

CONTACT-FREE ULTRASOUND: THE FINAL FRONTIER IN NON-DESTRUCTIVE MATERIALS CHARACTERIZATION

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ABSTRACT

Adhering to the objectives of non-destructive materials characterization, a contact-less --air-coupled -- method of ultrasound is highly desirable. However, exorbitant acoustic impedance mismatch between the coupling air and the test media presents a natural impediment to NCU. This impedance mis-match can be as high as seven orders of magnitude for some materials. Therefore, high frequency Non-Contact Ultrasound (NCU) propagation in materials has been regarded as an impossibility. On the other hand, low frequency ultrasound -- 25kHz to 100kHz -- can be propagated through materials in non-contact mode. However, these frequencies are practically useless for the interrogation of most materials where the industry demands high resolution and high detectability. Recent advances in high transduction high frequency piezoelectric transducers (200kHz to 5MHz) and an exceptionally high dynamic range nanosecond accuracy ultrasonic system have advanced the NCU practice to levels that rival conventional contact method. In this paper we provide an introduction to NCU and present examples of green and sintered ceramics and composites analysis. Applications of NCU are considered to be truly significant for cost-effective manufacturing of high reliability materials.

INTRODUCTION

It is now well-established that if ultrasound can be propagated in a given medium than significant information about that medium can be deciphered, Table I.^{1,2,3} Given the diversity of composition and microstructure of ceramics, powder metals, and composites, materials suitable acoustics and techniques have been developed during the last 10 years for accurate non-destructive characterization of these materials.^{4,5,6,7,8} Ultrasound method is nondestructive in nature, but the mechanism of ultrasound propagation in the test materials involves the use of liquids such as, water, oil, gels, etc. Specifically, these liquids are used between the transducer and the test material for efficient ultrasound propagation. From a practical standpoint, liquid contact with some materials is either not desirable, or would destroy green, porous, liquid-sensitive, and continuously formed materials. In order to circumvent this problem, it is imperative to eliminate transducer, or any other type of contact with the test materials.

Achievement of NCU first requires the generation of very high transduction transducers to overcome the exorbitant acoustic impedance barrier between air and most materials.

Table I. 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, interface analysis, etc.
Frequency Domain	Frequency-dependence of ultrasound attenuation, or ultrasonic spectroscopy.	Microstructure, grain size, grain boundary relationships, porosity, surface characterization, phase analysis, etc.
Image Domain	Time-of-flight, velocity, and attenuation mapping as functions of discrete point analysis by raster C-scanning or by synthetic aperture techniques.	Surface and internal imaging of defects, microstructure, density, velocity, mechanical properties, true 2-D and 3-D imaging.

After 20 years of intense R&D, piezoelectric transducers between <100kHz to ~5MHz have been successfully produced (international patents pending). Figures 1 and 2 show time, frequency, sensitivity, and signal to noise ratio data for 200kHz and 3MHz non-contact transducers in ambient air. The most significant aspect of this development is the very high sensitivity of our new transducers. For example, a comparison of these transducers in air and conventional contact transducers in water (with all other conditions remaining the same), shows that the sensitivity of the former is only 30dB below the latter from 100kHz to 3MHz. This is not only significant from the standpoint of transduction in air, but also for the applications of these transducers for NCU propagation in solids. By utilizing conventional ultrasonic pulsers these and capacitance air-coupled transducers showed the feasibility for several industrial and bio-medical applications.^{9,10,11}

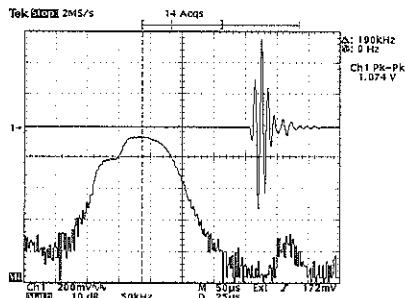


Fig. 1. 200kHz non-contact transducers separated by 100mm ambient air. Bandwidth: 100kHz (50%) Sensitivity: -46dB. SNR: 46dB

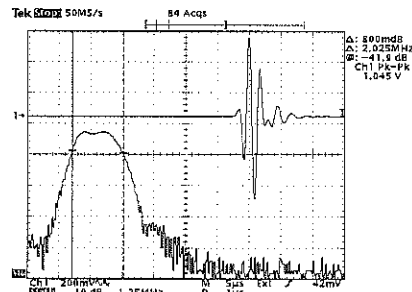


Fig. 2. 3.0MHz non-contact transducers separated by 10mm ambient air. Bandwidth: 2.0MHz (75%) Sensitivity: -64dB. SNR: 30dB.

