 581-592 (1983).

15. Yano, T., Tone, M., Fukumoto, A., "Range Finding and Surface Characterization using High Frequency Air Transducer," IEEE Trans. UFFC, v. 34, n. 2, pp. 222-236 (1987).

16. Haller, M.I. and Khuri-Yakub, B.T., "1-3 Composites for Ultrasonic Air Transducer," IEEE Ultrasonics Symposium, pp. 937-939 (1992).

17. Reilly, D. and Hayward, G., "Through Air Transmission for Ultrasonic Non-destructive Testing," IEEE Ultrasonic Symposium, pp. 763-766 (1991).

18. Bhardwaj, M.C., "Ultrasonic Transducer for High Transduction in Gases and Method for Ultrasound Non-Contact Transmission into Solid Materials," U.S. and international patents pending and in process (1997 - 1999).

19. Schindel, D.W., Hutchins, D.A., Zou, L., and Sayer, M., "The Design and Characterisation of Micromachined Air-Coupled Capacitance Transducers," IEEE Trans. Ultrason. Ferroelect. Freq. Control.,

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v. 42, pp. 42-51 (1995).

20. Ladabaum, I., Khuri-Yakub, B.T., and Spoliansky, D., "Micromachined Ultrasonic Transducers (MUTS): 11.4MHz Transmission in Air and More," App. Phys. Lett., v. 68, pp. 7-9 (1996).
21. Castaings, M. and Hosten, B., "The use of Electrostatic, Ultrasonic, Air-coupled Transducers to Generate and Receive Lamb Waves in Anisotropic, Viscoelastic Plates," Ultrasonics, v. 36, pp. 361-365 (1998).
22. Landa, M., Bhardwaj, M.C., and Neeson, I., "Non-Contact Ultrasound," Institute of Thermomechanics, Academcy of Sciences of the Czech Republic, Prague, CZ, report no. Z1266/99 (1999).
23. Bhardwaj, M.C., "Innovation in Non-Contact Ultrasonic Analysis: Applications for Hidden Objects Detection," Mat. Res. Innovat. (1997) 1:188-196.
24. Jones, J.P, Lee, D., Bhardwaj, M., Vanderkam, V., and Achauer, B., "Non-Contact Ultrasonic Imaging for the Evaluation of Burn-Depth and for Other Biomedical Applications," Acoust. Imaging, V. 23 (1997).
25. Bhardwaj, M.C., "Non-Contact Ultrasonic Characterization of Ceramics and Composites," Proceedings Am.Cer.Soc., V 89 (1998).
26. Carneim, T., Green, D.J., and Bhardwaj, M.C., "Non-Contact Ultrasonic Characterization of Green Bodies," Cer. Bull., April 1999.
27. Tittmann, B.R., Bhardwaj, M.C., Vandervalk, V. and Neeson, I., "Non-Contact Ultrasonic NDE of Carbon/Carbon Composite," Ceramic Engineering and Science Proceedings, 23rd Annual Conference on Composites, Advanced Ceramics, Materials, and Structures: A, editors, Ustundag, E. and Fischman, G., The American Ceramic Society, Westerville, OH (1999).
28. Bhardwaj, M.C., Neeson, I., Langron, M.E., and Vandervalk, V., "Non-Contact Ultrasound: The Final Frontier in Non-Destructive Materials Characterization," Ceramic Engineering and Science Proceedings, 24th Annual Conference on Composites, Advanced Ceramics, Materials, and Structures: A, editors, Jessen, T. and Ustundag, E., The American Ceramic Society, Westerville, OH (2000).
29. Vun, R.Y., Wu, Q., Bhardwaj, M., and Stead, G., "Through-Thickness Ultrasonic Transmission Properties of Oriented Strandboard," Proceedings of the 12th International Symposium on Nondestructive Testing of Wood, University of Western Hungary, Sopron, Hungary (2000).

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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.

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^2s.

MATERIAL Z_m (Mrayl)	INTERFACE Fig. 1	TRANSMISSION CO-EFFICIENT, T equation 1		ENERGY TRANSFER equation 4 (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

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 4 (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	---

**U.S. and international patents pending and in process (18).*

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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	-38	-18
	25	-46	-26
0.5	50	-44	-20
	25	-50	-24
1.0	25	-52	-32
	19	-54	-34
	12.5	-56	-36
	3.2	-62	-38
1.5	12.5	-58	-38
2.0	12.5	-58	-38
	1.5	-66	-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.

Table V. NCA 1000 Measurements and their Relevance to Materials Characterization

MEASURED PARAMETERS/FUNCTIONS	**RELATIONSHIP WITH MATERIAL CHARACTERISTICS**
Times of flight in air and through the test medium.	Thickness, velocity, imaging, and level detection.
Integrated response: Area underneath a selected transmission or reflected peak.	Defect detection, imaging, microstructure, density, and surface characterization.
Frequency dependence of ultrasonic attenuation.	Microstructure, scattering, and other frequency-dependent variables.
Phase analysis.	Subtle compositional and structural variations.

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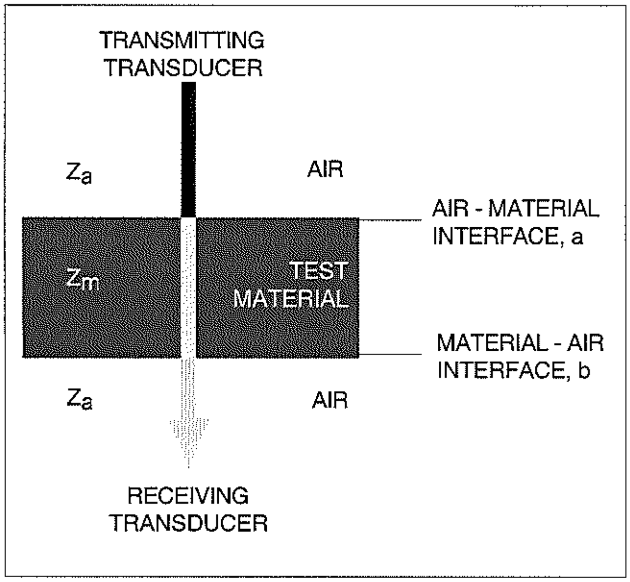

Fig. 1. Interfaces to be crossed by ultrasound (shown by arrow) in non-contact transmission mode in order to propagate ultrasound through a test material. Interface 'a' corresponds to air-material (from acoustic impedance Z_a to Z_m) transmission. Interface 'b' corresponds to material-air (from acoustic impedance Z_m to Z_a) transmission.

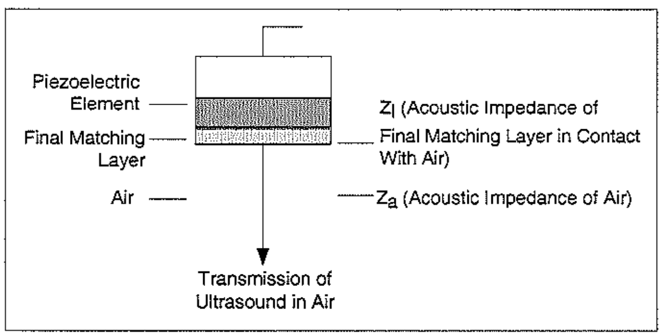

Fig. 2. Schematic of an ultrasonic transducer showing the critical final acoustic impedance matching layer relative to the piezoelectric element and coupling medium air.

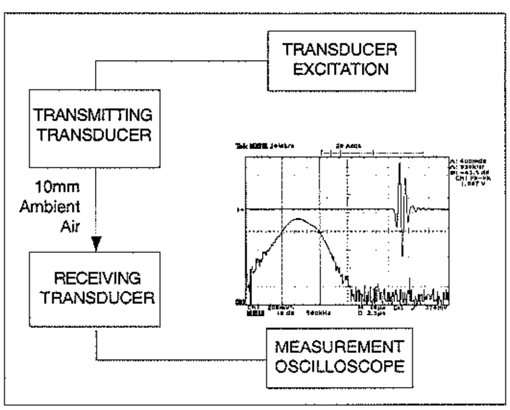

Fig. 3. Non-contact ultrasonic transducer characterization scheme in transmission mode.
Frequency, Bandwidth, Pulse Width, and Signal-To-Noise Ratio: Directly read from the oscilloscope.
Sensitivity = 20Log (V_x/V_0). V_0 = Excitation in volts. V_x = Received signal amplitude in volts

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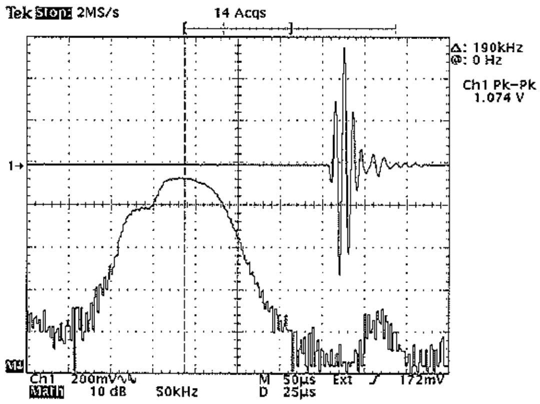

Fig. 4. Time and frequency domain of broadband 200kHz, 50mm active area transducers in transmission mode. T-R air separation: 100mm. Bandwidth Center Frequency: 200kHz. Bandwidth @ -6dB: 100kHz (50%). Pulse Width: <20µs. Sensitivity: -46dB. SNR: 50dB.

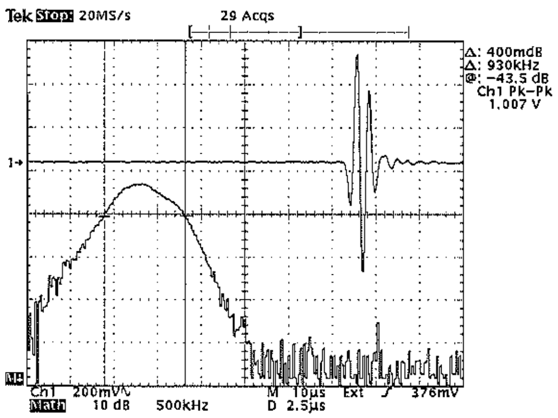

Fig. 5. Time and frequency domain of broadband 1.5MHz, 25mm active area transducers in transmission mode. T-R air separation: 10mm. Bandwidth Center Frequency: 1.4MHz. Bandwidth @ -6dB: 0.92MHz (65%). Pulse Width: <2µs. Sensitivity: -58dB. SNR: 46dB.

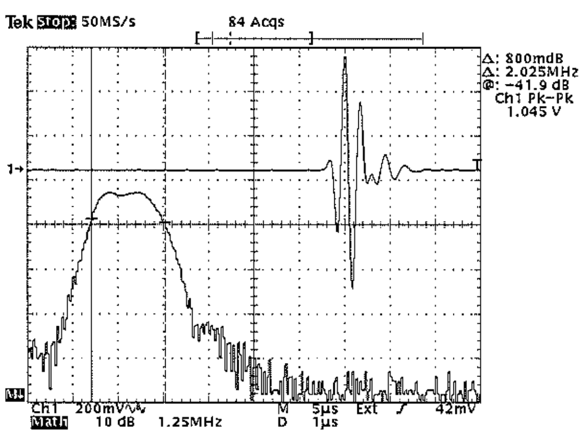

Fig. 6. Time and frequency domain of broadband 3.0MHz, 12mm active area transducers in transmission mode. T-R air separation: 10mm. Bandwidth Center Frequency: 2.6MHz. Bandwidth @ -6dB: 2.0MHz (75%). Pulse Width: <700ns. Sensitivity: -62dB. SNR: 40dB.

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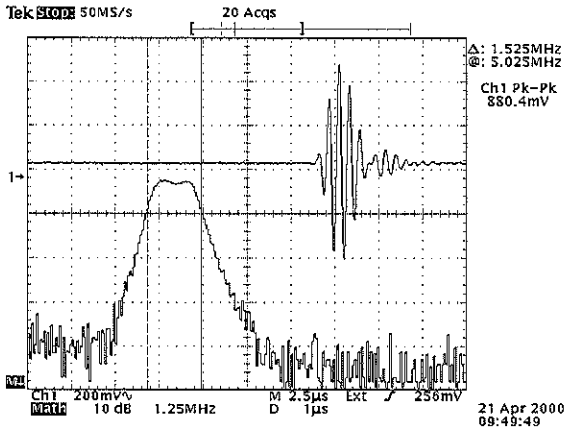

Fig. 7. Time and frequency domain of narrowband 5.0MHz, 12mm active area transducers in transmission mode. T-R air separation: 5mm. Bandwidth Center Frequency: 4.5MHz. Bandwidth @ -6dB: 1.5MHz (33%). Pulse Width: <800ns. Sensitivity: -68dB. SNR: 40dB.

