ULTRASONIC NDC - A HISTORICAL PERSPECTIVE AND PRACTICAL CONCEPTS

M. C. Bhardwaj
Ultran Laboratories, Inc.
State College, PA

A PUBLICATION OF ULTRAN LABORATORIES, INC., Series on NDC, EPN-101a - July 1987

ultran

redefining
the limits of
ultrasound

ultran laboratories, inc.
139R north gill street
state college, pa 16801 usa
814.238.9083 *phone*
82.0978 *telex*
814.234.3367 *fax*

ULTRASONIC NDC - A HISTORICAL PERSPECTIVE AND PRACTICAL CONCEPTS

M.C. Bhardwaj
ULTRAN LABORATORIES, INC.
State College, PA USA

Significance of characterization is well-established in the materials industry. NonDestructive Testing (NDT), is also well-established, albiet in the the metals industry. Whereas it has been desirable to nondestructively analyze other materials, until recently, such practice was not popular in non-metals industries. Whatever the reasons - apprehension, disbelief, apathy, etc. - for the late entry of nondestructive evaluation into the world of materials, its significance in materials manufacturing, development, and uses cannot be underestimated. This paper presents an introduction to ultrasonic NonDestructive Characterization (NDC) by tracing its history. Also described is the significance of critical elements of ultrasonic NDC with respect to modern materials analytical requirements.

MATERIALS CHARACTERIZATION AND NDT

Characterization of materials for their development, manufacture, and uses is an important subject for the modern materials industry. The National Research Council (1967)[1] presented a comprehensive report on the Characterization of Materials, describing the significance of this subject, and the then status of materials characterization techniques. According to this report:

> ***"Characterization describes those features of composition (including defects) of a material that are significant for a particular preparation, study of properties, or use, and suffice for the reproduction of a material."***

The term characterization means different things to different people. For example, a scientist concerned with single crystals and glasses views defects and structure at the molecular and atomic levels, while one involved with polycrystalline and granular materials views them at a macro level. As the magnitude of a given observation changes, so does the meaning of a given objective in materials characterization. How a material or a component is characterized is of importance to all those involved with its development, manufacture, and eventual use. Selection of a particular characterizing technique is entirely dependent upon the objectives of a particular study. At this time it is not possible to imagine a single - all-embracing - characterizing technique that would meet all the objectives and criteria of materials characterization. A number of different methods are used to characterize materials for their compositions, structures, and properties. Each method is limited by the information it provides, besides being either entirely destructive (wet chemical methods) or partially destructive (dry physical methods).

There are several NonDestructive Testing (NDT) techniques for materials evaluation that utilize a variety of waves - light, electro-magnetic, and mechanical - and light-sensitive liquids as the principle tool or vehicle in providing useful information. Once again, each method is limited in the information revealed. McMaster (1963)[2] has given an excellent review and applications of all popular industrial NDT methods. More currently, Vary (1973)[3] included some modern x-ray diffraction, magnetic resonance, laser spectrometry and other techniques for NonDestructive Evaluation (NDE) of materials. In our view, among all the known NDT/NDE/NDC techniques, no method other than that based upon ultrasonic waves is capable of revealing more and significant information. Not only is there no special sample preparation required for utilizing ultrasonic

methods, but also these methods are applicable to virtually any shape or size of the test material. However, ultrasound too, has limitations - it is not a *panacea!*

Ultrasound, besides being characterized by wave motion, is also elastic in nature. Therefore, ultrasonic waves when propagated in a material actually cause displacements in it -- the amount of displacement or elasticity being the function of a material's intrinsic behavior, Kinsler, et. al. (1982)[4]. Thus, for all practical purposes, once propagated in a material, ultrasound generates the phenomena of reflection, refraction, transmission, diffraction, interference, scattering, and dispersion when it interacts with the material. Investigation of these phenomena in light of test material characteristics is the key to NDC, Bhardwaj (1986)[5]. The significance and quality of information revealed by ultrasound are directly related to the performance of incident and receiving components of the ultrasonic characterizing system.

EVOLUTION OF ULTRASOUND FOR NDC

NDT use of ultrasound has been known almost since the 1880 discovery of piezoelectricity in quartz, and later in tourmaline, sphalerite, perovskite, and other minerals. Richardson (1913)[6] proposed the idea of utilizing high frequency sound waves for the detection of objects using water or air as the carrier medium of ultrasound. Mulhauser (1931)[7] applied ultrasonic waves for detecting flaws in solids.