However, in order to obtain non-contact ultrasound performance analogous to conventional liquid-coupled ultrasound more than high transduction transducers are needed. For example, if we have an ultrasonic excitation and amplification system that would provide 100dB extra gain (30dB to compensate for contact-non-contact mismatch and 70dB to overcome air-material acoustic impedance mismatch), only then we can have a non-contact ultrasound performance similar to that of the conventional contact mode.

In 1997 the non-contact transducer development was complemented by the creation of a dedicated ultrasonic non-contact analyzer, the NCA 1000 (U.S. patent pending), Fig. 3. This system is based upon the synthesis of a computer generated chirp with transducer characteristics and advanced signal processing. Ultimately, the NCA 1000 provides >150dB dynamic range, a nano-second accuracy, and high speeds for data acquisition. As will be seen in the subsequent sections, these features are significant for the execution of NCU analogous to the conventional contact or immersion mode of testing.

OPERATION OF NON-CONTACT ANALYZER

After routine calibration for air velocity and times of flight in air column and from material surfaces, the NCA 1000 determines the test material thickness and velocity simultaneously, Fig. 4. For non-dispersive and low acoustic impedance materials, this system also determines their densities by measuring the true attenuation in materials. In order to evaluate the surface and internal microstructure of materials, the NCA 1000 provides a mechanism for ultrasonic spectroscopy, Fig. 5. Test materials can also be imaged in non-contact mode by integrating this system with appropriate transducer scanning system. Parameters measured and functions performed by NCA 1000 are shown in Table II, relative to their significance in materials characterization.

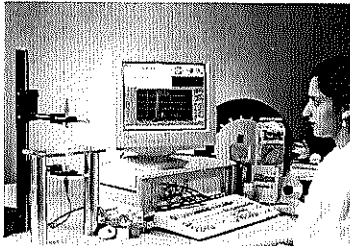


Fig. 3. Non-Contact Analyzer NCA 1000 shown with transducers and test material (left)

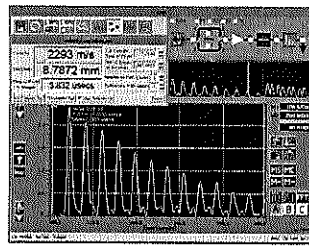


Fig. 4. NCA 1000 screen displaying the velocity and thickness of a test material.

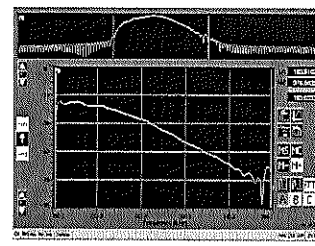


Fig. 5. NCA 1000 screen ultrasonic spectroscopy mode.

ULTRASOUND PROPAGATION IN NON-CONTACT MODE

In most cases it is desirable to operate the NCA 1000 in direct transmission mode, Fig. 6 and 7. In this mode a material can be characterized for thickness, velocity, density, defects, and microstructure. When the material surface needs to be evaluated, this system can be operated in direct reflection mode, Fig. 9 and 10. In this case reflectivity of ultrasound is directly related to the surface roughness or its microstructure. When a test material is accessible only from one side, the NCA 1000 can also be operated in T-R (Transmitter-Receiver) reflection mode, Fig. 11 and 12. It should be stated that operation in this mode is arduous since the optimization of reflected signal from the test material thickness is a sensitive function of the incident angles of two transducers, which (angles) tend to be very small in magnitude.

