EVOLUTION OF PIEZOELECTRIC TRANSDUCERS TO FULL SCALE NON-CONTACT ULTRASONIC ANALYSIS MODE

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Abstract: While non-contact – air/gas coupled – uses of sound waves are buried in the antiquities of our civilization, in modern times, presumably one of the first applications is related to Antarctic ice thickness measurement by sending high intensity sound waves from an airplane in the 1920s. Initial industrial Non-Contact Ultrasound (NCU) was confined between 20 kHz to <100 kHz. The primary hurdle to NCU is the transducer inefficiency in air/gases. This complication is further exacerbated in MHz regime. Consequently, NCU was not taken seriously. During the last 25 years a handful of laboratories have endeavored to develop NCU transducers by applying a variety of plastics, elastomers, and density gradient Z-matching layers on piezoelectric materials. While the transducer efficiency is increased, yet it is not significant for practical NCU. Recent transducer advances have phenomenally enhanced the efficiency between <60 kHz to ~10 MHz. Further increment of efficiency will depend on the piezoelectric material. To this effect, a new piezoelectric composite characterized by the highest possible coupling, has elevated NCU transducers to new heights. As a result of these unusual developments, NCU is not only a reality, but it has also opened doors to ultrasound, hitherto, closed to conventional contact or liquid coupled modes. In this paper we review the significance of materials characterization in light of non-contact ultrasound. Also provided are NCU *modus operandi,* applications, limitations, and recommendations.

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

Characterized information is of value in materials processing, including process variables (composition, temperature, pressure, and time), and materials applications and uses, Fig. 1. Summarily, it is important to know that all materials processing conditions are right in generating the right properties and features of the material. In order to obtain this information a number of methods for materials characterization – for chemical composition, texture/microstructure, defects, and properties -- are required. Since the early 1970s attention has been focused on developing Non-Destructive Characterization (NDC) methods by utilizing electro-magnetic, thermal, and mechanical waves as the characterizing tools. This paper deals with ultrasonic method that underscores the recent advances in non-contact and analytical methodologies.

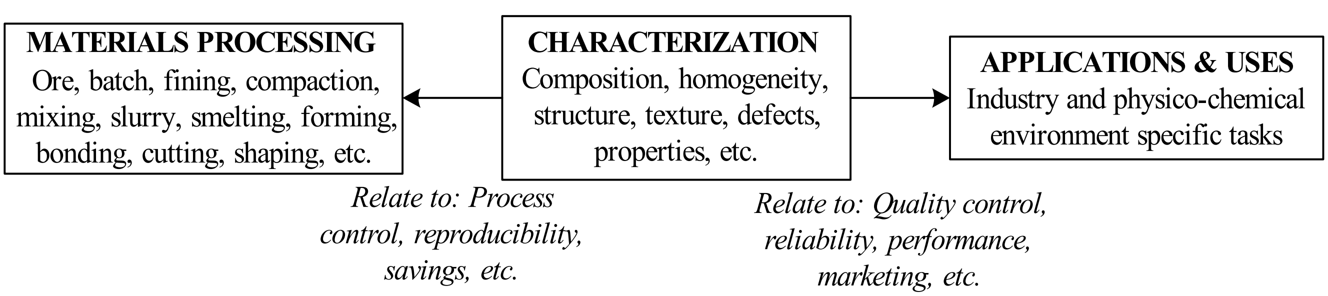


Fig. 1. Significance of materials characterization (1.)

In Pursuit of Non-Contact Ultrasound: While ultrasound and its applications have grown phenomenally in the recent years, the mode by which it is transmitted in a given test medium is severely limited by physical contact between the transducer and the test medium by a liquid gel (2). Elimination of contact would facilitate:

1. Analysis of early-stage materials formation – powders, green, consolidated, un-polymerized, liquid-sensitive, porous, hygroscopic and other materials, or when contact is simply a nuisance.
2. Testing of materials, components, containers, etc., that are continuously rolled on a production line.
3. Evaluation of food, pharmaceutical, and bio-medical products.
4. Analysis of materials where liquids are scarce or impractical to use, such as in zero gravity environment.
5. Non-invasive diagnostics where contact with a patient is harmful or painful.