A cursory glance at more current literature indicates that the theory of wave-material interaction is well developed. Bhatia (1967)[8] has given an excellent review of some of the earlier theoretical and experimental work dealing with the nature of ultrasound and its interaction with all three states of matter. From the standpoint of extracting even more useful information about materials, the theory of wave-material interaction has been refined further by Varadan, et. al. (1985)[9]. McGonnagle (1961)[10], Blitz (1963)[11], Nozdreva (1964)[12], and Filipczynski, et. al. (1966)[13] have clearly demonstrated the applications of ultrasound for the evaluation of materials. Papadakias (1975)[14] and Vary (1980)[15] applied ultrasound of varying frequencies in time and frequency domains for evaluating material composition and micro-structure. All serious investigators of materials by ultrasound have stressed the use of these methods for *"more than overt flaw detection."* However, for want of adequate and suitable ultrasonic hardware, ultrasonic waves did not draw the attention of the materials community until about 15 years ago.

With the exception of a few early references directly dealing with property and texture evaluation in ceramics and some special alloys, most literature on nondestructive testing of materials by ultrasound is preoccupied with its applications to primary metals. Baab and Kraner (1948)[16] showed the application of the resonance technique for the determination of the elastic modulus. This technique was later applied toceramics by Crosby (1968)[17]. Resonance, popularly known as the sonic method has been dropped in favor of ultrasonic method because of the former's complexity as well as its dependency upon the shape of the test material. Baudran and Deplus (1958)[18] in France, Ueda (1963)[19] in Japan, Davis and Brough (1971)[20] in England, Matveev, et. al. (1970)[21] in USSR, and Bhardwaj (1976)[22] in USA have reported direct reflection and direct transmission ultrasonic techniques for the evaluation of elastic constants, mechanical properties, and corrosion measurements in refractories and other ceramics. Oron, et. al. (1974)[23] measured the grain size in U-Cr alloys by estimating attenuation of ultrasound at discrete frequencies. Phase transformation studies in Bi-Sn and SnGe-Te systems by the application of ultrasound as a function of temperature have been reported by Gopinathan and Padmini (1974)[24], and Rehwald and Lang (1975)[25], respectively.

Despite the early work into diagnostic uses of ultrasound in materials characterization, it remains a *"mystery"* as to why this important subject did not attract the attention of the materials community. We present the following observations on this matter:

1. *Early transducers were designed for the detection of large discrete flaws in metals. These designs actually managed to conceal much of the information*

about material properties and micro-structure which must be revealed to meet the NDC objectives.

2. *Early transducer excitation and amplification systems were concerned with the generation of high power and thus ignored the possibility of more efficient transducer designs, although significant progress in crystal chemistry and ferro-electric materials had already taken place in the 1940s and 1950s, Muller and Roy (1974)[26].*

3. *Early commercial manufacturers and users of ultrasonic hardware were obsessed with the "overt" flaw detection use of ultrasound, surprisingly ignoring the values of ultrasound in property and microstructure evaluation at the industrial levels. Their desire to "supress nonrelevant indication" ran counter to materials characterization objectives.*

4. *Several manufacturers of ultrasonic equipment regarded ceramics as "foams and sponges," thereby concluding the impossibility of characterization of such materials by ultrasound.*

5. *There existed a lack of fundamental empirical studies describing the actual relationships between ultrasonic parameters and material characteristics.*

6. *Proper education in the NDC discipline was also practically non-existent.*

Indeed, the status of ultrasonic NDC was grim. However, the efforts of serious users and developers of ultrasound, in conjunction with an urgent industrial demand for reliable NDC techniques, have completely revolutionized the status of ultrasound during the recent years. In this paper our intention is to present this subject with a perception analogous to other characterizing techniques (that also utilize some wave phenomena) besides providing the significance of critical elements of ultrasound of value in the manufacturing and quality control functions.

