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FINAL FRONTIER OF ULTRASOUND: REALIZATION OF HIGH FREQUENCY NON-CONTACT ANALYSIS

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Abstract: For true non-destructive materials characterization, a contact-less (air-coupled) method of ultrasound is highly desirable. However, exorbitant acoustic impedance mis-match between the coupling air and the test media presents a natural impediment to Non-Contact Ultrasound (NCU). This impedance mis-match can be as high as seven orders of magnitude for some materials. Therefore, high frequency 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 piezoelectric transducers (100kHz 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 its applications for analyzing a variety of materials.

Key Words: Aircoupled; analysis; characterization; defects; density; noncontact; ultrasound; velocity.

Introduction: It is well-known 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 also 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 generally involves the use of liquid couplants between the transducer and the test materials. 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.

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 merely 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. Therefore, by utilizing conventional ultrasonic pulsers these and capacitance air-coupled transducers showed the feasibility for several industrial and bio-medical applications [9,10,11].

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 over come air-material acoustic impedance mismatch), only then we can have a non-contact ultrasound performance similar to that of the conventional contact mode.

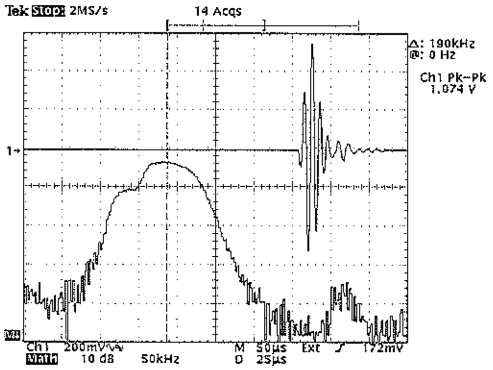


Fig. 1. 200kHz non-contact transducers
separated by 100mm ambient air.
Bandwidth: 100kHz (50%)
Sensitivity: -46dB. SNR: 46dB

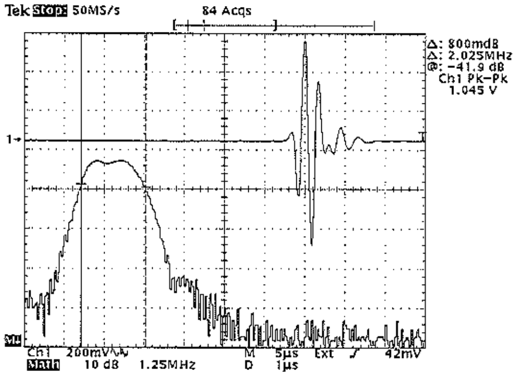


Fig. 2. 3.0MHz non-contact transducers
separated by 10mm ambient air.
Bandwidth: 2.0MHz (75%)
Sensitivity: -64dB. SNR: 30dB.

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, 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.

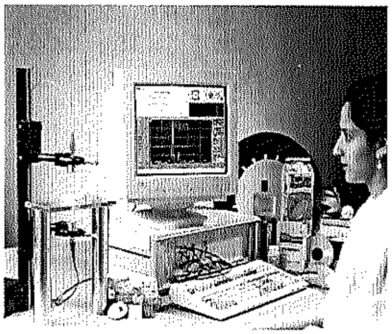
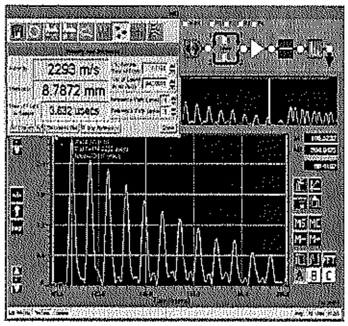


Fig. 3. Non-Contact Analyzer
NCA 1000 shown with trans-
ducers and test material (left).



2293 m/s
8.7872 mm
3.832 usecs

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

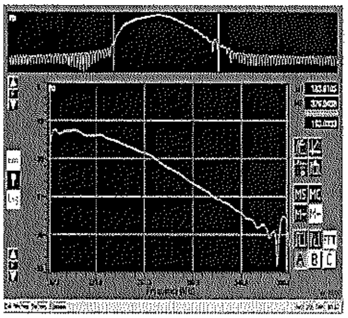


Fig. 5. NCA 1000 screen in
ultrasonic spectroscopy
mode.

Ultrasound Propagation in Non-Contact Mode: In most cases it is desirable to operate the NCA 1000 in direct transmission mode, Fig. 6. 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. 7. 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. 8. 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. Figures 9, 10, and 11 respectively, show typical signals as functions of test material per figures 6, 7, and 8.