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 giant hurdle. 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 side tracked or considered a figment of one's imagination. This is understandably due to the phenomenal acoustic impedance mismatch between the coupling air and the test media that can run more than as six orders of magnitude. 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 transduction efficiency in air/gases.

In pursuit of NCU wave transmission in solids, a variety of methods have been under development for 40 years. In 1963, White (3) 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. (4). It was used to characterize the Rayleigh waves in metals (5) and for subsurface materials evaluation (6). 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 the laser-based ultrasound method is questionable when analyzing heat and shock sensitive materials, such as polymers, green ceramics and powder metals, pharmaceutical and food products, tissue, etc. Ultrasound generated by electromagnetic acoustic transducers has been used in the NCU mode for non-destructive testing (7). This method is only applicable to ferromagnetic materials.

These methods do provide useful information about the test materials. However, all of them are limited to specific materials and are partially destructive, complex, or expensive. On the other hand, in order to increase the transduction efficiency of piezoelectric transducers we have been experimenting with acoustic impedance of the transitional layers in front of the piezoelectric element for quite some time. From a practical standpoint we were successful in creating dry coupling longitudinal and shear wave transducers up to 25 MHz in 1982. This was achieved by planting a solid compliant and acoustically transparent layer on the piezoelectric material. By doing so the liquid couplant between the transducer and test material was eliminated, nevertheless, it was still necessary to make a physical contact. At behest this development we were successful in analyzing green ceramics, powder metals, consolidated and porous materials, polymers, etc. (8, 9, 10.)

In 1983 the design of dry coupling transducers lead to the development of air/gas propagation transducers due to significant improvement in transduction efficiency in air. These commercially available transducers have been successfully produced in a frequency range of ~100 kHz to ~5MHz. These devices quickly found applications in aircraft/aerospace industries for imaging and for defect detection in fibrous, low and high density polymers, and composites.

Similar transducers of 1MHz and 2MHz frequency were also produced at Stanford University by utilizing silicone rubber as the front acoustic impedance matching layer (11). 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 (12, 13). Researchers at Strathclyde University (14) 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 mill volt level transmitted signals through a composite laminated honeycomb structure at 500kHz.

More recently, we developed piezoelectric transducers featuring perfect acoustic impedance matched layers for optimum transduction in air from <60kHz to ~10MHz (15, 16). The sensitivity of these new NCU transducers in air is between 16 to30dB lower than their conventional contact counterparts. As a result of this 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.

Air coupled transducers based upon capacitance (electrostatic) phenomena have also undergone substantial developments in recent years. Researchers at Kingston and Stanford Universities have successfully produced micro-machined capacitance air transducers with the latter claiming a high 11 MHz frequency (17,18). 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 (19).

Recently (20) we have also developed a piezoelectric composite, characterized by unusually high electro-mechanical conversion efficiency, broad bandwidth, near zero acoustic cross-talk, and several other positive features. This material in conjunction with NCU transducer design has further enhanced the already high efficiency of NCU transducers. As a result of this non-contact ultrasound has emerged a novel method of multiple applications, many of which were not possible by conventional ultrasound.

NCU Techniques and Applications: Analogous to conventional ultrasound techniques, NCU also offers the same. This subject has been examined in details elsewhere (16, 21.) Here we provide the details techniques, observations, and applications potential.