Table II. Measurements by NCA 1000 and their Relevance to Materials Characterization

MEASURED PARAMETERS/FUNCTIONS	RELATIONSHIP WITH MATERIAL CHARACTERISTICS
Times of flight: Displayed on the screen.	Determination of thickness and velocity simultaneously and automatically.
Integrated response: Area underneath a selected transmission or reflected peak: Displayed on the screen.	Estimation of microstructure and density, surface texture and profiling, and detection of defects, delaminations, etc.
Time of flight in conjunction with integrated response: Displayed on the screen.	Determination of thickness, velocity, density, and attenuation simultaneously and automatically.
Frequency dependence of ultrasonic attenuation: Performed by simple spectroscopy routine.	Determination of microstructure and subtle variations.
Phase detection: Performed by simple steps.	Detection of subtle compositional and structural variations.

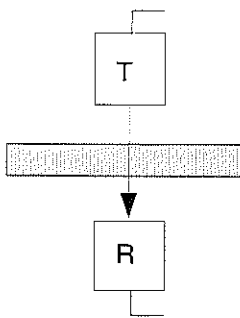


Fig. 6. Direct transmission mode.

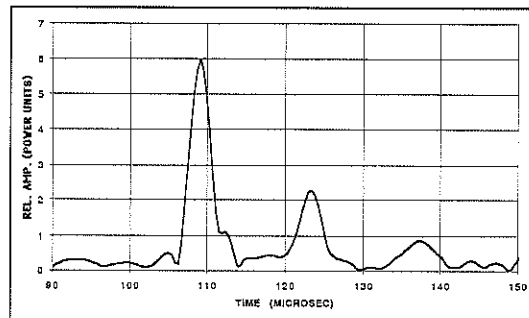


Fig. 7. Signal through 18mm green SiC @ 1MHz, per Fig. 6. 1st peak: Direct transmission in material. 2nd & 3rd peaks: Thickness reflections.

APPLICATIONS OF NON-CONTACT ULTRASOUND

Non-contact transducers and the analyzer NCA 1000 have been fully developed and applied to a number of industrial and bio-medical applications for the evaluation of thickness, velocity, density, defects, delaminations, and microstructure.^{12,13,14}

In this section we provide several examples of the feasibility of NCU method for ceramics and composite characterization.

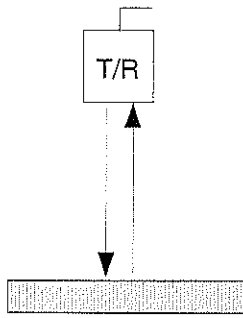


Fig. 8. Direct reflection mode.

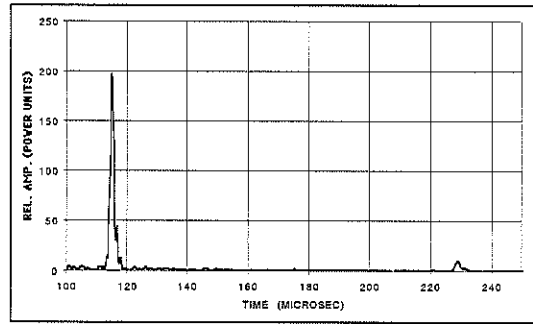


Fig. 9. Signal from 35µm SiC surface @ 2MHz, Per Fig. 8. Transducer to material distance in Ambient air: 10mm.

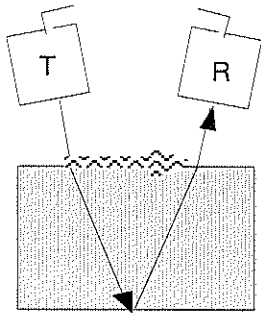


Fig. 10. Transmitter-Receiver in reflection mode.

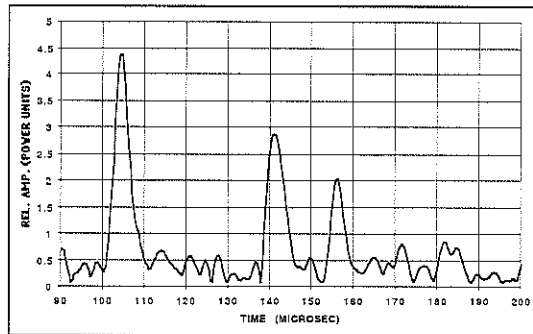


Fig. 11. Signal through 32mm polystyrene @ 1MHz, per Fig. 10. 1st peak: Reflection from material thickness. Other peaks: surface waves.