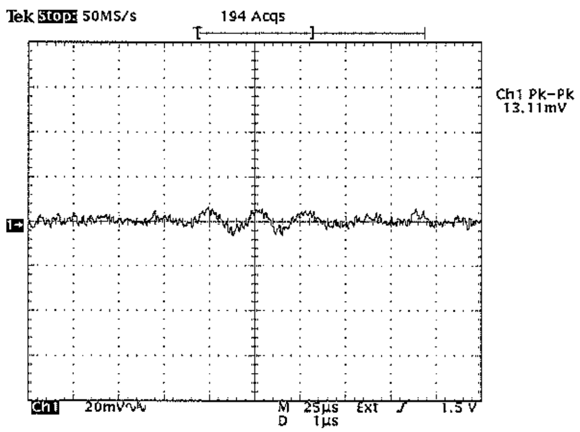

Fig. 8. A 1MHz non-contact transmitted signal through 20mm aluminum by using transducers based upon soft porous polymer matching layer. Excitation of the transmitting transducer: 400V into 4Ω input impedance. Receiving transducer amplification: 64dB. Transmitting and receiving transducers are 5mm away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

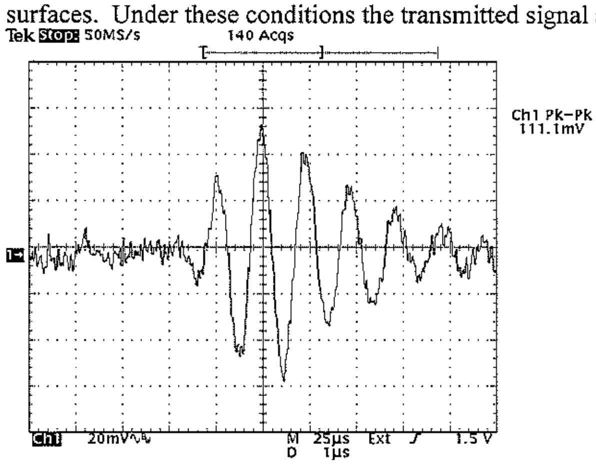

Fig. 9. A 1MHz non-contact transmitted signal through 20mm aluminum by using new transducers based upon compressed fiber matching layer. Excitation of the transmitting transducer: 400V into 4Ω input impedance. Receiving transducer amplification: 64dB. Transmitting and receiving transducers are 5mm away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

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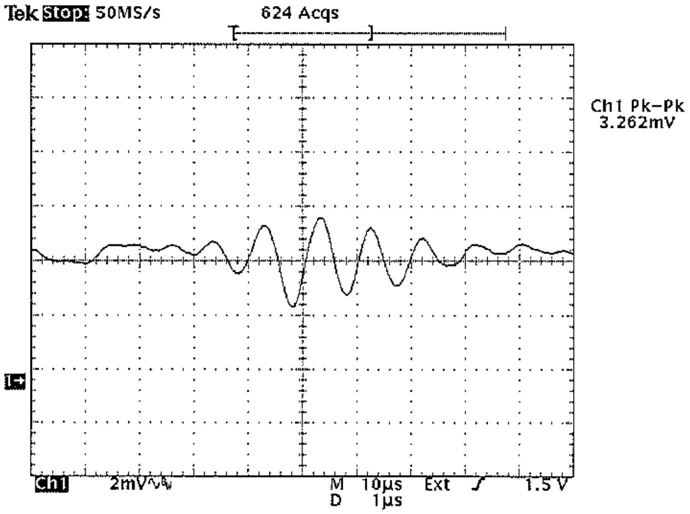

Fig. 10. A 1MHz non-contact transmitted signal through 20mm aluminum by using new transducers based upon compressed fiber matching layer. Excitation of the transmitting transducer: One burst 16V sine wave. Receiving transducer amplification: 64dB. Transmitting and receiving transducers are 5mm away from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

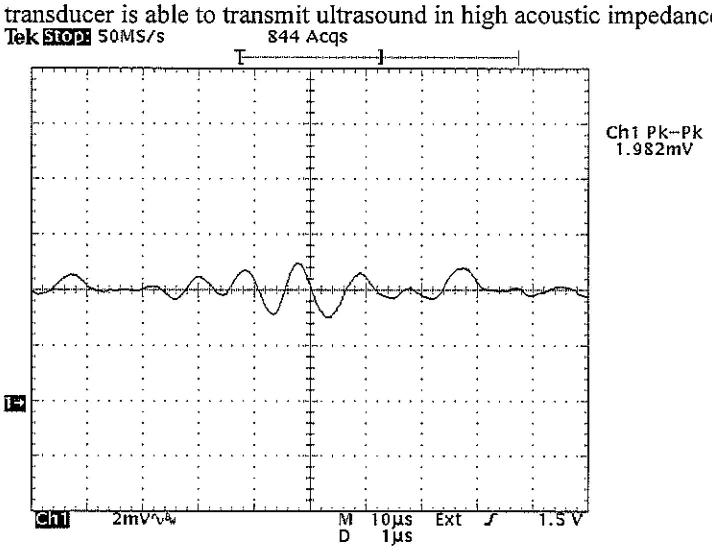

Fig. 11. Ultrasound transmission through 25mm carbon steel (Z, 51Mrayl) by utilizing the new non-contact transducers (1MHz 20mm active area diameter) with a single burst of 16 volt sine wave excitation and 64db amplification of the received signal by an equivalent transducer. Under similar conditions,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

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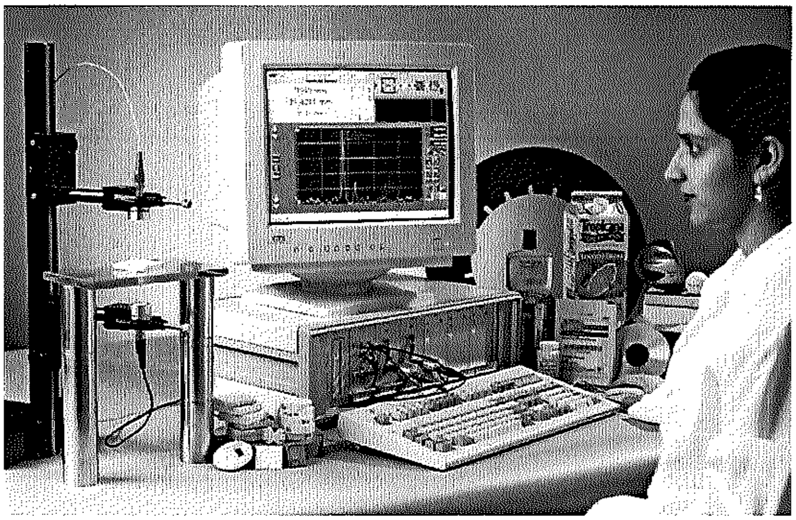

Fig. 12. Ultrasonic Non-Contact Analysis system, the NCA 1000, shown here with non-contact transducers and monitor screen displaying the thickness and velocity of the test material.

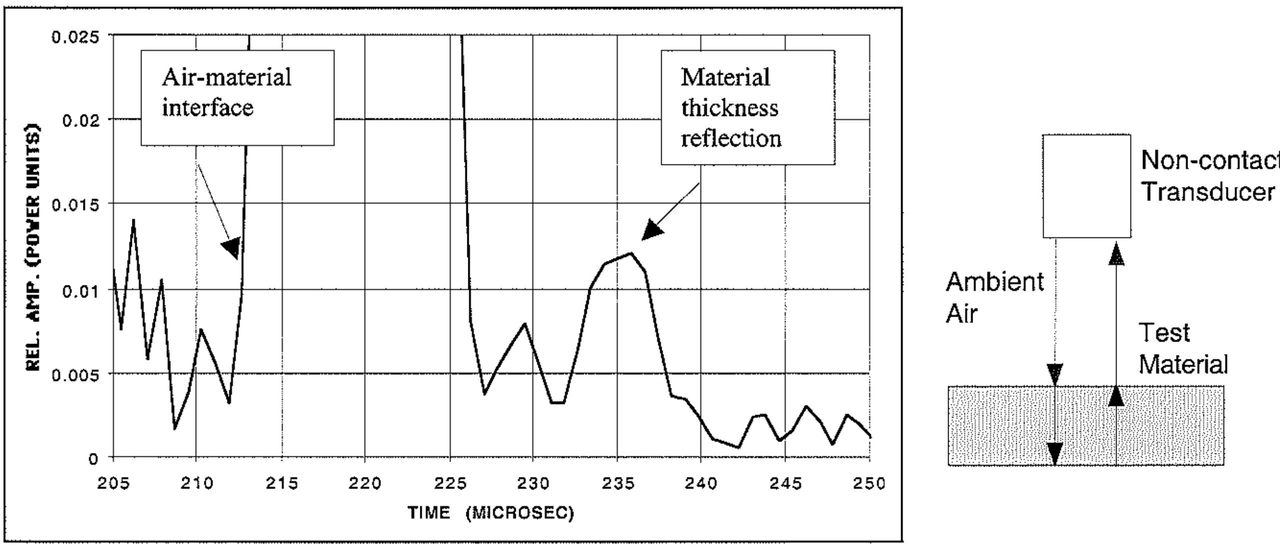

Fig. 13. Non-contact ultrasound pulse echo reflection from a 9mm thick silicone rubber. Transducer: 1MHz, 12.5mm active area diameter, and 76mm point focused. Transducer to material distance in air: 40mm. It is important to note that the material thickness reflection is ~40dB lower than that of the air-material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

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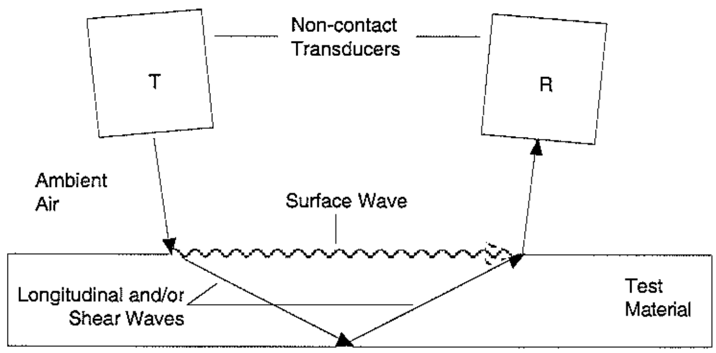

Fig. 14. Schematic of a setup for same side operation of separate Transmitting (T) and Receiving (R) transducers, also showing various types of wave propagation in the test material.

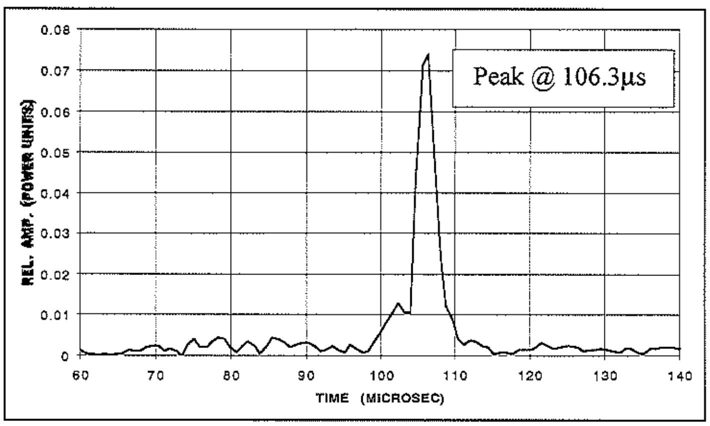

Fig. 15. Thickness reflection of longitudinal wave propagation in 12mm thick aluminum per Fig. 14 setup. Distance between the transducers and the material surface: ~15mm ambient air. Distance between T and R: ~50mm. Incident angle in air: ~3.0°.

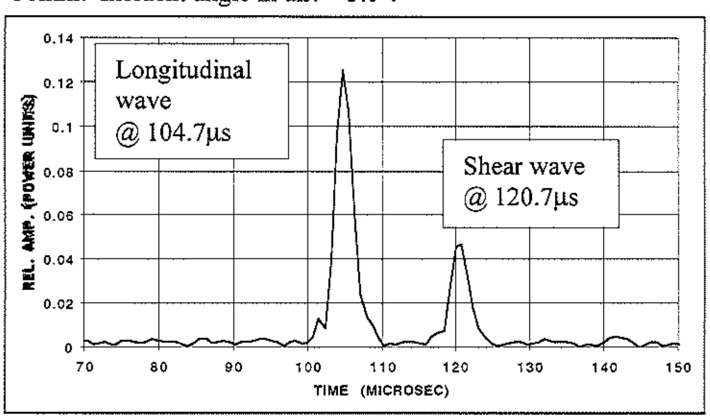

Fig. 16. Thickness reflections of longitudinal and shear waves in 32mm thick transparent polystyrene per Fig. 14 setup. Distance between the transducers and the material surface: ~13mm ambient air. Distance between T and R: ~50mm. Incident angle in air: ~6.0°.

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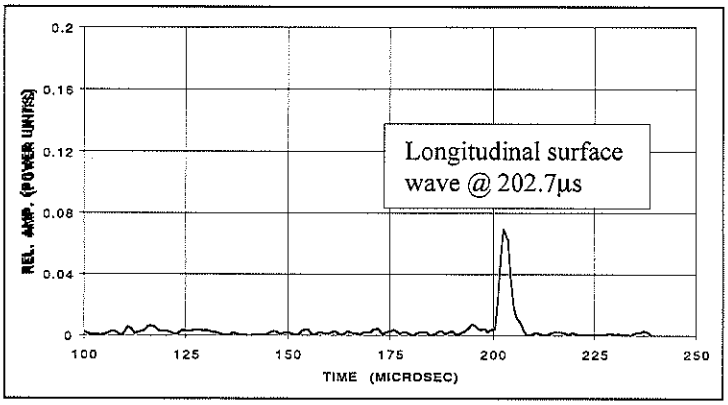

Fig. 17. Surface wave in aluminum produced by total reflection of longitudinal wave when the incident angle is equal to the first critical angle. Setup for this is shown in Fig. 14. Distance between the transducers and the material surface: ~15mm ambient air. Distance between T and R: ~100mm. Incident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

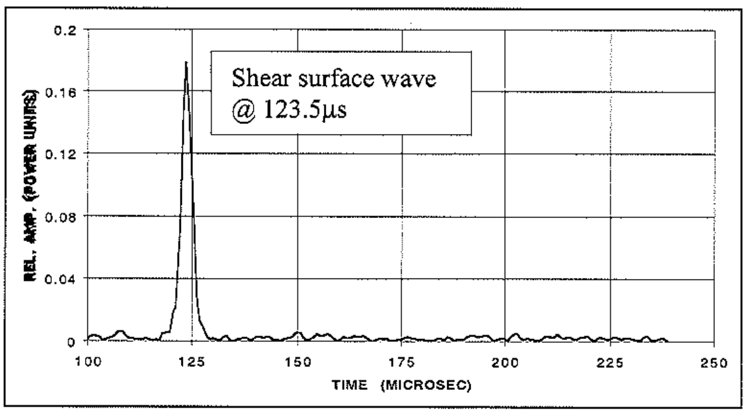

Fig. 18. Surface wave in aluminum produced by total reflection of shear wave when the incident angle is equal to the second critical angle. Setup for this is shown in Fig. 14. Distance between the transducers and the material surface: ~15mm ambient air. Distance between T and R: ~100mm. Incident angle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

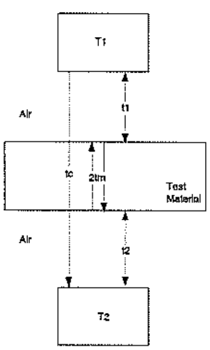

Fig. 19. Propagation of ultrasound in direct transmission non-contact mode. Here, tc is the complete Time of Flight (ToF) corresponding to propagation of ultrasound in air and the test material, 2tm is the round-trip ToF through the test material thickness, t1 and t2 are, respectively, ToFs from transducer T1 to the top surface of the materials, and transducer T2 to the bottom surface of the material. For further significance of this, see Fig. 20.