1. **Direct or Through Transmission:** This technique is easiest to apply in NCU mode. Here ultrasound transmission from a transmitting transducer is received by a receiving transducer on the opposite side of the other with a test material between the two. Fig. 2 shows how ultrasound travels in this mode through a solid material along with location and significance of various peaks corresponding to the material. By utilizing this technique materials can be analyzed for thickness and velocity measurements and for defect detection. Fig. 3 shows velocity-density relationship for green alumina. Fig. 4 shows an image of a green ceramic floor tile, presumably varying in density. Fig. 5 shows the images of consolidated (uncured) and cured multi-layered CFRP composite varying in porosity. Fig. 6 shows texture analysis of paper towels by NCU transmission spectroscopy using 4 MHz NCU transducers. By utilizing this technique materials can also be analyzed for anisotropy, shear wave, elastic properties, etc., by oblique incidence and reception of ultrasound.

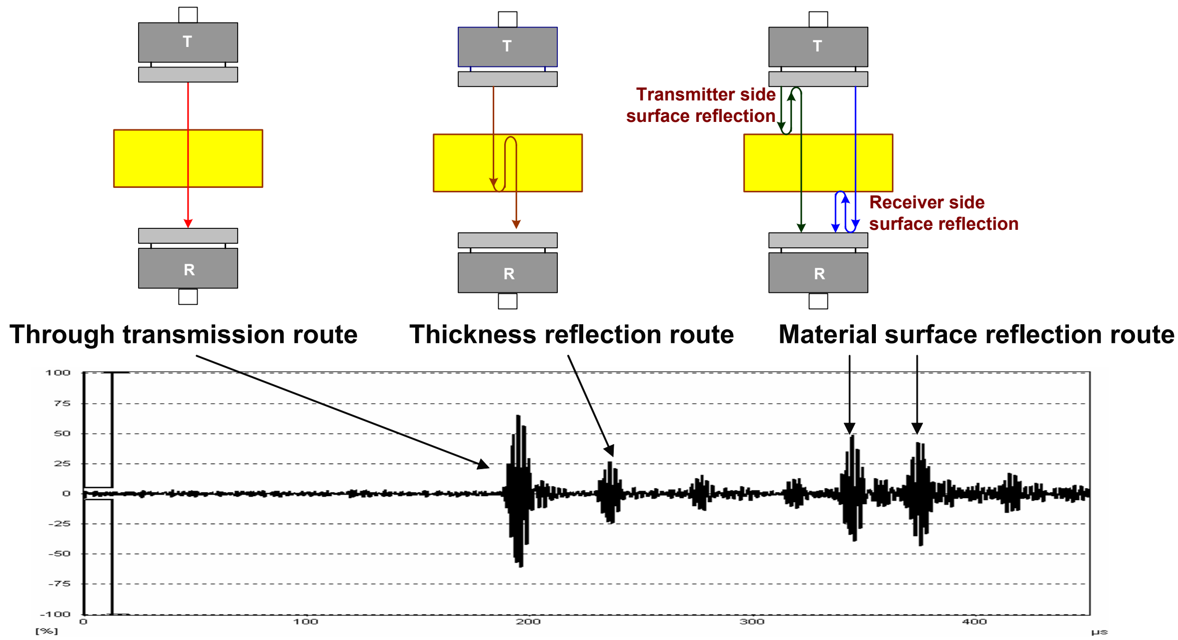


Fig. 2. Mode of ultrasound propagation in direct transmission. Shown here are various routes in this mode and their significance with respect to material.