Velocity-Density Characterization in Green and Sintered Ceramics

Several samples of green and sintered Al_2O_3 of known density were characterized for ultrasonic velocity in order to establish reference relationship, for comparison with unknown density samples. Figures 12 and 13 respectively, show these relationships for green and sintered Al_2O_3 . These observations were generated in direct transmission mode (Fig. 6) by utilizing 1MHz 12.5mm active area diameter non-contact transducers. Transducer to material surface distance in ambient air is 20mm each for the transmitter and the receiver. For very high velocity sintered Al_2O_3 2MHz transducers were used. Fig. 14 shows the comparison of physically and ultrasonically determined densities of green Al_2O_3 . This method of materials characterization has been successfully applied to green ceramics from <1mm to >200mm; porous materials from <3mm to >200mm; and dense materials from <5mm to >50mm.

Based upon the repeatability of data at a given point of observation the accuracy of velocity, and thus the density, for green ceramics is better than $\pm 0.5\%$, for porous materials, it is $\sim \pm 1\%$; and for dense sintered materials, it is $\sim \pm 5\%$. At first these observations appear to defy the known norms of ultrasound. However, when we consider the fact that in non-contact mode it is much easier for ultrasound to propagate through low acoustic impedance materials (green, porous,

fibrous, polymeric, etc.), then the observations relative to accuracy and repeatability make perfect sense. This conclusion is based upon the fact that the transmission efficiency is higher when

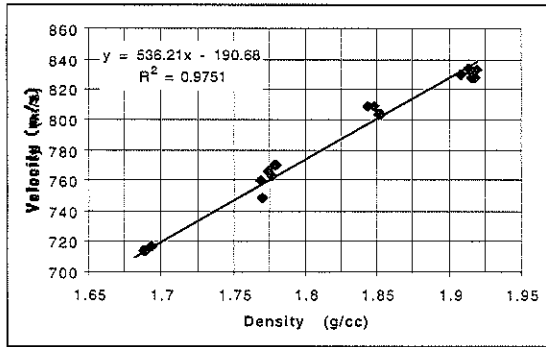


Fig. 12. Velocity-density relationship for green Al₂O₃.

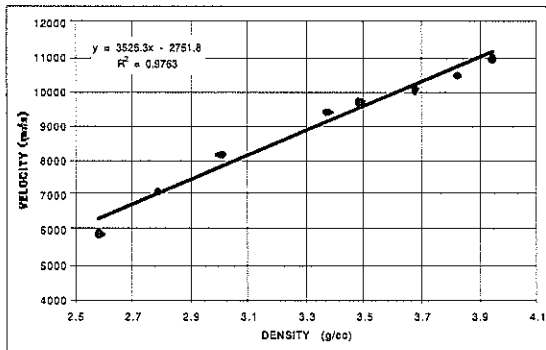


Fig. 13. Velocity-density relationship for sintered Al₂O₃.

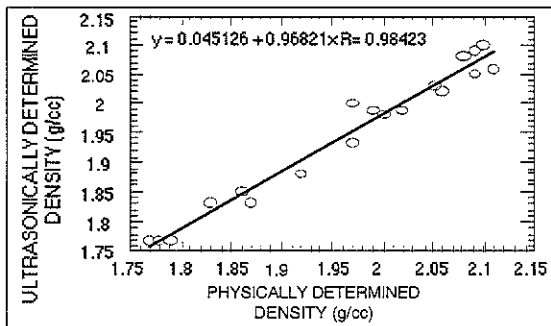


Fig. 14. Comparison of ultrasonically and physically determined densities for green Al₂O₃.

ultrasound travels from the coupling medium air to test materials with relatively low acoustic impedances. Therefore, from the standpoint of the applicability, non-contact ultrasound may not be highly effective for materials that are characterized by 20 MRAYL or higher acoustic impedance and velocities greater than 7000m/s. Such materials are single or multi-phase superdense impervious sintered oxides, carbides, nitrides, borides, and diamonds; and ferrous metals and alloys. However, if it is absolutely necessary to apply non-contact ultrasound for the characterization of these materials, it can be accomplished by modifying the environment of testing and the material. Details of this subject are beyond the scope of this paper.