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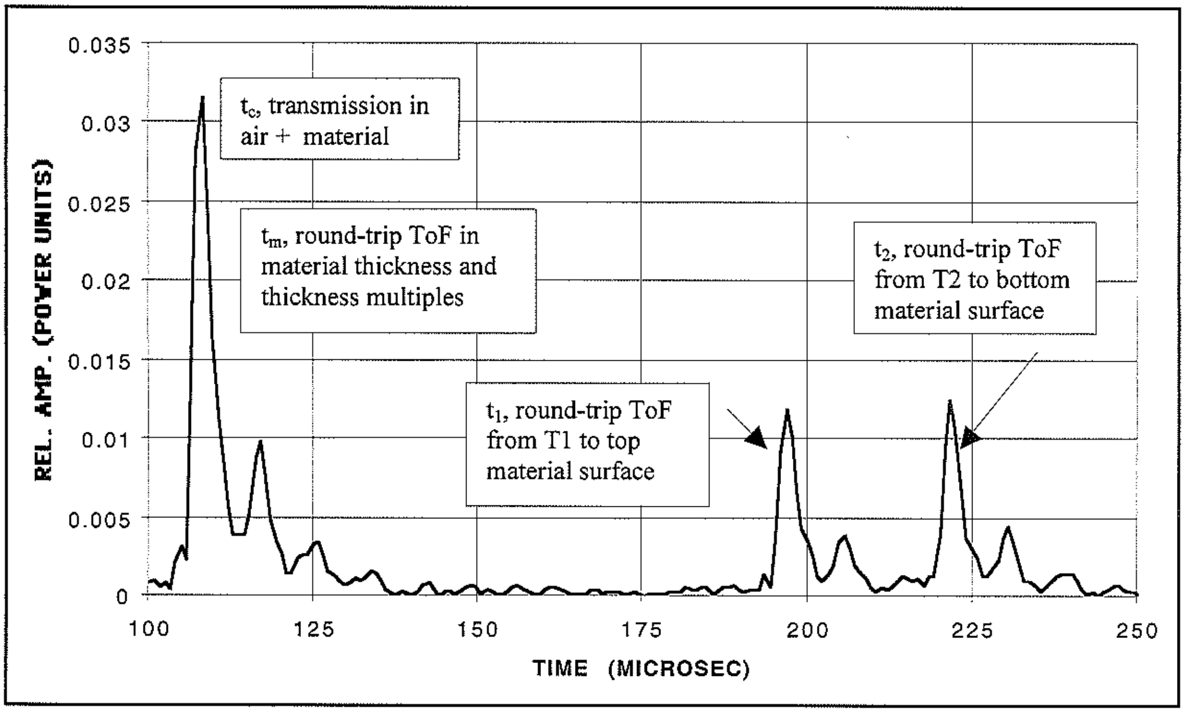

Fig. 20. Direct transmission non-contact ultrasound propagation through a test material (in the present case, 7mm thick cheese) per Fig. 19 setup.

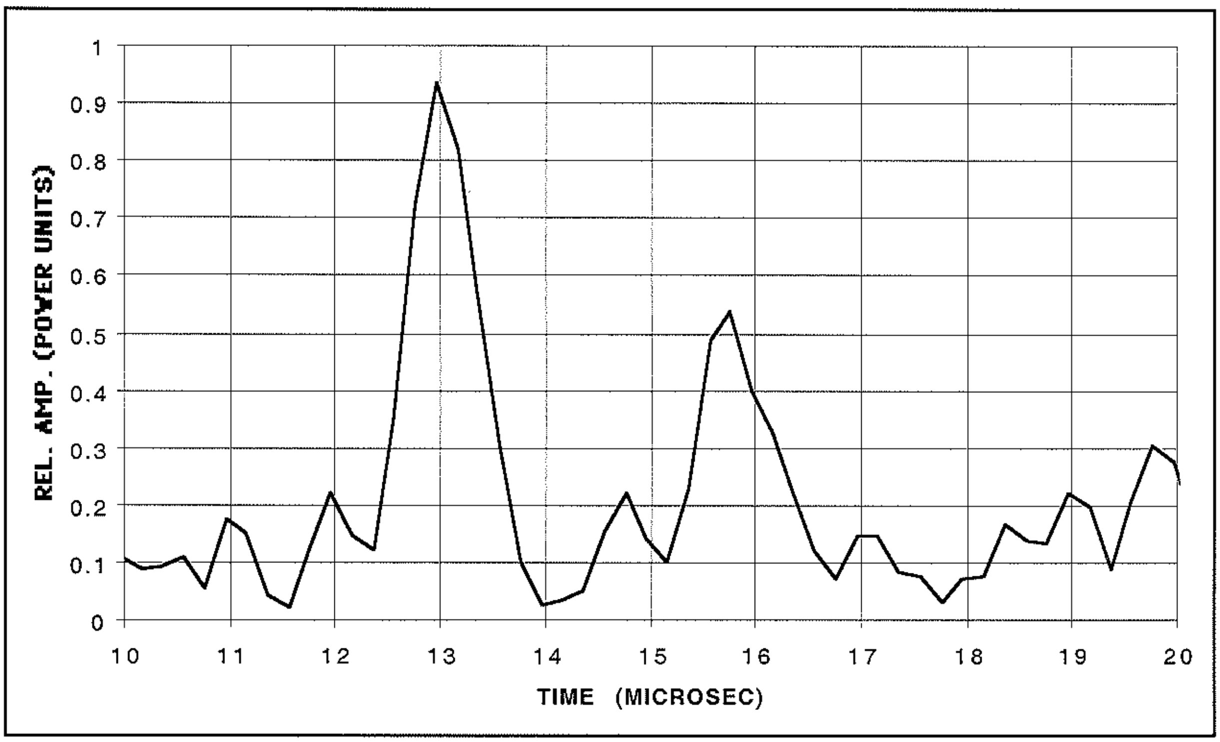

Fig. 21. Non-contact ultrasound direct transmission through 4.5mm thick multi-layer graphite fiber reinforced plastic composite at 4MHz under ambient air environment per Fig. 18 setup. Transducers are 4MHz and 12.5mm active area diameter. Transducers to test materials surface distances are ~3mm. 1st peak: directly transmitted signal through air and the test materials. Subsequent peaks: Test material thickness reflection and its multiples.

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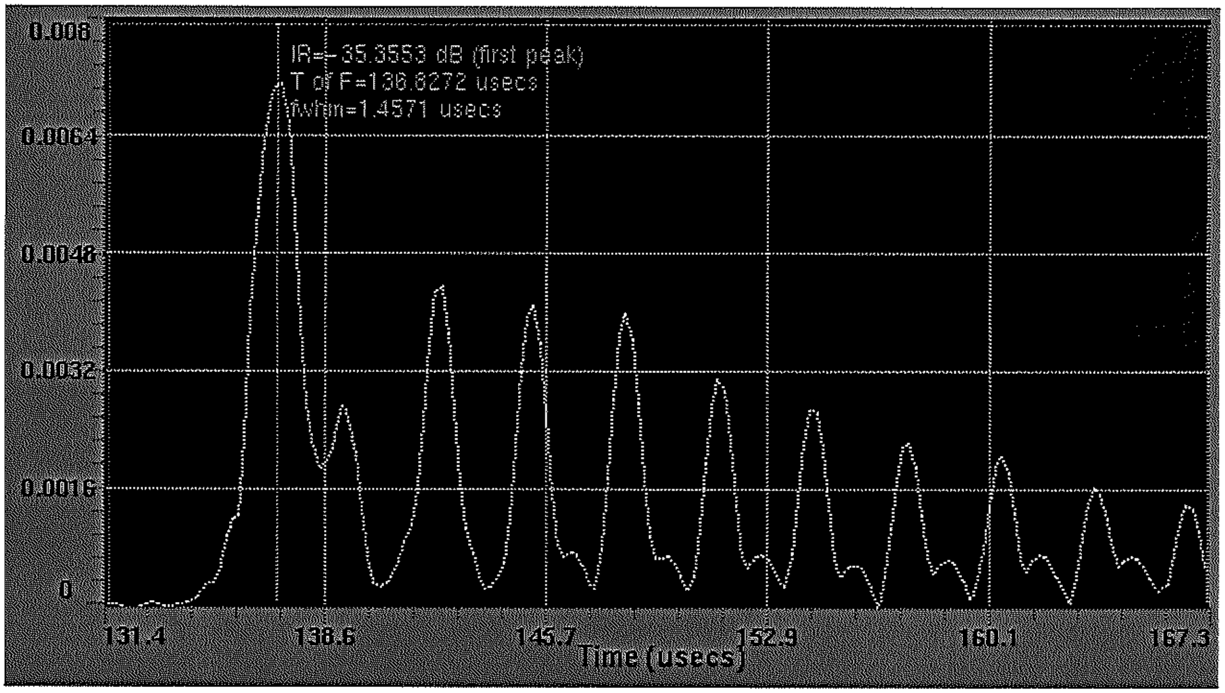

Fig. 22. Single transducer (pulse echo) signal through 8mm thick section of steel at 4MHz under 60 bar nitrogen pressure. Transducer used is 4MHz and 12.5mm active area diameter. Distance of transducer to the surface of test material is ~25mm. 1st peak: gas-materials interface. Subsequent peaks: Thickness and thickness multiples corresponding to the test material.

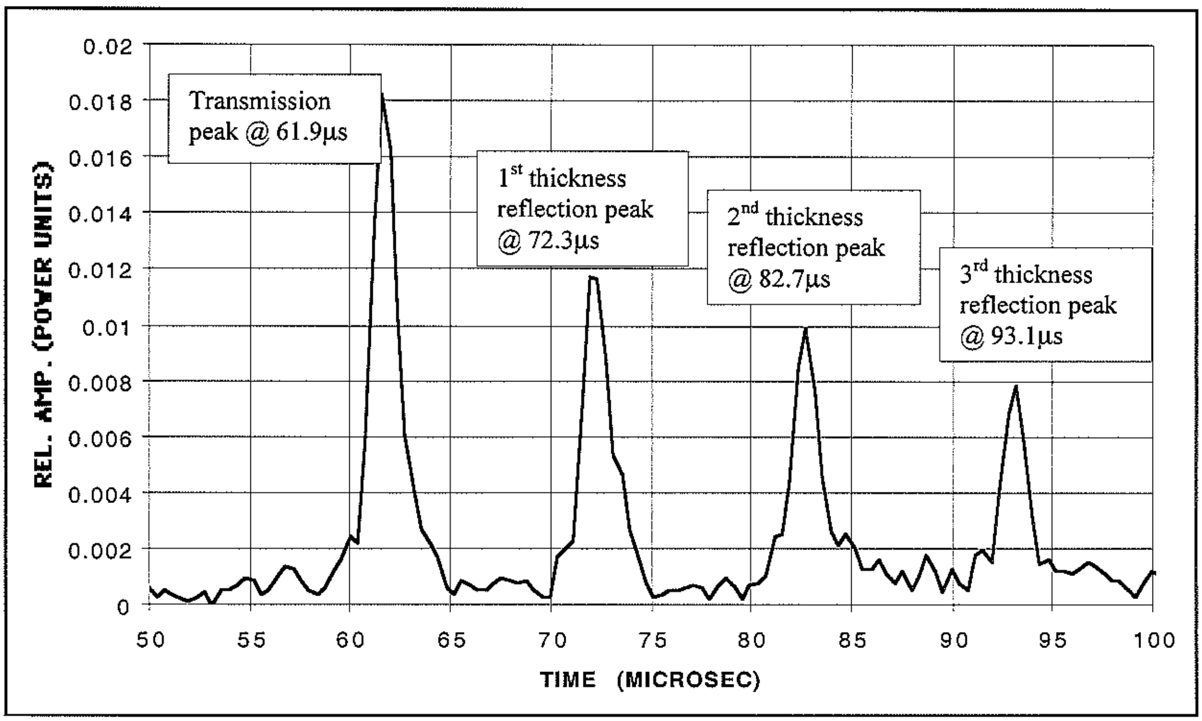

Fig. 23. Material velocity determination by direct transmission NCU propagation in a test material (in this case, 13.5mm thick isotropic graphite) characterized by multiple thickness reflections. Note that the ToF (round trip ToF through the material) between any two successive peaks is 10.4µs, thus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

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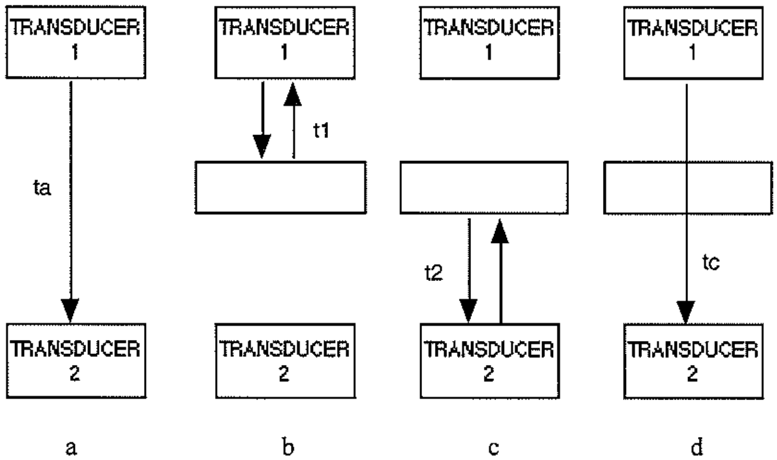

Fig. 24. Propagation of ultrasound with respect to test material in non-contact transmission mode. The NCA 1000 measures and calculates all times of flight shown in this figure, then displays them on the monitor screen, Fig. 25. See text for details.