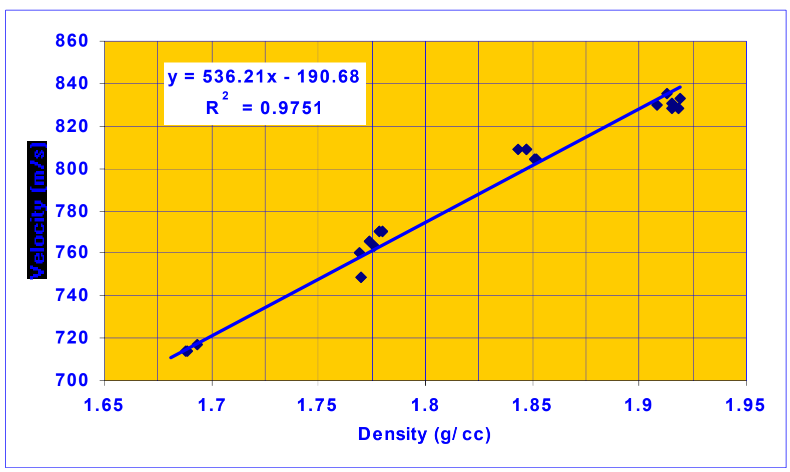
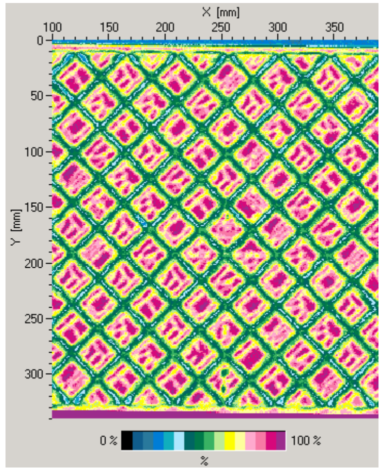


Fig. 3. Velocity-density relationship for green alumina



.Fig. 4 Green ceramic tile

2. **Pulse-Echo Surface Reflection:** Since the magnitude of ultrasound reflection in NCU mode is the highest, thus it is extremely easy to investigate its behavior as a function of surface texture, profiling, proximity analysis, and like applications. With respect to the strength of reflected signal, an unusual experiment was performed. A 500 kHz 19x19 mm transducer was excited by an ordinary -200 volt spike pulse. A flat reflector was placed 1 m away from it and without any amplification one observes a reflected signal from the target, Fig. 7. Fig. 8 shows reflectivity as a function of particle size (SiC abrasive discs) obtained by using a 2.0 MHz transducer. Fig. 9 shows two sides of a Japanese 500 Yen, chosen because of its intricate pattern. This image was obtained by using a 3.0 MHz transducer with beam size approximately 0.1 mm.

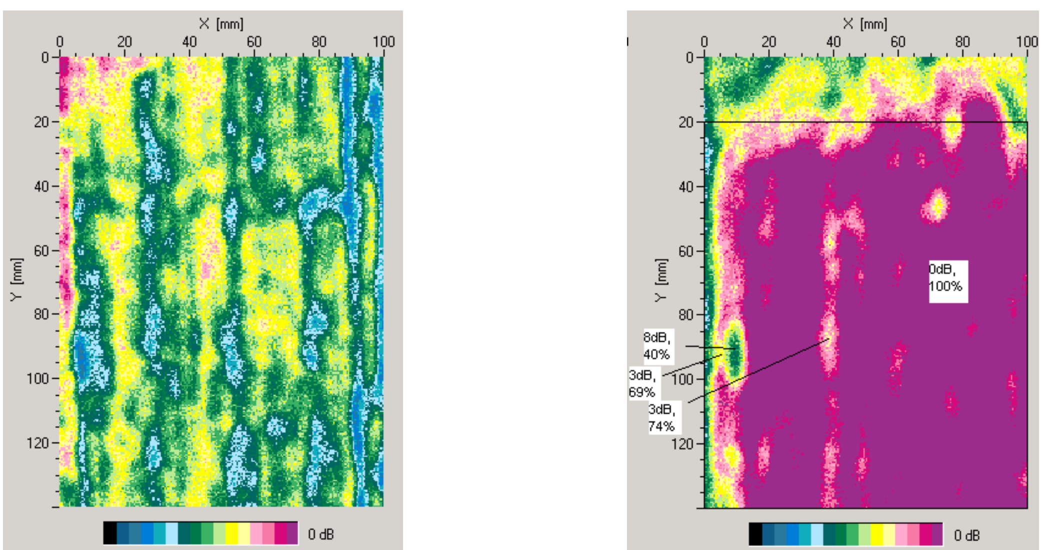


Fig. 5. 500 kHz NCU images of uncured consolidated (left) and cured CFRP composite. Lighter regions in the cured material indicate porosity, also detected before curing. By permission from HEXCEL Composites, UK.