Here we have shown the mechanism of density measurement by first establishing a reference velocity relationship with known density materials. This is analogous to conventional liquid or dry coupled modes of ultrasound.^{5,6,7,8} However, NCA 1000 has been further advanced to make

absolute density measurements, but their accuracy at the present time is limited to non-dispersive and relatively low acoustic impedance materials.

Estimation of Material Quality when Velocity or Density cannot be Measured

Automatic velocity and density measurements cannot be reliably made for those materials whose thicknesses are within the proximity of the ultrasonic wavelengths and those that are extremely dispersive such as, extremely coarse-grained refractories, abrasive wheels, cellular ceramics, etc. In order to meaningfully analyze such materials it is possible to relate their relative ultrasound attenuation as a function of material density or microstructure. Relative attenuation, measured by subtracting the integrated response (Table II, area underneath a given peak) of transmitted signal through the material from that of the air column, has been found to be directly related to material velocity and density figures 15 and 16. Such cross-relationships can be extremely beneficial in not only estimating the densities of difficult-to-measure materials, but also in the detection of overt defects and micro-cracks. For example, in some pressed ceramics while the velocity-density relationship was found to be linear, but the same was not true when density/velocity was related to relative attenuation. Sudden increase in attenuation for samples pressed at extremely low and high pressures can be indicative of defects such as delaminations.

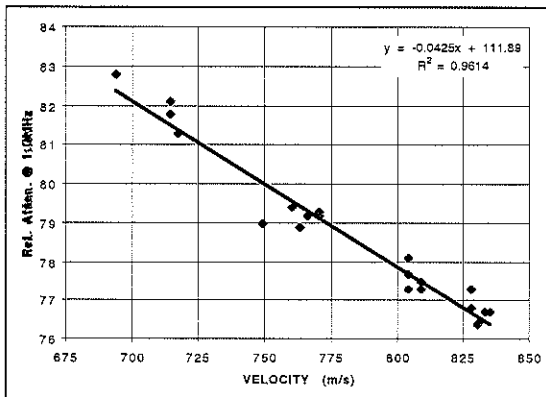


Fig. 15. Relationship between velocity and Relative attenuation for green Al_2O_3 .

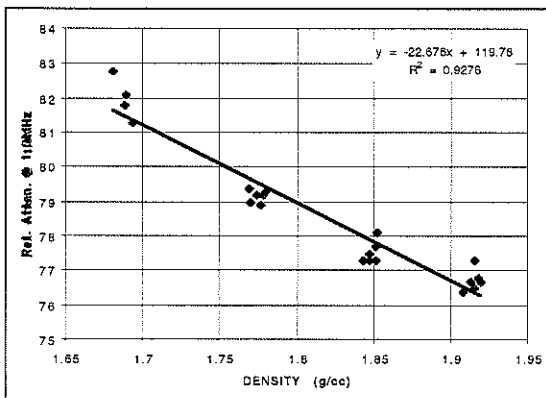


Fig. 16. Relationship between density and Relative attenuation for green Al_2O_3 .

Defect Detection in Green and Sintered Ceramics

In order to determine the feasibility and detectability of defects in non-contact ultrasonic mode, 1.5mm diameter side drilled cylindrical holes were made in green and sintered ceramics. The green ceramic is a 14mm thick porcelain and the sintered material is a 20mm porous (80%

dense) NZP ceramic. Fig. 17 shows typical transmitted ultrasonic signal as a function of defect-free and defective regions in the green ceramic. Fig. 18 shows similar observations from the sintered ceramic. From these observations it is apparent that when ultrasound encounters a discontinuity in its path of propagation, then the amount of energy transmitted is reduced, relative to that from a defect-free region.