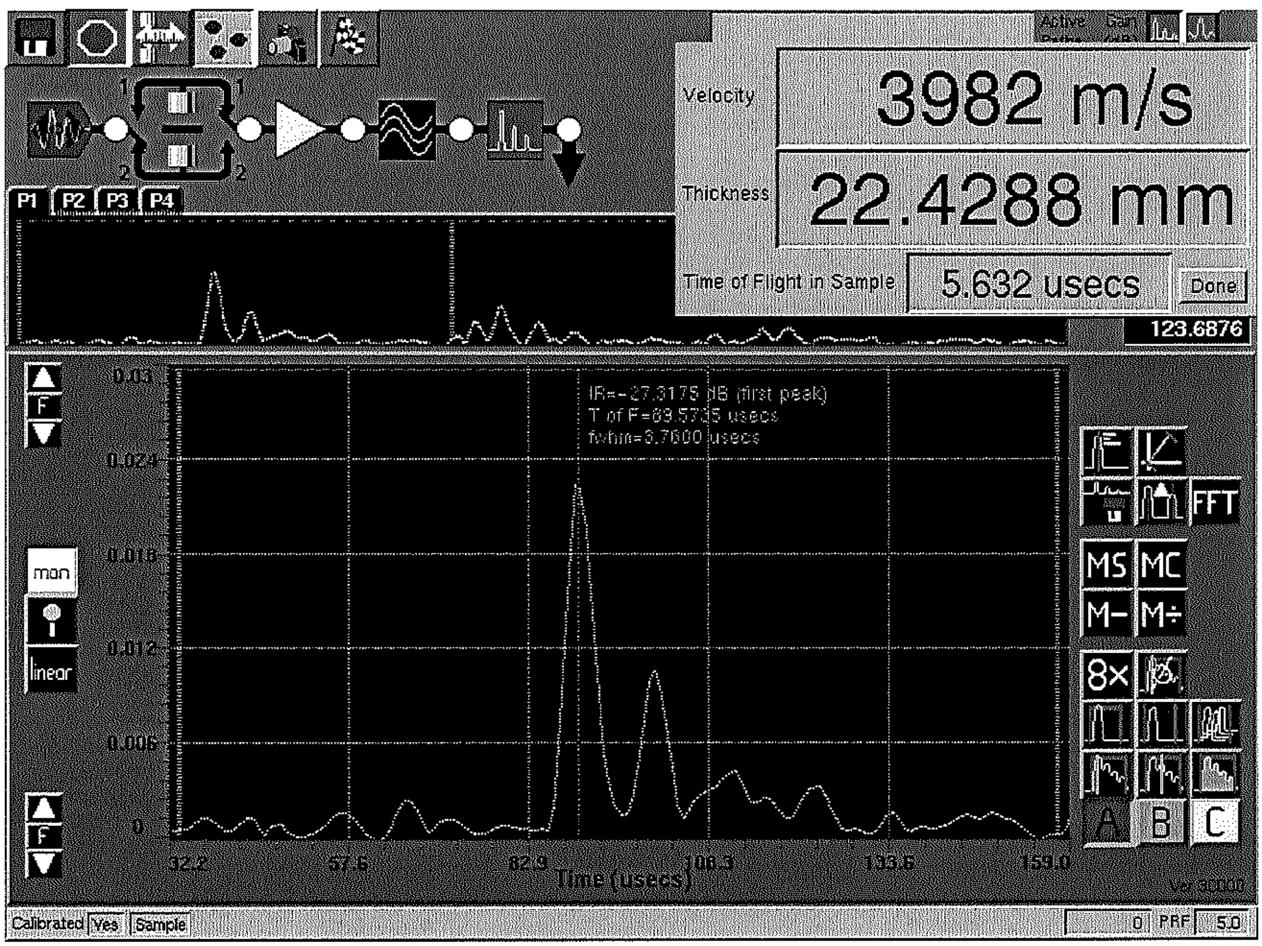

Fig. 25. The NCA 1000 screen displaying velocity and thickness of a material. The test material in this case is a 22.5mm porous sintered ceramic.

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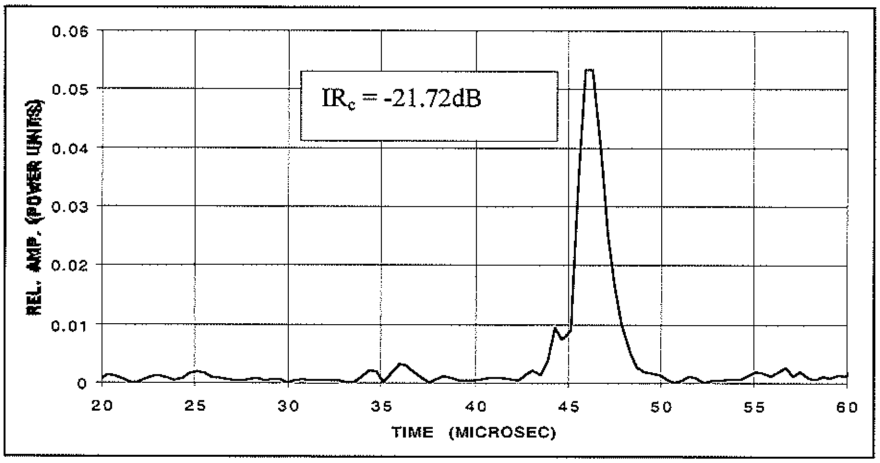

Fig. 26. Non-contact transmission through a 20mm thick flat and polished polystyrene showing the Integrated Response, IR_c of the transmitted peak.

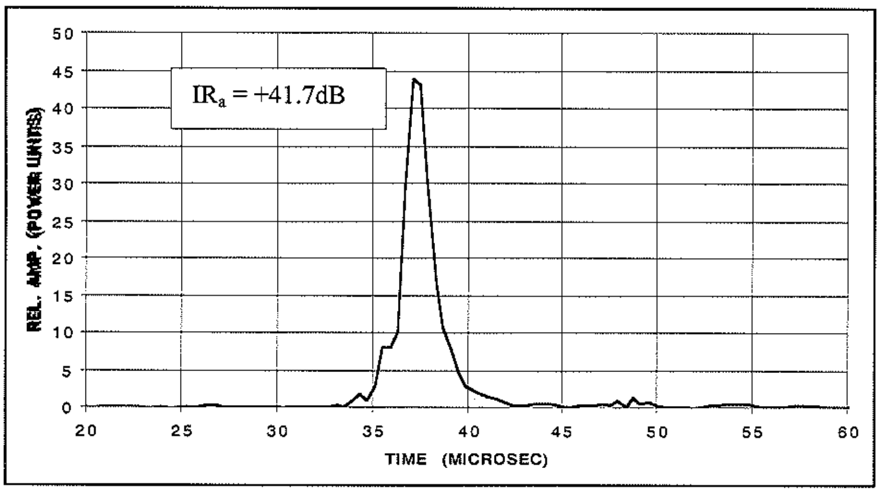

Fig. 27. Non-contact transmission through air column showing the Integrated Response, IR_a of the transmitted peak. Note that while making this measurement, the distance between the transmitting and receiving transducers was compensated for the 20mm thickness of the specimen in Fig. 26.

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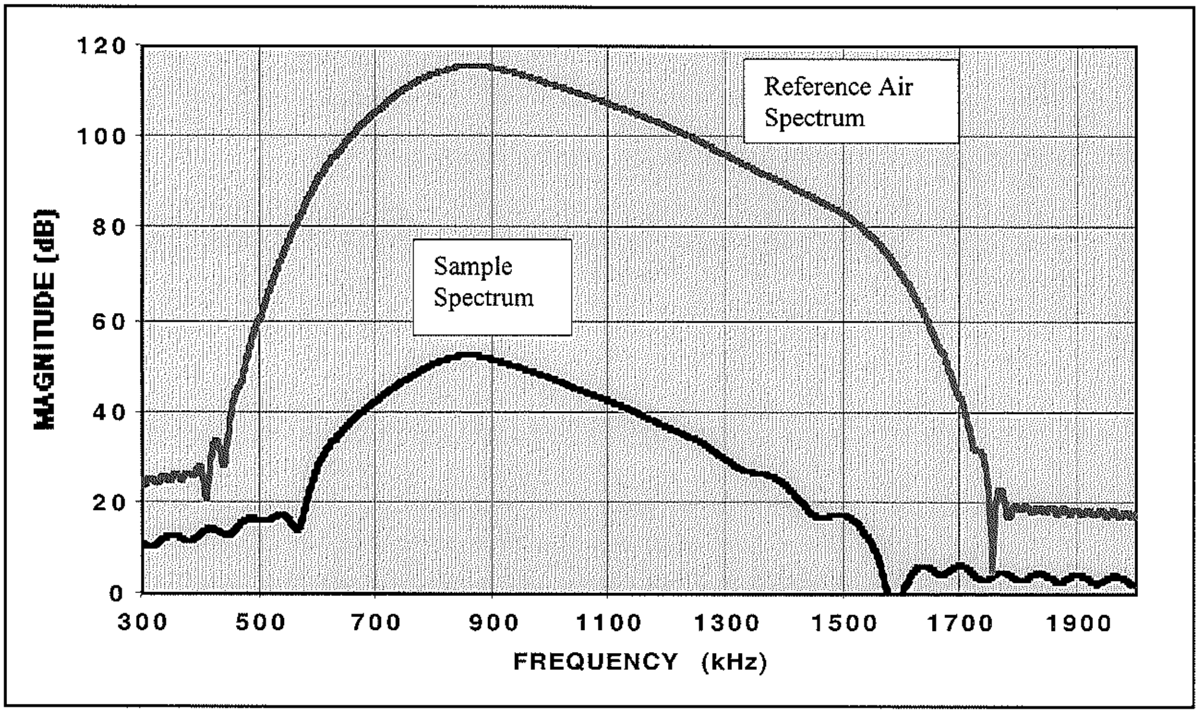

Fig. 28. Procedure for non-contact ultrasonic spectroscopy. Top: FFT magnitude spectrum of ultrasound transmission through air as a reference. Bottom: FFT magnitude spectrum of ultrasound transmission with the test material (in this case composite rubber) between the transmitting and receiving transducers in air.

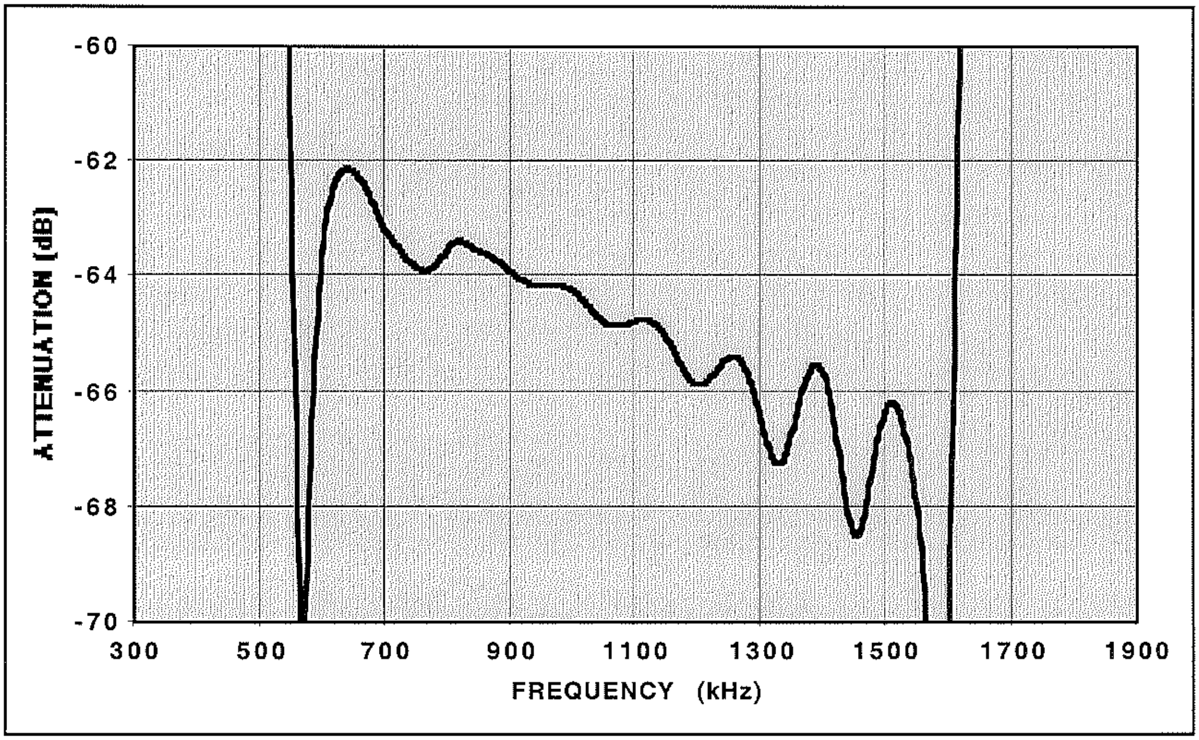

Fig. 29. Frequency dependence of ultrasonic attenuation by subtracting the sample spectrum from that of air reference, Fig. 28.

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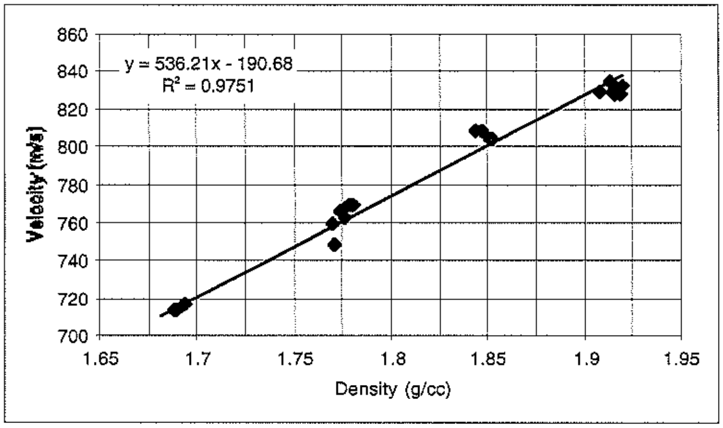

Fig. 30. Relationship between density and non-contact ultrasonic velocity of low density green alumina. Transducer: 1MHz 12.5mm active area diameter.