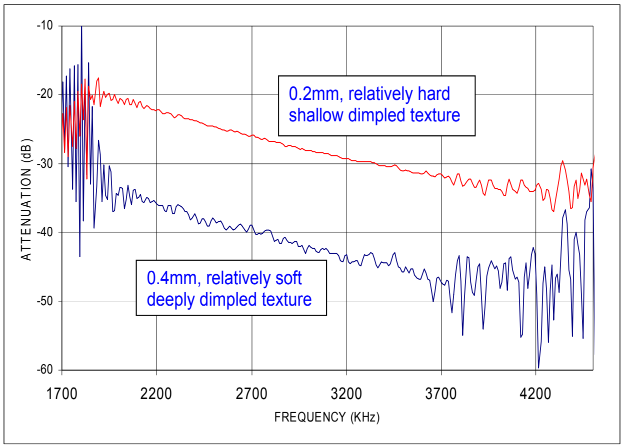


Fig. 6. High frequency NCU spectroscopy of paper for texture analysis

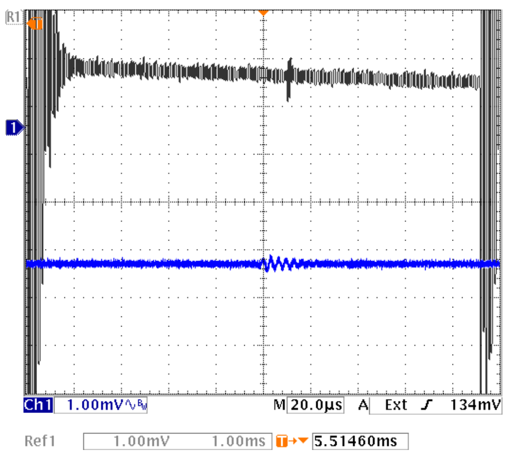


Fig. 7. Reflection from a flat surface located at 1 m From 500 kHz, 19x19 mm transducer. Excitation: -200 V spike. Amplification: **NONE.**

3. **Pulse-Echo Transmission through Solids:** Under NTP conditions due to phenomenal reflectivity (thus broadening of the pulse width) it is extremely arduous to generate far side material thickness reflection from solids. However, with NCU transducer and the test material under gas pressure it is relatively easy to perform pulse-echo analysis of materials. Fig. 10 shows an rf trace of multiple reflections from a 10 mm steel plate at 50 bar air pressure with a broadband 3.0 MHz NCU transducer. It is interesting to note that even at air pressure as low as <7 bar the thickness reflection signal could be detected.
4. **Pitch-Catch T-R Reflection:** By suitably angulating the NCU transducers in air or other gases, longitudinal, shear, and surface waves can generated in the materials for same side defect detection and for other applications. Fig. 11 shows rf traces corresponding to defect-free and defective regions in a 50 mm plastic block obtained by 1.0 MHz transducers 12.5 mm active diameter ~7 mm away from surface. Fig. 12 shows surface wave in steel by 500 kHz 12.5 mm active diameter transducers. Transducers are ~10 mm away from surface and separated by ~150 mm linear distance from each other. Fig. 13 is an image from 2 mm

CFRP-NOMEX honeycomb interface with embedded defects obtained with 500 kHz 12.5 mm active diameter transducers located ~10 mm away from the surface.