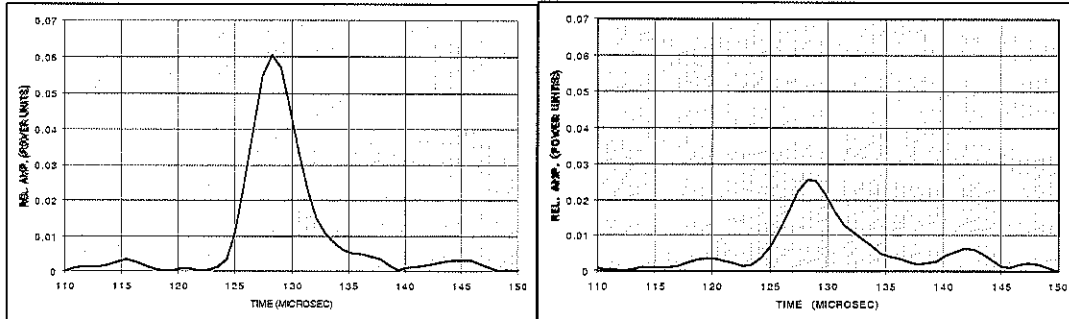


Fig. 17. Defect detection in green material -- 14mm porcelain. Left: Defect-free region. Right: With 1.5mm diameter side-drilled cylindrical hole.

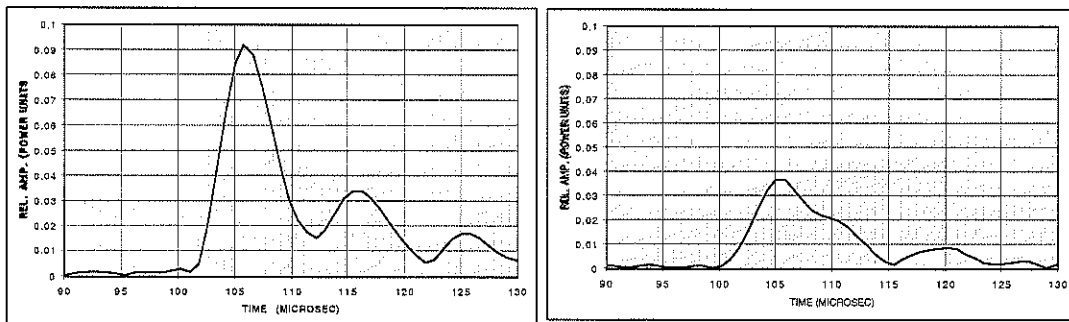


Fig. 18. Defect detection in sintered material – 20% porous NZP. Left: Defect-free region. Right: With 1.5mm diameter side-drilled cylindrical hole.

Surface Characterization

When ultrasound is reflected from the surface of a material, Fig. 8, its strength can be indicative of surface density, inter-granular relationships, roughness, etc. The reflectivity of ultrasound at a given frequency varies as a function of scattering. Relatively speaking, the higher the scatter (coarse-grained surfaces), the lower will be the reflectivity. NCA 1000 measures this signal strength in terms of integrated response of the reflected peak, Table II. In order to exhibit the sensitivity of non-contact ultrasound for surface characterization several SiC abrasive disks, varying in particle size, were used as surface reflectors. By using a 2MHz and 12.5mm active area diameter non-contact transducer placed 10mm away from the reflecting surface, the integrated response from SiC disk surfaces was measured. A similar measurement from the polished surface of carbon steel was assumed as a reference. Fig. 19 shows reflectivity of ultrasound from SiC surfaces as a function of polished steel surface reference.