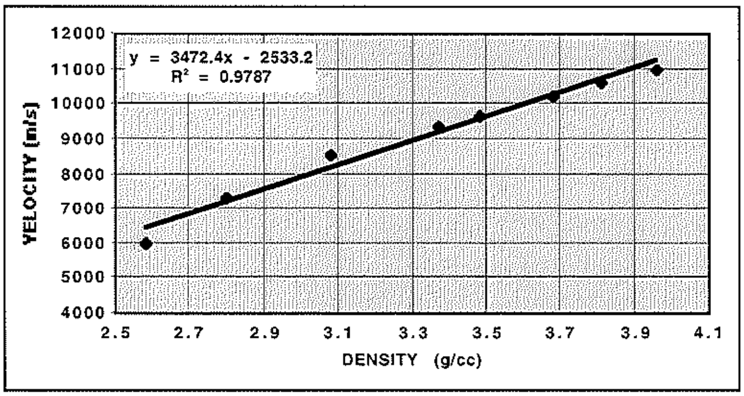

Fig. 31. Relationship between density and non-contact velocity of sintered alumina. Transducers: 1MHz for samples below 3.5g/cc and 2MHz for samples higher than 3.5g/cc.

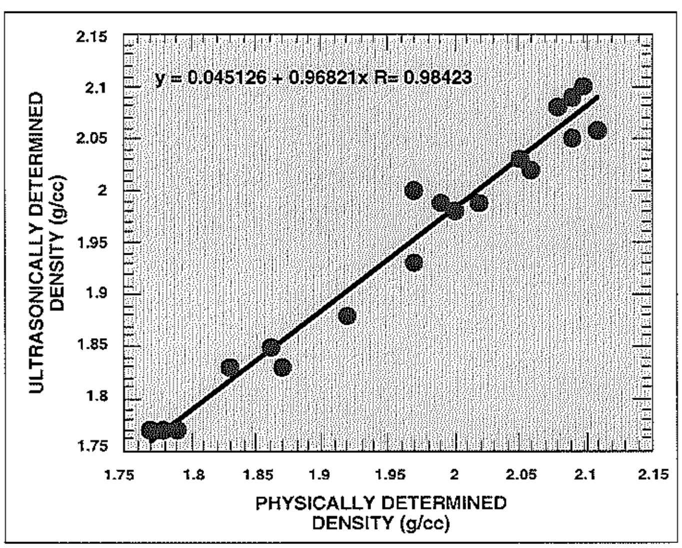

Fig. 32. Comparison of ultrasonically and physically determined density of green alumina.

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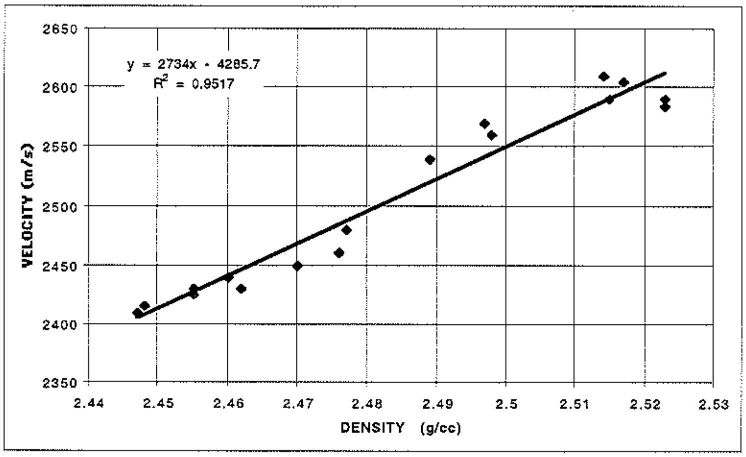

Fig. 33. Relationship between velocity and density for isostatically pressed high density green alumina. Transducers: 1MHz 12.5mm active area diameter.

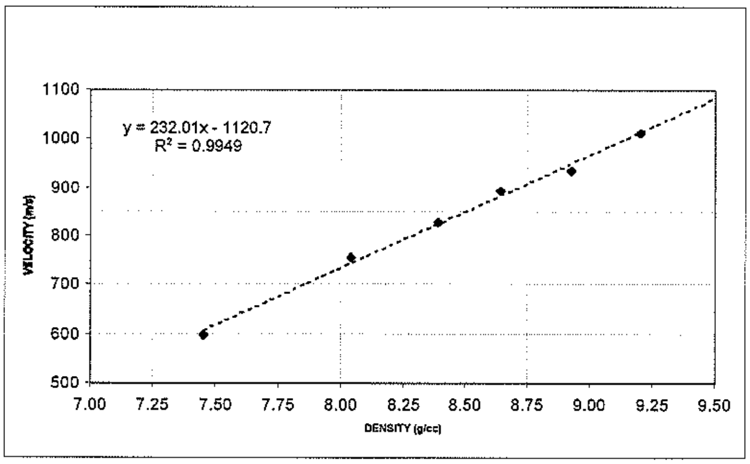

Fig. 34. Relationship between velocity and density for pressed green tungsten carbide. Transducers: 500kHz 12.5mm active area diameter.

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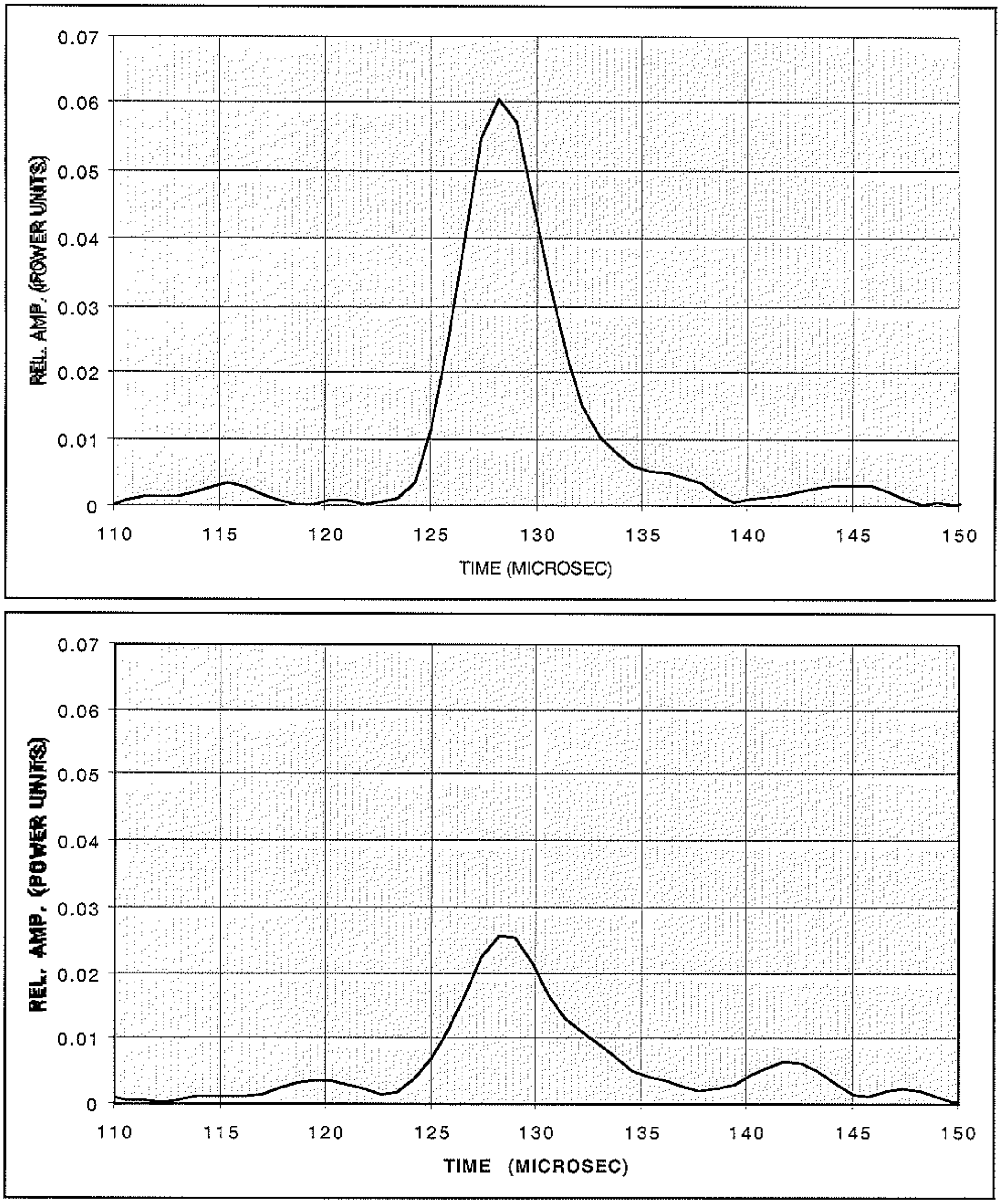

Fig. 35. Defect detection in a sample of 14mm thick green porcelain. Top: Ultrasound transmission through a defect-free region. Bottom: Ultrasound transmission through a region with 1.5mm diameter side-drilled cylindrical hole. Compare the amplitudes of the transmitted ultrasound intensity of the two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

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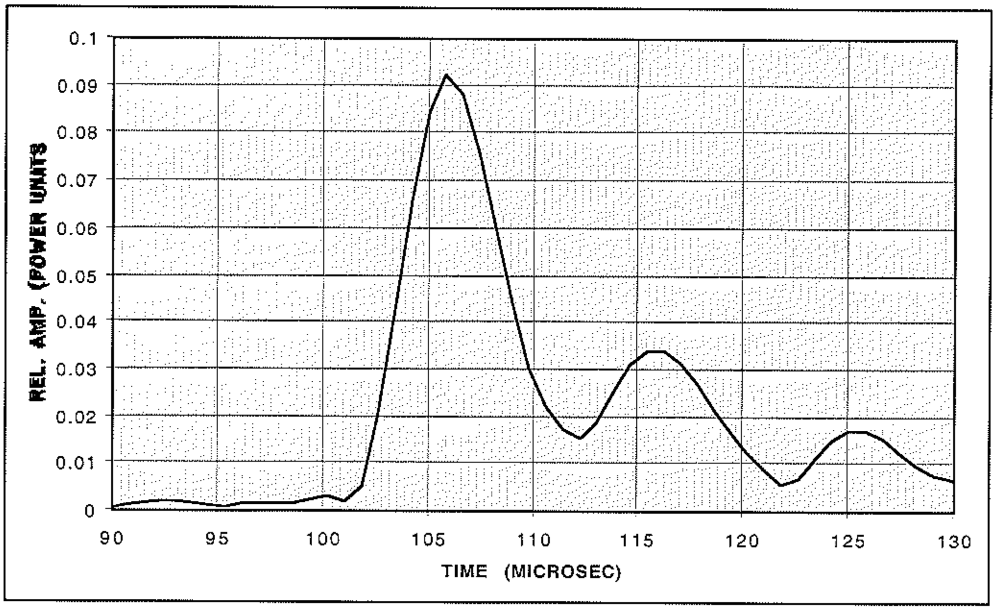

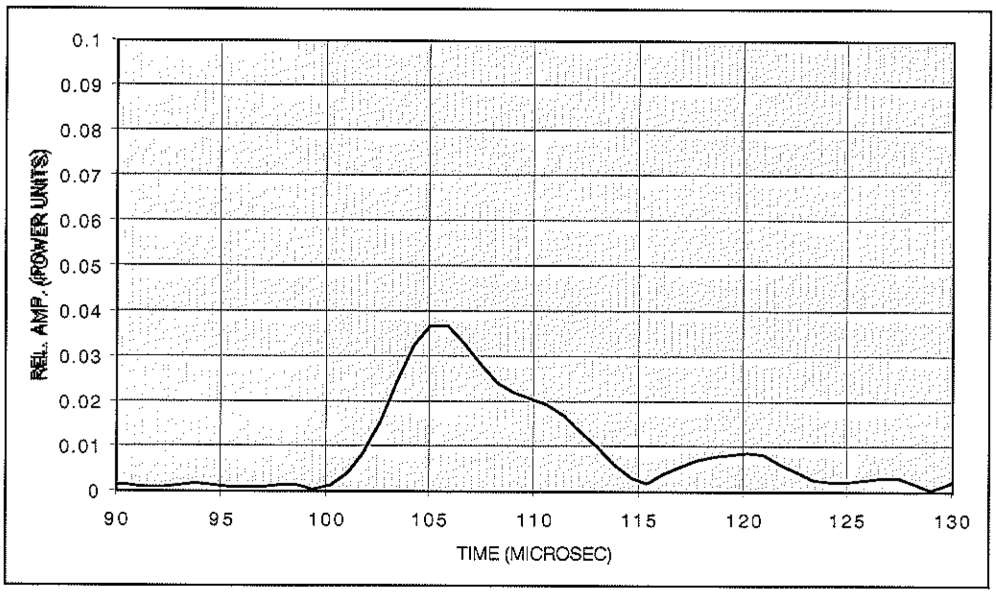

Fig. 36. Defect detection in a sample of 20mm thick, 20% porous, low thermal expansion sintered ceramic. Top: Ultrasound transmission through a defect-free region. Bottom: Ultrasound transmission through a region with 1.5mm diameter side-drilled cylindrical hole. Compare the amplitudes of the transmitted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

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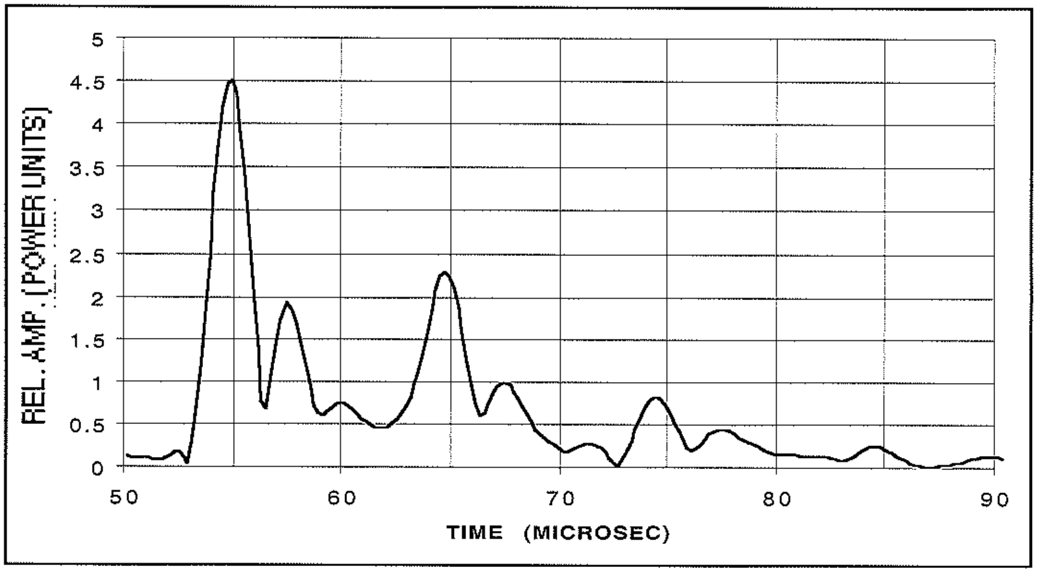