AN INDUSTRIAL PERSPECTIVE OF ULTRASONIC NDC

From a practical industrial standpoint, materials characterization serves the following important functions in the development, manufacture and uses of materials:

1. *Characterized parameters determine the suitability and applicability of a given material in one or more uses of that material.*

2. *Characterized parameters also throw light on those features of material synthesis that are significant in its preparation or in determining the conditions of a particular preparation.*

While ultrasound should not be regarded as a *panacea* for all NDC applications, it is reasonable to conclude that ultrasound demonstrated to be feasible in a given application can be reliably and repeatably used. For example, if a material exhibits heterogeneous distribution of the velocity of sound (when not specified, velocity of sound is always for the longitudinal waves), thus indicating corresponding changes in the material density and/or micro-structure, then this information can be used to monitor or control a material's manufacturing process. Furthermore, such information can also be used to establish accept/reject criteria for the intended use of the material. With this important analytical information on hand, we conclude that ultrasonic NDC can serve the above mentioned characterization functions well.

Twenty years ago when the report on Materials Characterization was published, the NRC addressed characterization methods based upon optical, x-ray, neutron, γ-ray, electron, and other similar mechanisms. This further indicates that ultrasound for materials characterization was *"not mature"* then, or that ultrasonic waves *"had not attracted"* the attention of modern materials

scientists and engineers. This is certainly no longer true. Using different transducers, we can nondestructively determine the quality and contents of practically any material, *"including foams and sponges!"* Continuing with the philosophy presented by the NRC (1967)[1], we present our perspective on ultrasonic characterization of materials and processes, Fig. 1. We should alert the reader, particularly a newcomer to ultrasonic NDC, that while ultrasound and its techniques are fairly well-developed today, to a large extent it is the user's responsibility to generate appropriate ultrasound-materials relationships of importance to a specific test objective. Let the objective be the measurements of elastic constants, density, porosity, defect detection, micro-structure evaluation, or stress measurements. The developments in ultrasonic science are relatively new with respect to materials characterization, therefore, its applications need to be developed and optimized. It may help to imagine the status of ultrasound today as being analogous to that of x-ray diffraction 30 years ago.

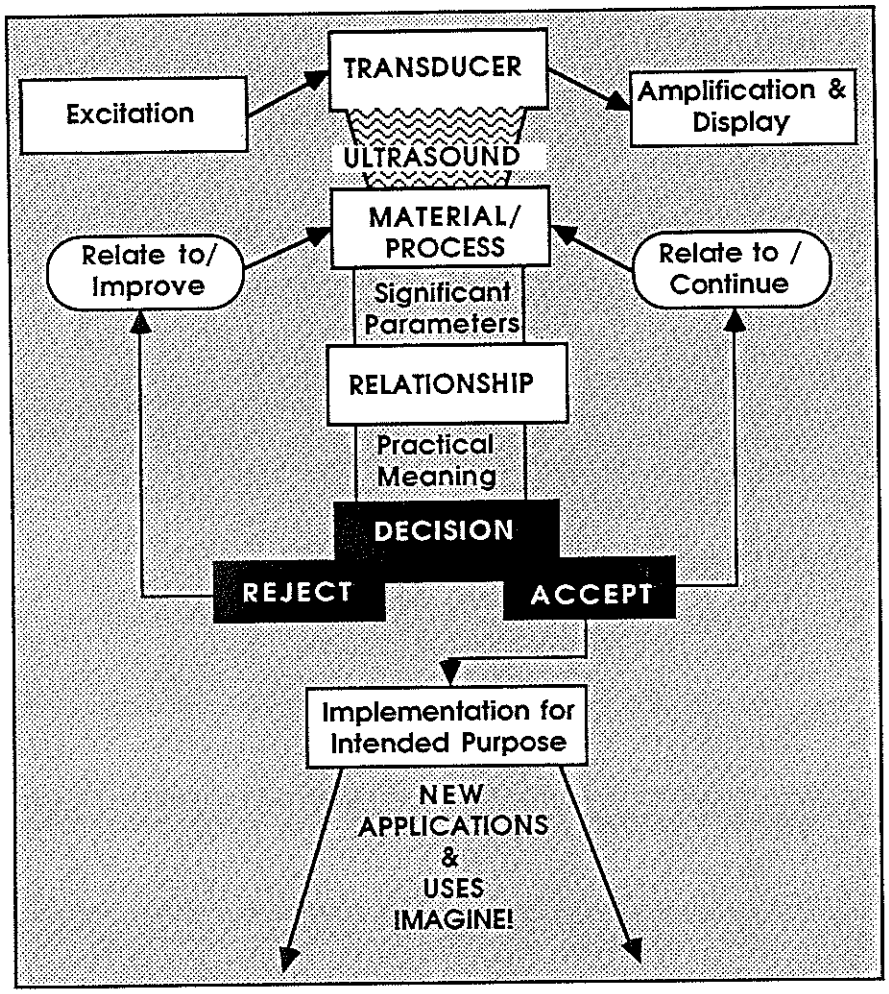

Fig. 1. An industrial perspective of ultrasonic NDC.