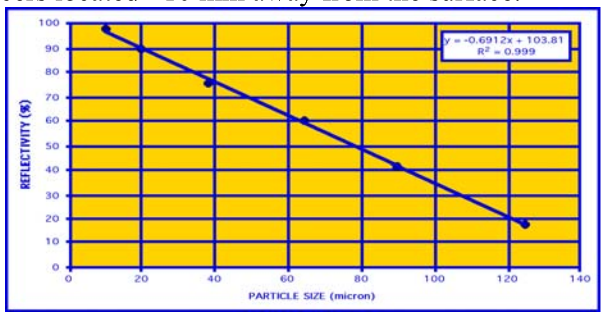


Fig. 8. Reflectivity as a function of particle size

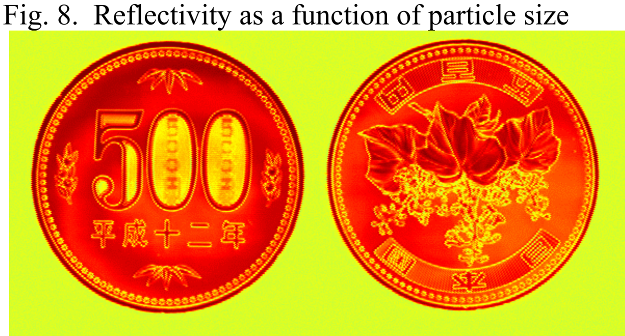


Fig. 9. Reflectivity as a function of surface texture.

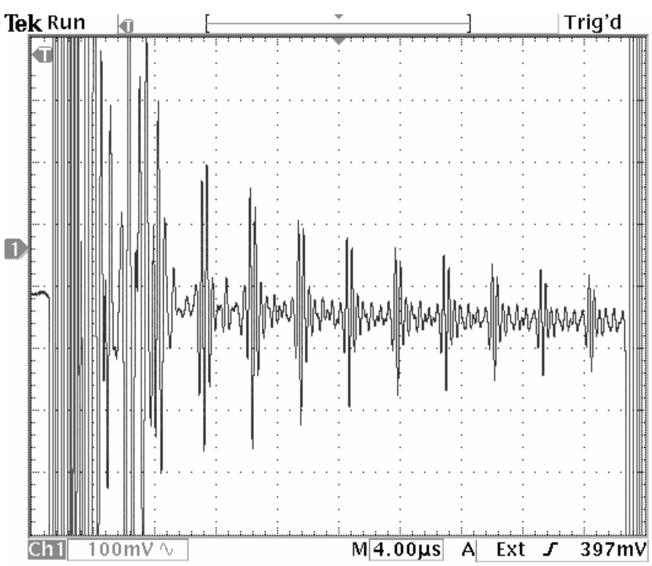


Fig. 10. Pulse-echo multiple reflection from a 10 mm steel block at 50 bar air pressure. By permission

from Gas Technology Institute, USA.

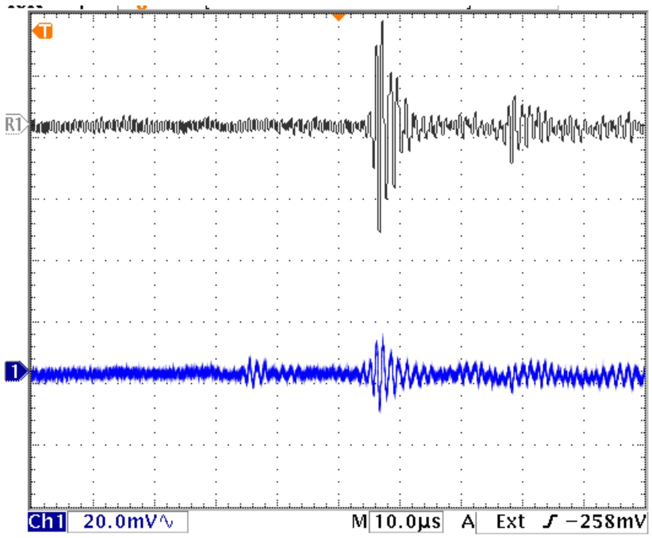


Fig. 11. Same side defect-free (top) and defective
(bottom) 3.0 mm cylindrical hole) regions in a 50 mm polystyrene block