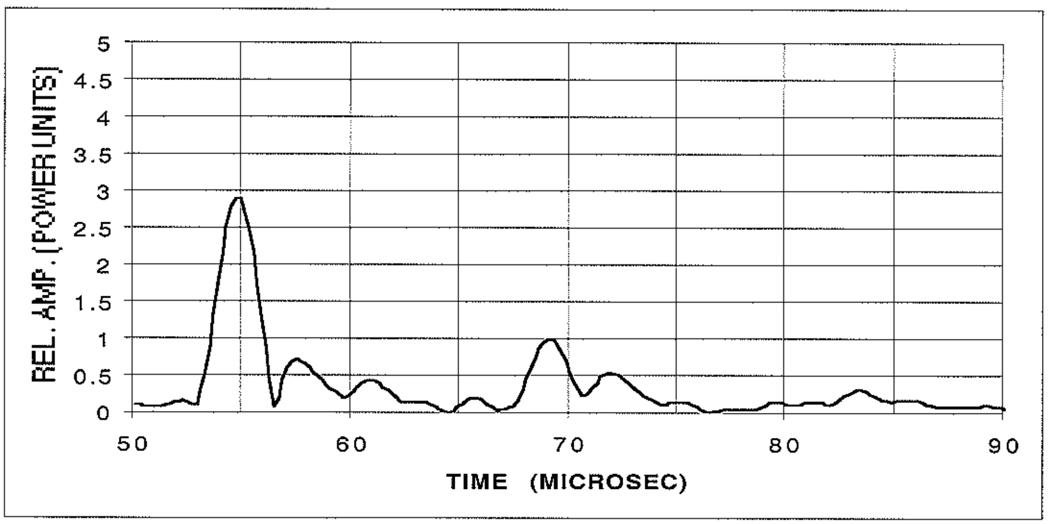

Fig. 37. Detection of defects in an 8mm thick sheet of aluminum by non-contact transmission mode. Top: Defect-free region. Bottom: Region with 1.5mm cylindrical hole. Transducers: 2MHz and 12.5mm active area diameter.

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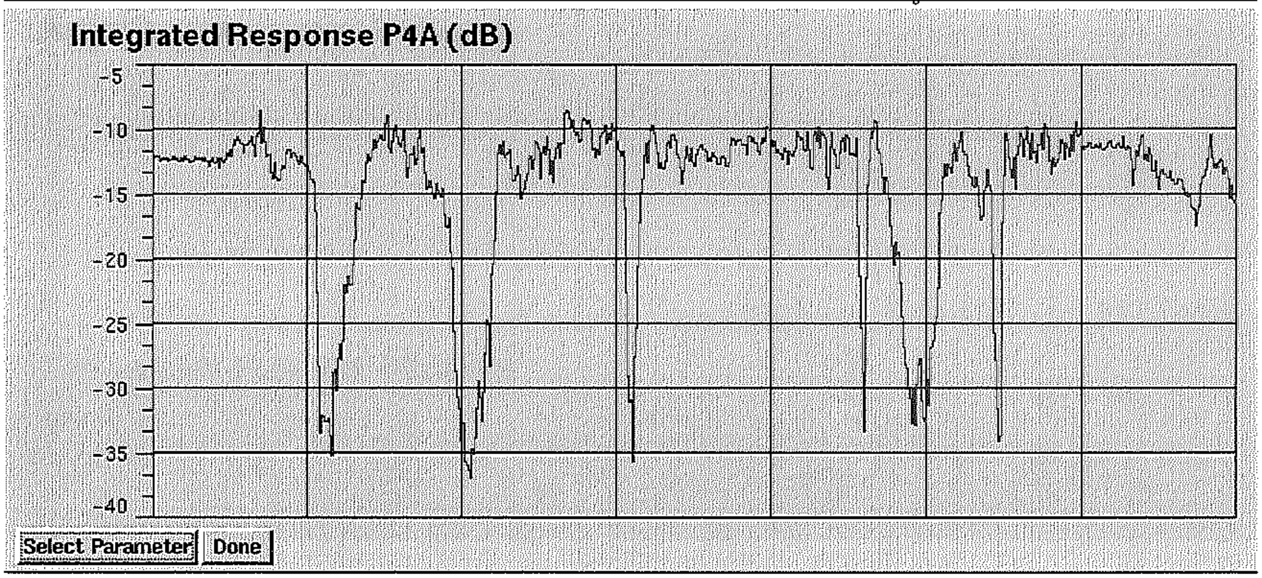

Fig. 38. NCA 1000 trend plot showing the direct transmission through a GFRP composite bonded honeycomb structure at various points. Regions showing the sharp drop in transmission are indicative of defects, such as delaminations. Transducers: 500kHz and 12.5mm active area diameter, separated by ~40mm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

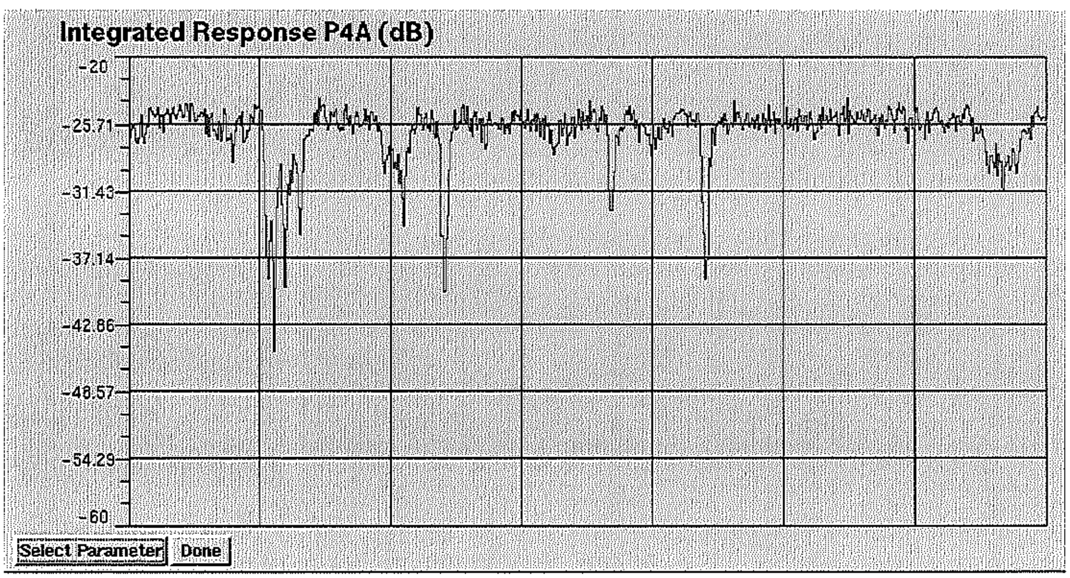

Fig. 39. NCA 1000 trend plot showing the T-R reflection from same side in a GFRP composite bonded honeycomb structure at various points. Regions showing the sharp drop in reflected ultrasound from composite to honeycomb bond are indicative of defects, such as delaminations. Transducers 500kHz and 12.5mm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

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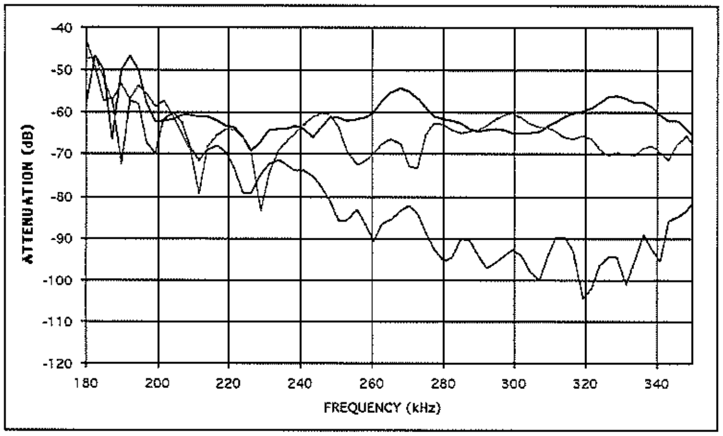

Fig. 40. Non-Contact transmission ultrasonic spectroscopy of extremely porous ceramics (space shuttle tiles) for microstructure characterization. Top: 0.38g/cc. Middle: 0.28g/cc. Bottom: 0.1g/cc. Transducers: 250kHz 25mm active area diameter.

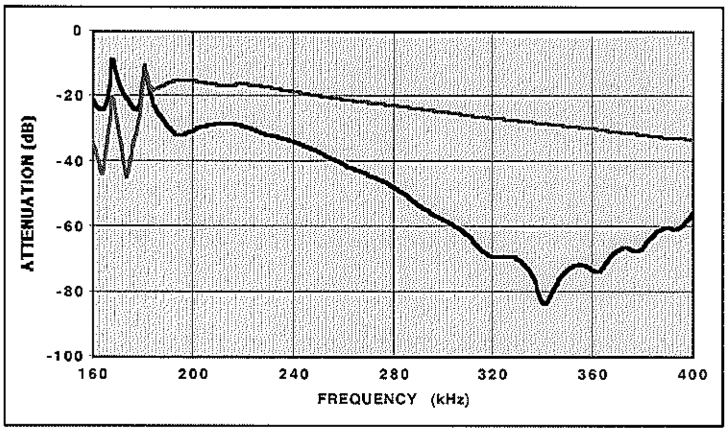

Fig. 41. Non-Contact transmission ultrasonic spectroscopy of packaging foam. Top: small cell. Bottom: large cell. Transducer: 250kHz and 25mm active area diameter.

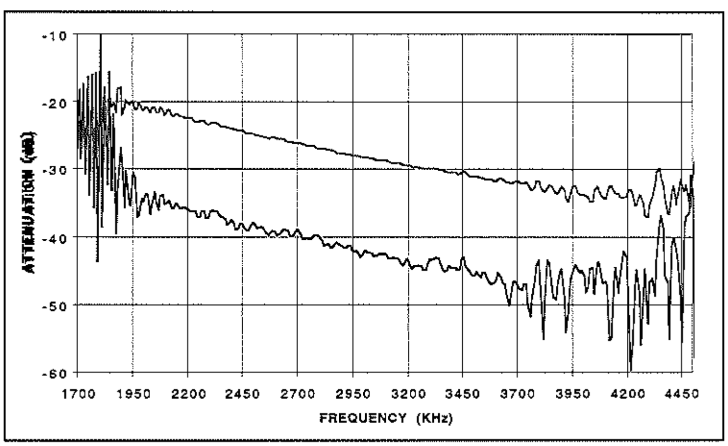

Fig. 42. Very high frequency non-contact transmission ultrasonic spectroscopy of two different paper towels. Top: 0.2mm thick, relatively hard shallow dimpled texture. Bottom: 0.4mm thick, relatively soft and deeply dimpled texture.

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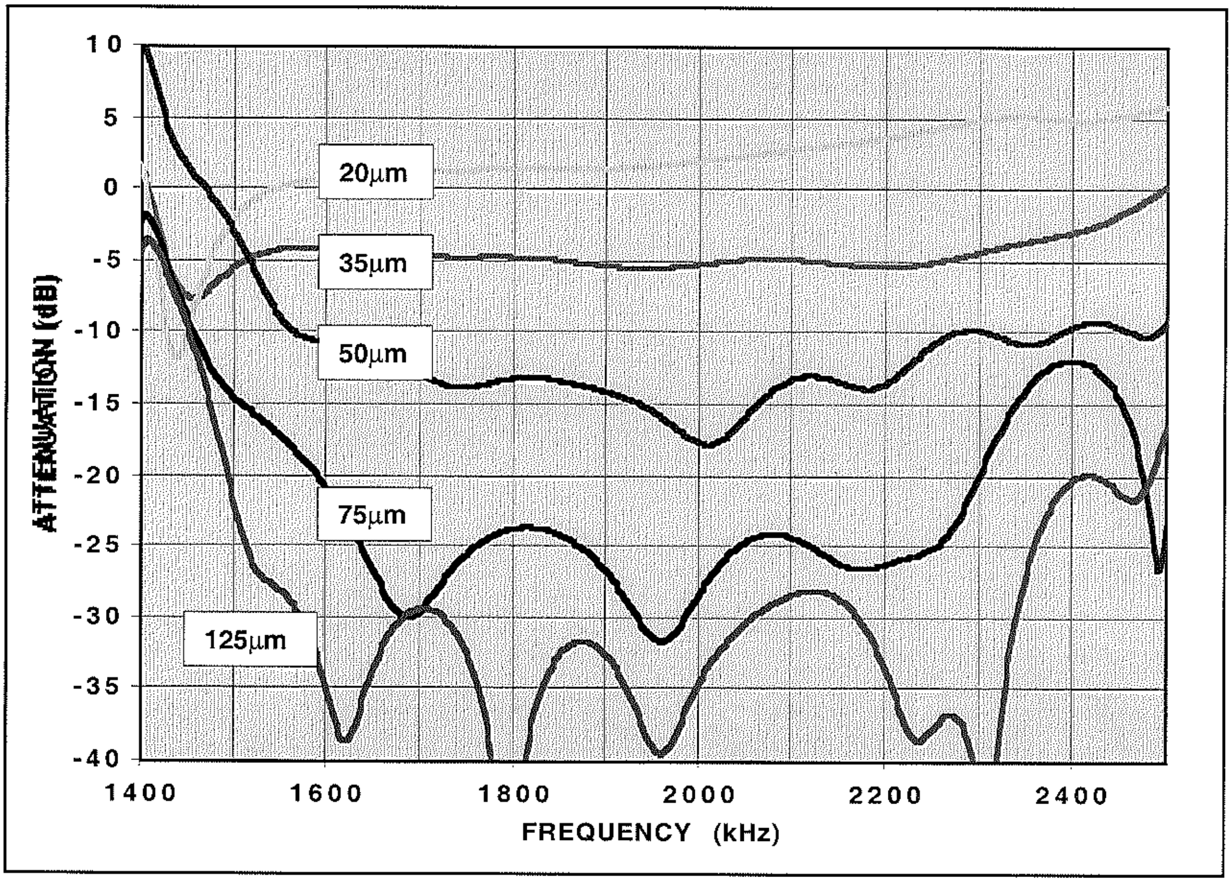

Fig. 43. Non-Contact reflection ultrasonic spectroscopy for surface characterization of materials. Note that as the surfaces become rough, the attenuation of ultrasound increases. Transducer: 2MHz and 12.5mm active area diameter.