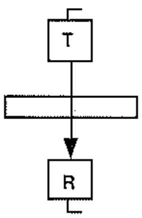


Fig. 6. Direct transmission mode.

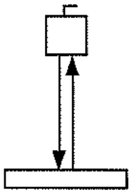


Fig. 7. Direct reflection Mode.

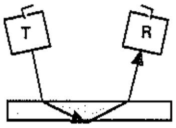


Fig. 8. Transmitter Receiver in reflection mode.

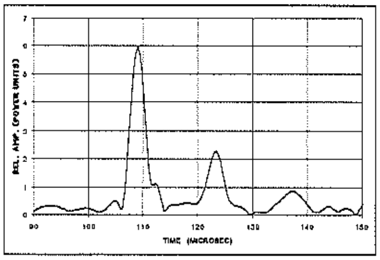


Fig. 9. Signal through 18mm green SiC @ 1MHz, per Fig. 6.

1st peak: Direct transmission in material. 2nd & 3rd peaks: Thickness reflections.

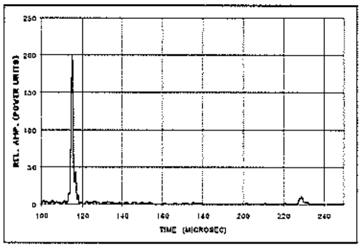


Fig. 10. Signal from 35µm SiC surface @ 2MHz, per Fig. 7.

Transducer to material distance in air: 20mm.

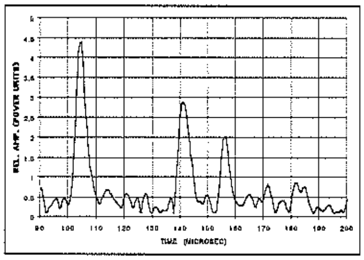


Fig. 11. Signal through 32mm polystyrene @1MHz, per Fig. 8.

1st peak: Reflection from material thickness. Other peaks: Surface waves.

Applications of Non-Contact Ultrasound: Non-contact transducers and the analyzer NCA 1000 have been fully developed and applied for a number of industrial and biomedical applications for the evaluation of thickness, velocity, density, defects, delaminations, and microstruture [12,13,14,15].

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

<u>Velocity-Density Characterization of Green and Sintered Materials</u>: Several samples of green and sintered Al_2O_3 of known density were characterized for ultrasonic velocity in order to establish reference relationship, to be used for the determination of 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. Transducers to materials 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.

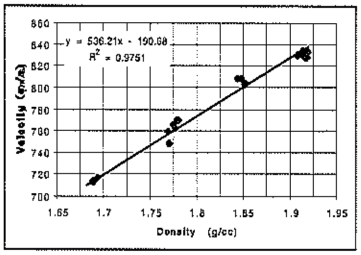


Fig. 12. Velocity-density relationship for green Al_2O_3.

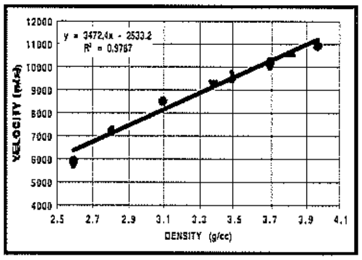


Fig. 13. Velocity-density relationship for sintered Al_2O_3.

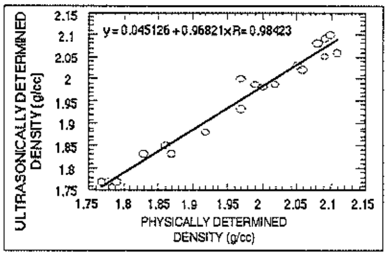


Fig. 14. Comparison of ultrasonically and physically determined densities for green Al_2O_3.

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 +/-0.5%, for porous materials, it is ~+/-1%; and for dense sintered materials, it is ~+/-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 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 super-dense 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 is limited to non-dispersive and relatively low acoustic impedance materials. Thus far we have successfully measured absolute densities of materials such as, polymers, graphite, dense green materials, some glasses, and liquids.

Surface Characterization: When ultrasound is reflected from the surface of a material, Fig. 7, its strength can be indicative of surface characteristics such as, density, inter-granular relationships, roughness, etc. 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 signal strengths from SiC disk surfaces were measured. A similar measurement from the polished surface of carbon steel was assumed as a reference. Fig. 15 shows reflectivity of ultrasound from SiC surfaces as a function of polished steel surface reference.