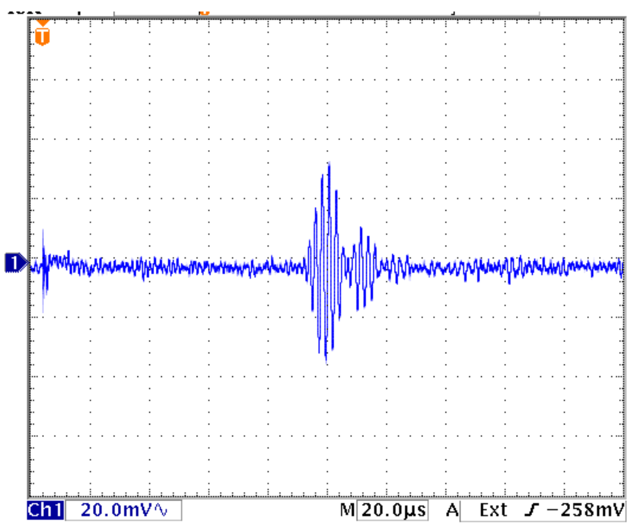
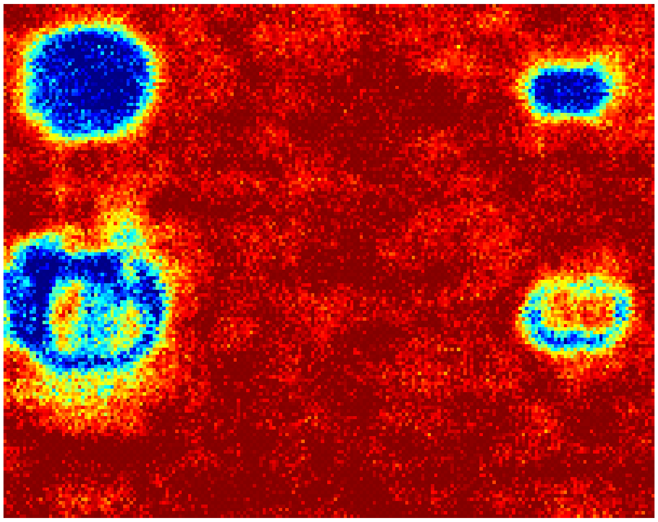


Fig. 12. Surface wave in steel



.Fig. 13. Same side image from a 2mm CFRP-NOMEX interface with embedded defects.

Limitations of NCU: While the applications of NCU abound, yet it should not be regarded as a panacea. During the development of transducers, *modus operandi,* and applications of NCU we have found the following limitations of this new method in non-destructive testing and analysis of materials:

1. Analogous to conventional ultrasound, NCU is also limited by the complexity of material shape and size. These complexities are overcome by manipulating the transducer geometrical-acoustics and electro-mechanical means.
2. Normally, extremely high acoustic impedance materials – heavy metals and super dense oxides, carbides, nitrides, and borides of metals and non-metals – are not suitable for on-line NCU. However, if it is necessary, special NCU mechanism for such materials is possible.
3. Single transducer (pulse-echo) NCU at the present moment is a formidable challenge, though there is evidence for its possibility. Under high gas pressure pulse-echo is relatively easily applicable. On the other hand, two transducers can be used to interrogate from the same side under ambient environments.
4. Without special considerations, it is nearly impossible to transmit ultrasound through materials at temperatures >250C.