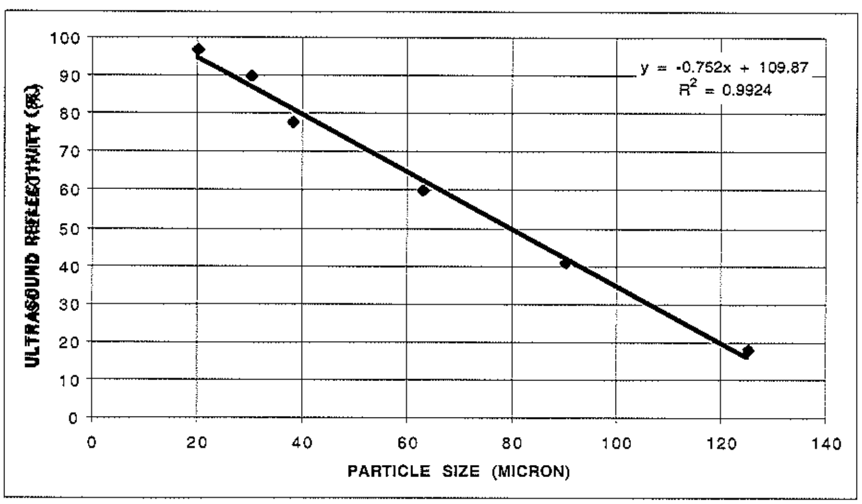

Fig. 44. Non-Contact reflectivity measurement for surface characterization of materials. Compare the reduction in reflectivity and high ultrasound attenuation (Fig. 36) as functions of increasing particle size. Transducer: 2MHz and 12.5mm active area diameter.

*Pre-print of a chapter, Encyclopedia of Smart Materials, editor A. Biderman, John Wiley & Sons, New York (expected in 2001).

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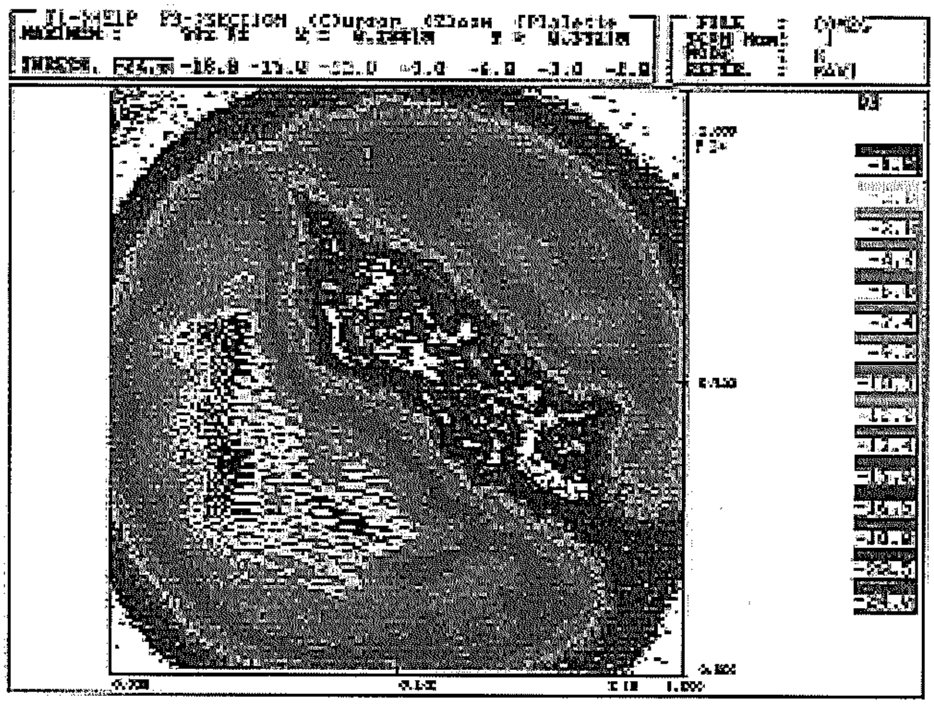

Fig. 45. Partial contact ultrasonic image of an impact damaged 8-ply graphite fiber reinforced plastic composite 1.5mm thick. Area scanned: 25 x 25mm. This image was generated by using a 2MHz and 25mm active area diameter transmitter in contact with the material surface, while a 2MHz, 3mm diameter receiver was raster scanned in non-contact mode over the other surface of the material. A conventional pulser with 400V into 4Ω input impedance square wave and 64dB receiver gain was used.

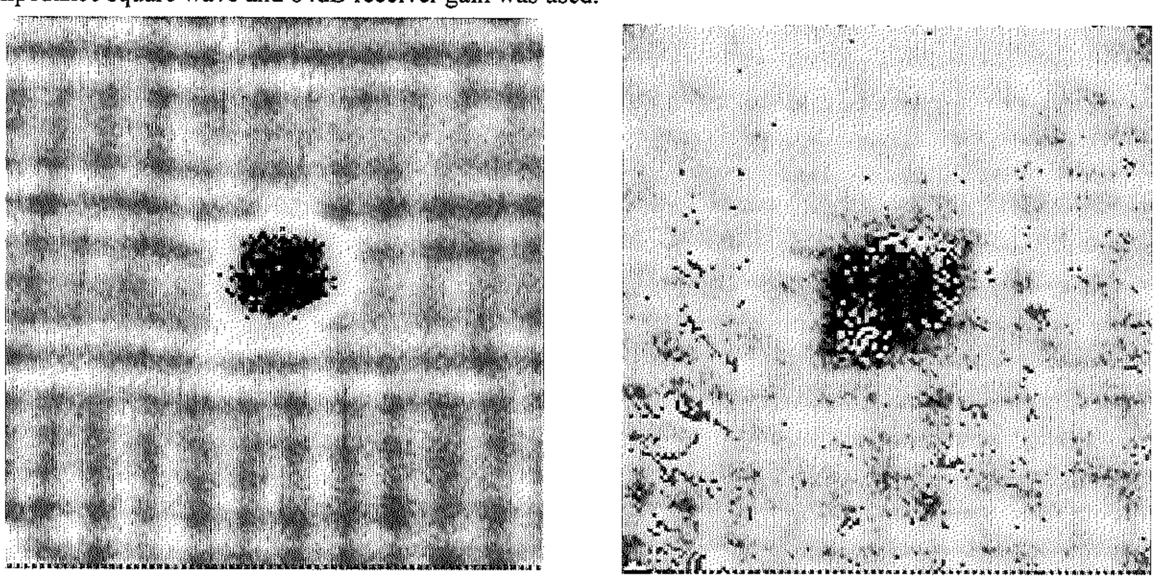

Fig. 46. Non-contact ultrasonic imaging of a mild, impact-damaged 6.4mm thick multi-layered glass fiber reinforced plastic composite by using NCA 1000 and 1MHz, 12.5mm active area diameter transducers with 1mm aperture. Left: Direct transmission image. Right: First thickness reflection image.

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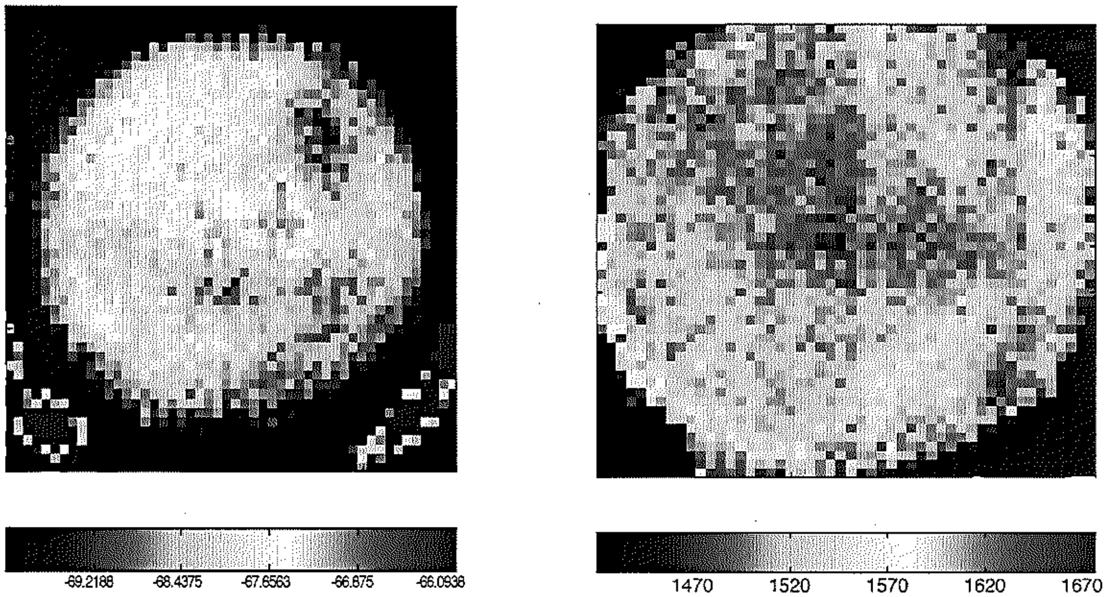

Fig. 47. Non-contact imaging of a green 14mm thick iron compact by using the NCA 1000 and 500kHz, 12.5mm active area diameter transducers with 3mm aperture in direct transmission mode. Left: Relative attenuation of Integrated Response (dB). Right: Velocity (m/s). Area scanned: 50x50mm. Note that the outer high velocity region is also characterized by high attenuation (low IR), and the inner region of low velocity with lower attenuation.

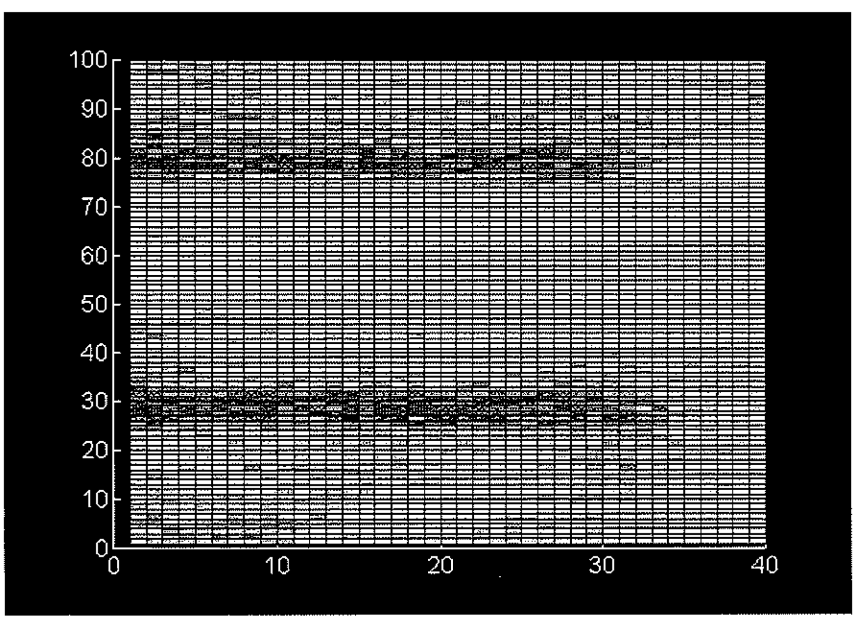

Fig. 48. Non-contact ultrasonic image of a 8mm thick sheet of aluminum in transmission mode showing 1.5mm (top) and 2.0mm (bottom) side-drilled cylindrical holes. Also compare with Fig. 37. Transducers: 2MHz and 12.5mm active area diameter. Image provided by E. Blomme, Katholiieke Hogeschool, Kortrijk,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

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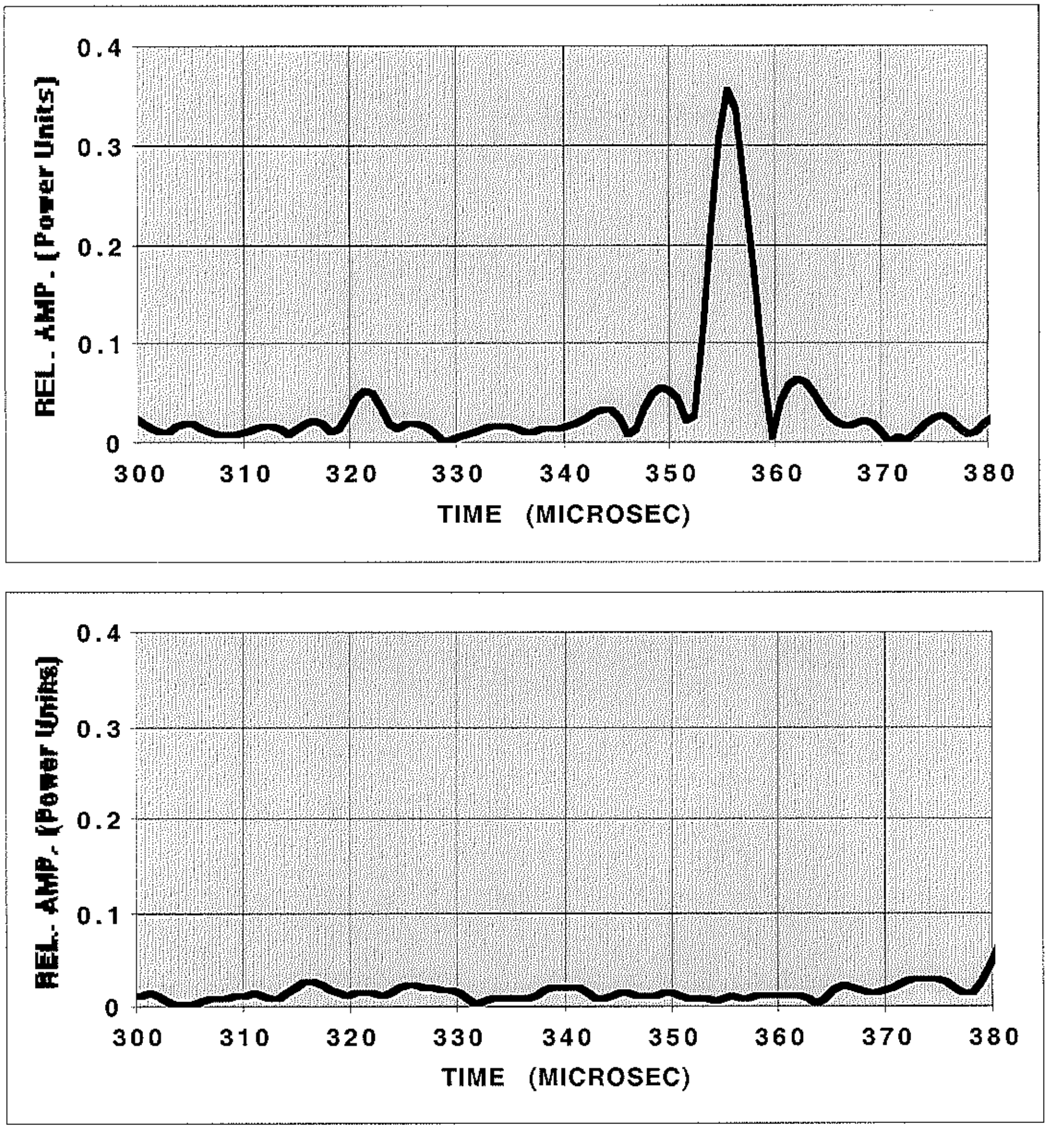

Fig. 49. Detection of absence or presence of almonds in milk chocolate. Top: Region without almonds. Bottom: Region with almonds. Transducer: 1MHz 12.5mm active area diameter.