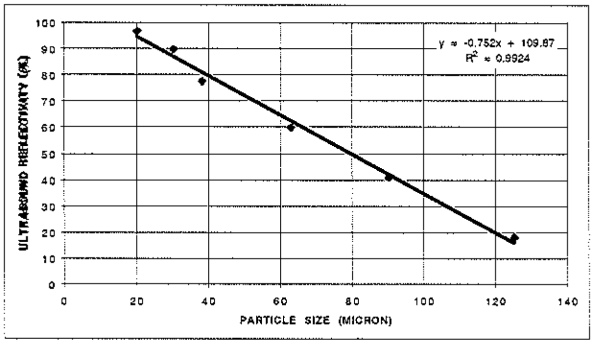


Fig. 15. Reflectivity of 2MHz ultrasound from SiC surfaces varying in particle size.

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 response (area underneath the peak) from the directly transmitted (1st peak) and the reflected (1st thickness reflection of the material) signals from this material. Figures 16 and 17, respectively show transmission and reflection images of this material.

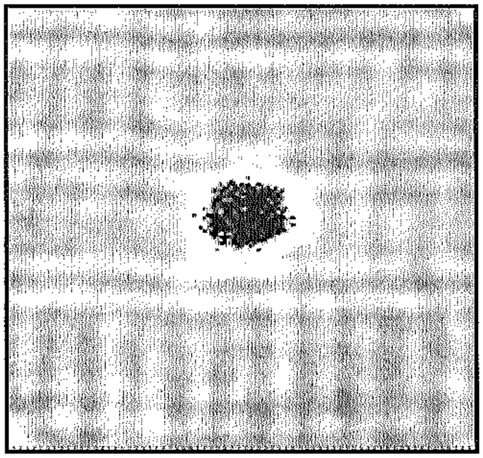


Fig. 16. Transmission image of an impact damaged GFRP composite. Scanned area: 38x38mm.

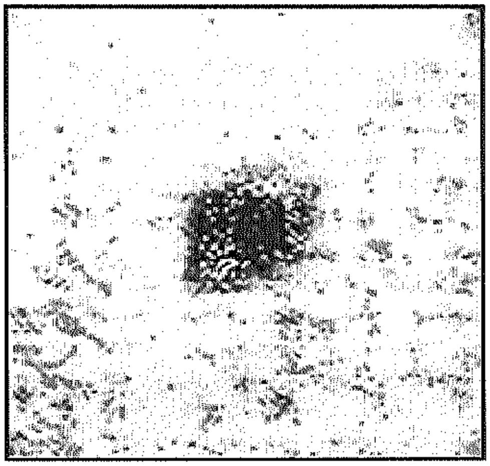


Fig. 17. Same as Fig. 20, except image acquired from the first thickness reflection from the material.

Fig. 18 shows the image of discontinuities in an 8mm aluminum plate generated by raster scanning of 2MHz 12.5mm active area diameter transducers in direct transmission mode, analogous to the arrangement shown in Fig. 6 [16].

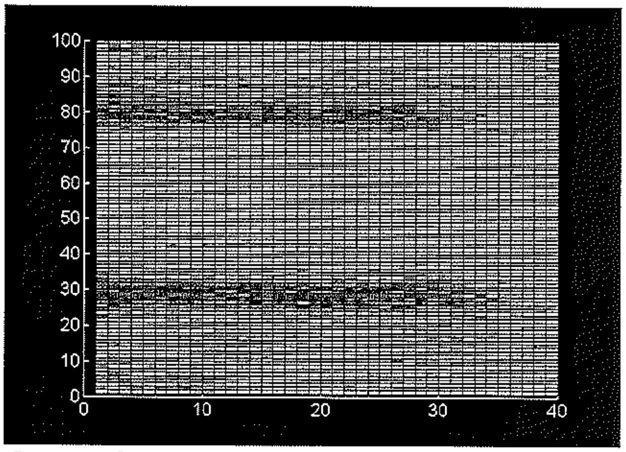


Fig. 18. Non-contact C-scan of a 8mm thick aluminum plate with 3mm (top) and 2mm (bottom) side-drilled cylindrical holes.

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. According to our experience in the development of ultrasound and its applications, we find that the non-contact mode presented here rivals the conventional liquid-coupled ultrasound. Further, the analytical functions of the NCA 1000 have also surpassed any other ultrasonic system known. For example, it provides complete time, frequency, and phase analysis of any medium through which ultrasound can be propagated. In that sense our presentation rivals any other wave based characterizing method and provides more significant information about the material. Non-contact ultrasound also 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 materials analysis for velocity, density, surface texture, and imaging. 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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