THE SCOPE OF ULTRASONIC NDC

Generally speaking, ultrasonic waves are capable of propagating in any medium with the exception of the vacuum. This alone describes the scope of ultrasound. Investigation of reflected or transmitted ultrasonic waves from a medium of propagation can provide valuable information about that medium. Therefore, it is possible to evaluate a wide variety of materials - ceramics, powder metals, polymers, composites, blood , tissue, and bones, rocks and minerals, concretes,

etc. - and processes - crystallization, polymerization, liquefaction, solubility, phase transformation, densification, superconductivity, etc. - by ultrasound.

Besides the detection of overt flaws in metals, ultrasound can be used to reveal valuable information about materials, such as texture, microstructure, density, porosity, elastic and mechanical properties, applied and residual stress measurement, dimensional analysis, corrosion measurement, liquid level sensing, defect and microstructure imaging and microscopy, etc. Ultrasound can also be used for in-situ testing, remote sensing, robotic, artificial intelligence, and other applications where signals from reflected ultrasound are deemed beneficial. The key, however, in every application is the propagation of ultrasound through a medium of interest.

ELEMENTS OF ULTRASOUND OF IMPORTANCE IN NDC

In order to gainfully apply ultrasonic waves for a particular materials characterization objective, it helps to perceive ultrasonic method in light of other characterizing techniques that use some wave phenomena for material analysis. For example, while using x-ray diffraction for atomic structure analysis, the target material in the x-ray tube may be changed with respect to its (x-ray) wavelength and the test material d-spacings. Similarly, it may be necessary to alter the characteristics of incident or receiving ultrasound with respect to the changing characteristics of test materials or test objectives.

The source and receiver of ultrasound is a piezoelectric transducer - **THE HEART OF AN ULTRASONIC SYSTEM.** Improper selection or misuse of an ultrasonic transducer can generate misleading observations, making it extremely difficult to draw inferences from the observed data. The selection of a given transducer MUST complement the objectives of a given application as well as the anticipated interaction of ultrasonic waves with the test material. The significant electro-mechanical elements of ultrasound from the standpoint of a transducer are: its frequency, pulse width, bandwidth, sensitivity, acoustic impedance matching to the test medium, and electrical impedance matching to the transducer excitation system. Its significant geometrical elements are: beam size, beam shape, and depth of field in a given medium. Transducer physical styles are also influenced by the test environment such as temperature, pressure, and chemical conditions.

Transducer acoustics for NDC

Majority of materials and transducer characterization functions can be accomplished by exciting the transducer with a short burst electrical impulse - one featuring fast rise time and an equally fast decay time. The reception and amplification of ultrasonic signals (reflected or transmitted from a material/target) are performed by a "broad" bandwidth amplifier. A suitable amplifier is one that exhibits bandwidth greater than that of the transducer. Commercially available are transducer excitation systems varying in rise time from <1ns to >500ns, and amplification systems with bandwidths ranging from <10KHz to >100MHz.

Among all the parameters of the transducer, we believe that the most significant for materials characterization is the transducer pulse width at a given frequency. Our reasons for singling out the importance of transducer pulse width are:

1. *Short pulse widths facilitate high time/distance resolution.*

2. *Short pulse width transducers are characterized by "broader" bandwidths, thus facilitating "wideband ultrasonic spectroscopy."*

3. *Large pulse width transducers are poor time/distance resolvers, however, being high in energy, they are good for long distance travel in materials.*

4. *Large pulse width transducers are characterized by "narrower" bandwidths, thus emitting monochromatic ultrasound useful for the analysis of materials at discrete frequencies.*

Time domain of characteristics of ultrasound

Acoustic characteristics of an NDC transducer are achieved and controlled by careful selection and processing of piezoelectric materials, Bhardwaj (1986)[5]. One of the critical requirements in materials characterization is the achievement of extreme time/distance resolution. This is particularly true for dense and thin materials sections. Resolution of two closely lying planes - top and bottom surface of a test material, or distance of a discontinuity from the test material surface when direct reflection technique is used - is directly dependent upon the width of the transducer pulse. Pulse width of a transducer is measured by investigating a reflected signal from a standard target such as optically flat and polished clear fused quartz (CFQ). The rf trace so obtained is known as "the time domain" or "realtime envelope" of ultrasound. Fig. 2 is an idealized time domain of a 10MHz broadband transducer. The measured pulse width in this example is 150ns or