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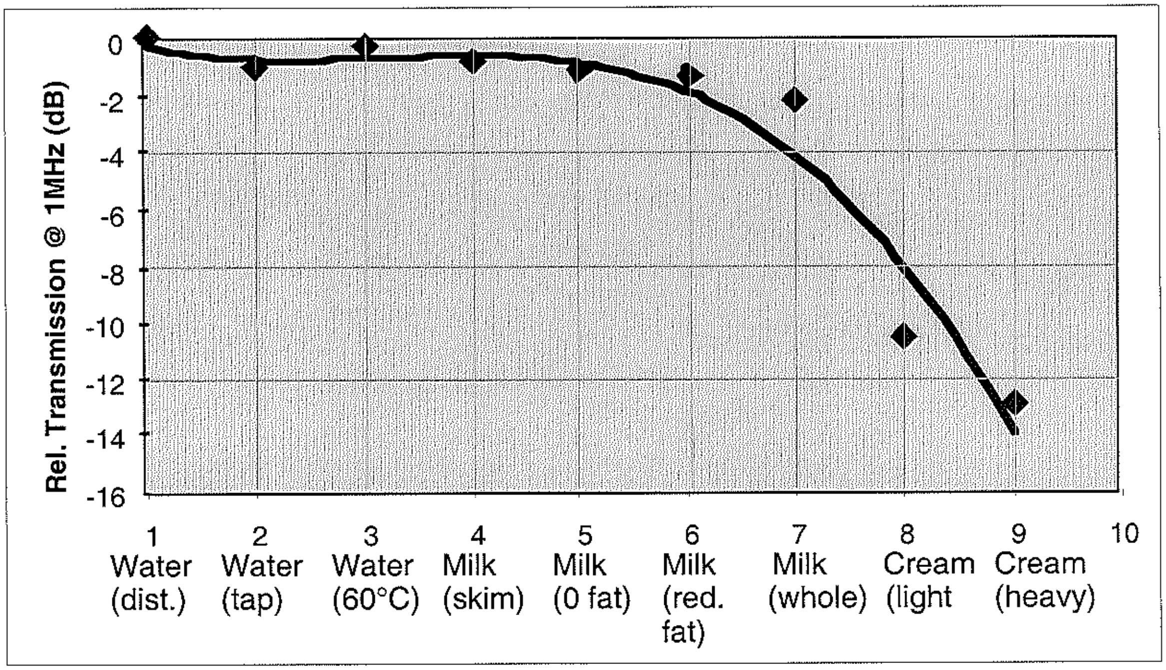

Fig. 50. Estimation of fat content in various types of milk and milk products with distilled water as a reference. Ultrasound measurement here is the relative transmission of 1MHz frequency in samples. Samples in plastic bottles were analyzed in transmission mode with transmitting and receiving transducers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

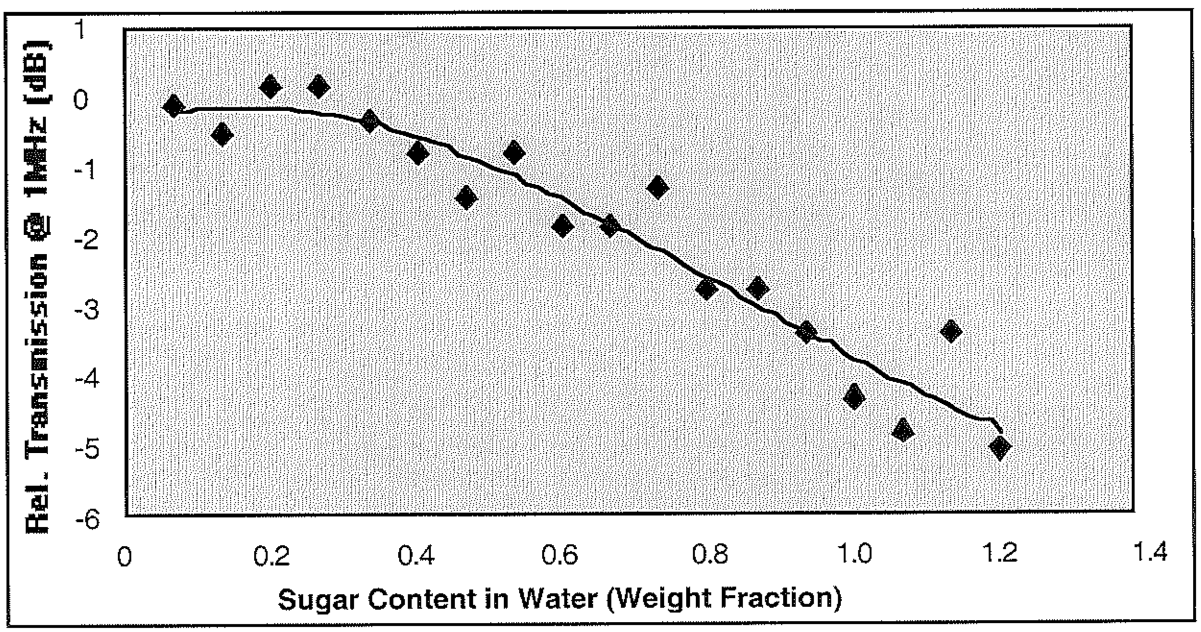

Fig. 51. Estimation of sugar content in water. Ultrasound measurement here is the relative transmission of 1MHz frequency in samples. Samples in plastic bottles were analyzed in transmission mode with transmitting and receiving transducers separated by ~15mm of ambient air from the bottles.

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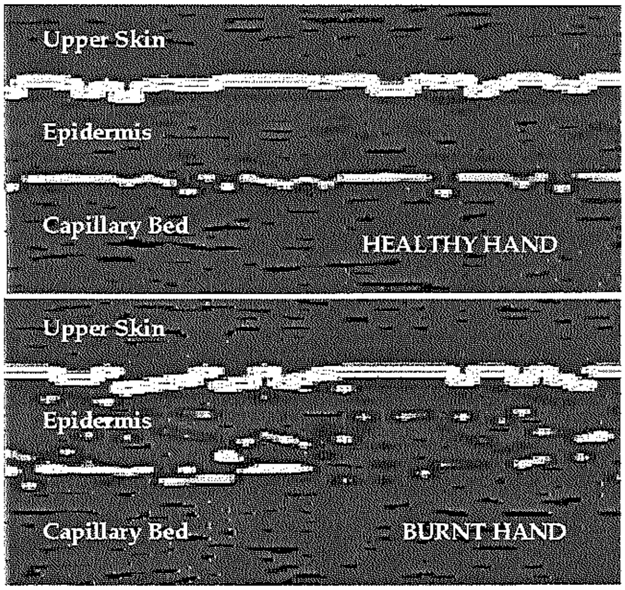

Fig. 52. Non-Contact ultrasound image cross-section of healthy (top) and burnt (bottom) human hands. Note the damaged region between the epidermis and capillary bed in the burnt hand. The transducer used for this analysis is non-contact 2MHz in reflection (pulse-echo) mode. These images were generated by Joie P. Jones, University of California, Irvine, and his Burn Center team.

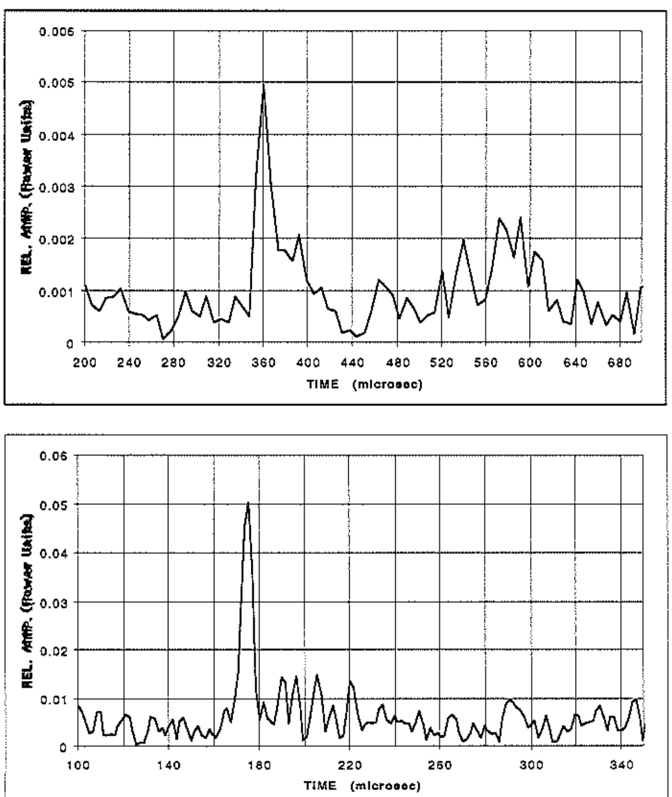

Fig. 53. Non-contact ultrasound transmission through a human heel with 250kHz (top) and 500kHz (bottom) frequency transducers. The first peak corresponds to ultrasound transmission through air, skin, tissue, and heel bone. Other peaks are not identified.

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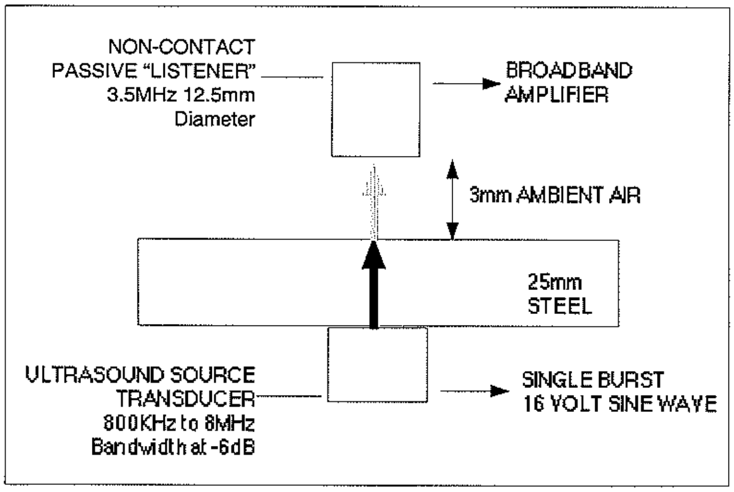

Fig. 54. Experimental setup for passive operation of non-contact transducer.

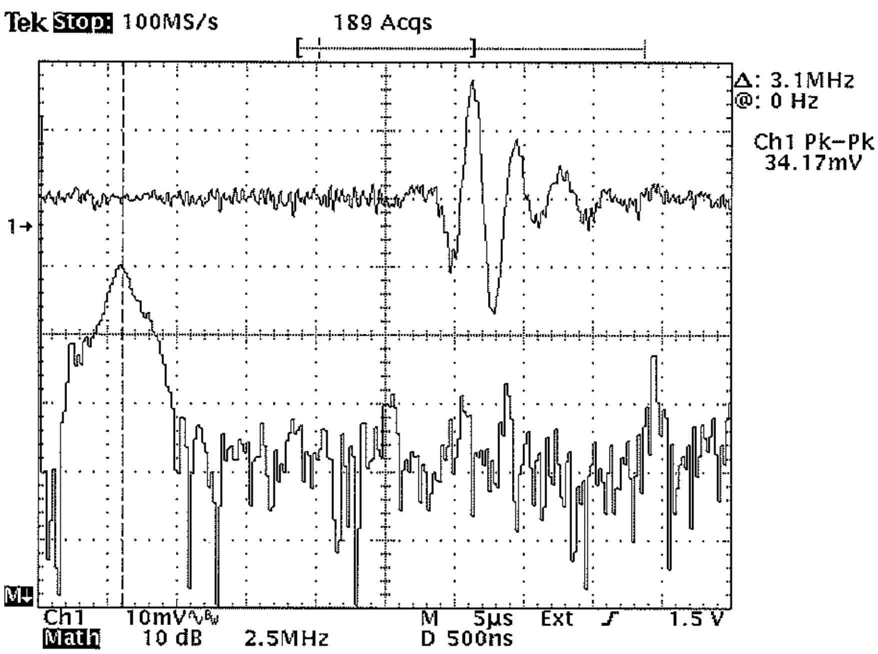

Fig. 55. Time and frequency domains of ultrasound detected by non-contact transducer, per Fig. 54 setup.

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