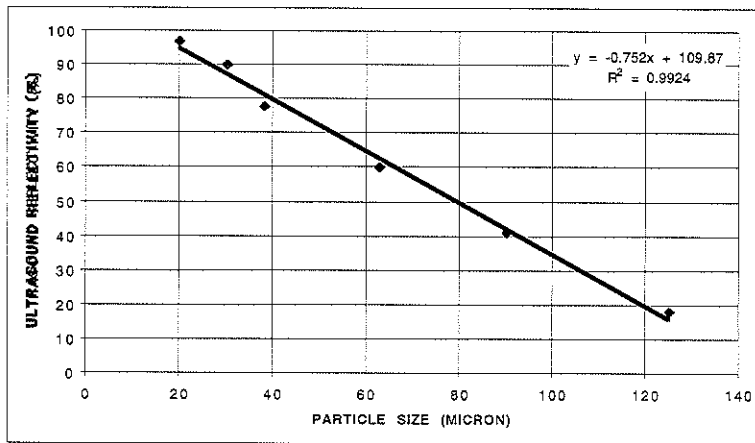


Fig. 19. Reflectivity of 2MHz ultrasound from SiC surfaces varying in particle size.

Non-Contact Ultrasound Imaging

When the NCA 1000 is interfaced with a suitable motorized x-y scanning hardware, it can also be used to generate ultrasonic images in the familiar format of conventional C-scan mode. In order to illustrate this 1MHz non-contact transducers with an aperture of 2mm were raster scanned in transmission mode over a mildly impact-damaged 6.3mm thick sample of glass fiber reinforced plastic composite in order to generate its image. This data was produced by monitoring the integrated responses from the directly transmitted (1st peak) and the reflected (1st thickness reflection of the material) signals from this material. Figures 20 and 21, respectively show transmission and reflection images of this material.

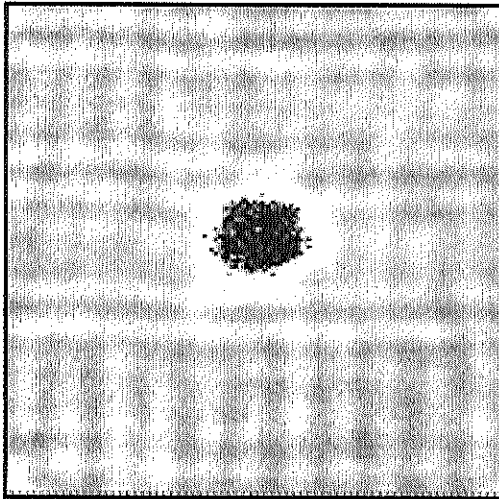


Fig. 20. Transmission image of an impact damaged GFRP composite. Scanned area: 38x38mm.

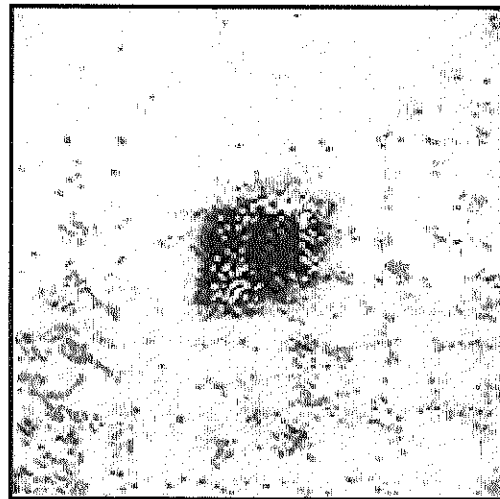


Fig. 21. Same as Fig. 20, except image acquired from the first thickness reflection from the material.

CONCLUSIONS

Non-contact ultrasound is a new method, which has been the dream of materials and ultrasound scientists and engineers. In this paper we have provided an introduction to high frequency non-contact ultrasound. The analytical functions of NCA 1000 provide time, frequency, and phase analysis of any medium through which ultrasound can be propagated. In that sense our presentation rivals not only conventional liquid-coupled ultrasound, but also other wave based characterizing methods. Non-contact ultrasound presents an affirmative alternative to hazardous and expensive X-ray, NMR, and Laser methods for materials characterization.

In this paper we have also given several examples of green and sintered ceramics characterization for velocity, density, surface texture, and imaging of composites. For these applications our transducers and systems have been fully integrated in off-line and on-line applications in manufacturing and laboratory environments. We also believe that in the hands of materials manufacturing and developing experts this development will find numerous uses of value to our increasingly complex world.

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