Conclusions and Suggestions: NCU has been highly sought after nondestructive materials testing and analysis method. Recent advancements in transducer design and piezoelectric materials clearly demonstrate that NCU is now a reality with wide ranging industrial, bio-medical, food & pharmaceutical, and other applications. It is now possible to characterize materials in early stages of their formation for obvious advantages. It is also possible to test porous or contact and liquid sensitive media. Concurrent with any new and major development in science, we believe NCU will also broaden the imagination of thinkers and researchers for further advancements. To this effect, we offer some ideas and suggestions:

1. Despite the wealth of information provided by ultrasound, this age-old method is still struggling for recognition unlike other wave-based methods developed and perfected in the last 150 years. Even conventional ultrasound has not earned the serious attention of materials community. It is the experience of this author, near absence of proper practical knowledge about wave-material interaction and interfacial phenomena that are the key impediments to proper utilization and interpretation of ultrasound. We believe the absence of right education will cause extremely serious problems in our techno-society that demands

extraordinary reliability and performance of materials deemed to operate under extreme physico-chemical conditions.

2. In order for ultrasound to rival other well-known methods, it is imperative to initiate inter-disciplinary materials research and education in this subject of immense significance to our complex world. Classical materials science, not engineering alone, is absolutely necessary, since it is this that creates the foundation.
3. We need to define *What material features and properties (micro and macro) are responsible for its ultrasonic behavior.* We need to challenge ourselves to extend non-destructive methods for chemical composition analysis and not just physical & structural evaluation.
4. While the vision of materials industry is generally very bright and ahead of times, yet it is the one of public funding agencies' that needs to catch up with harsh realities to determine the status of education and R&D into non-destructive analysis and testing of materials befitting economic, safety, and creative objectives.
5. We can learn a great deal from the ultrasound-biomedical model. 25 years ago, ultrasound in medical diagnostics was barely known. Today it is a widely used method. The medical community and related industry gave ultrasound a respectable place in both education and research due to its advantages over hazardous x-rays.

References:

1. The Committee on Characterization of Materials, "Characterization of Materials," Publication MAB-229-M, National Academy of Sciences – National Academy of Engineering, Washington, DC (1967).
2. Green, R.E., "Ultrasonic Non-destructive Materials Characterization," in Alex Vary, ed., Materials Analysis by Ultrasonics, Noyes Data Corporation, New Jersey, 1987, p. 6.
3. White, R.M., "Generation of Elastic Waves by Transient Surface Heating," J. App. Phys., v. 34, pp. 3559-3567 (1963).
4. 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).
5. Ledbetter, H.M. and Moulder, J.C., "Laser-Induced Rayleigh Waves in Aluminum, J. Acoust. Soc. Amer. V. 65, pp 840-842 (1979).
6. 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).
7. 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.
8. 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.
9. Bhardwaj, M.C. and Bhalla, A., "Ultrasonic Characterization of Ceramic Superconductors," J. Mat. Sci. Lett., v. 10 (1991).
10. 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).
11. 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).
12. 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).
13. Haller, M.I. and Khuri-Yakub, B.T., "1-3 Composites for Ultrasonic Air Transducer," IEEE Ultrasonics Symposium, pp. 937-939 (1992).

14. Reilly, D. and Hayward, G., "Through Air Transmission for Ultrasonic Non-destructive Testing," IEEE Ultrasonic Symposium, pp. 763-766 (1991).
15. Bhardwaj, M.C., "Ultrasonic Transducer for High Transduction in Gases and Method for Ultrasound Non-Contact Transmission into Solid Materials," U.S. Patent #6,311,573 (2001.)
16. Bhardwaj, M.C., "High Efficiency Non-Contact Transducers and a very high Coupling Piezoelectric Composite," proc. WCNDT-2004, Montreal, Canada, August 30 – September 3, 2004.
17. 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., v. 42, pp. 42-51 (1995).
18. 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).
19. 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).
20. Bhardwaj, M.C., "Gas Matrix Piezoelectric Composite," US and international patents pending.
21. Bhardwaj, M.C. "Non-destructive Evaluation: The Introduction to Non-Contact Analysis," Encyclopedia of Smart Materials, editor Mel Schwartz, John Wiley & Sons, NY (2002).