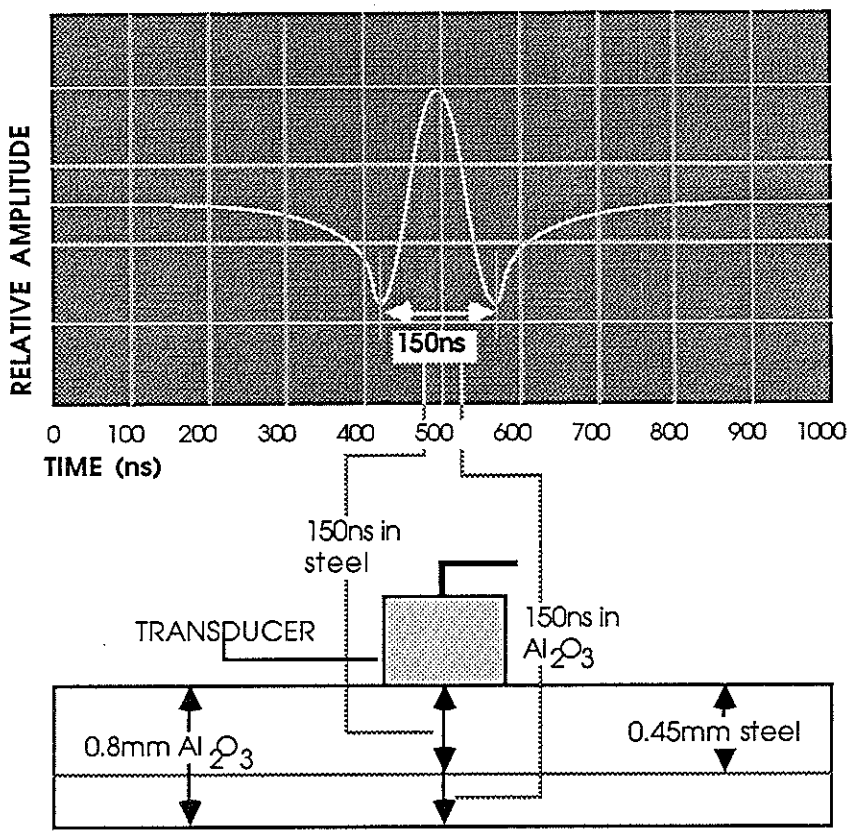

Fig. 2. TOP - an idealized time domain envelope of a 10MHz transducer with 150ns pulse width, and its relationship with maximum resolvability in steel and Al_2O_3 specimens.

1.5 wavelengths (one wavelength , in time units, of a 10MHz frequency is 100ns). In practical terms this information is valuable in deciding time/distance resolution in a given test material. For example, this transducer would resolve down to a minimum of:

0.45mm in steel (longitudinal wave velocity 5,970m/s), i.e., when direct reflection technique is used, the round-trip time of flight (TOF) in this material is 150ns.

0.8mm in dense Al_2O_3 (longitudinal wave velocity 10,900m/s), i.e., when direct reflection technique is used, the round-trip time of flight (TOF) in this material is 146ns.

Graphically, these relations are shown in Fig. 2.

The minimum measurable thickness of a material, or the minimum distance within it at which ultrasonic observations can be made, depends upon the actual pulse width of the transducer, not necessarily upon the frequency. The indiscriminate increase in the frequency of the transducer can generate severe complications. These may be due to system limitations and exponential decay of otherwise significant reflections as a function of increasing frequency - frequency-dependence of ultrasonic attenuation.

Frequency domain characteristics of ultrasound

The frequency components of an NDC transducer are measured by performing spectrum analysis or FFT (Fast Fourier Transformation) of the realtime rf envelope, such as the one shown in Fig. 2. An idealized frequency domain of a 10MHz transducer is shown in Fig. 3. Definitions of various parameters measured from the example of this frequency domain are as following:

F_p, (peak or "nominal" frequency) = 8.2MHz

bcf (bandwidth center frequency or the real frequency) = $(F_1 + F_2)/2$, where F and F are, respectively low and high values of frequencies at -6dB (50%) level. From Fig. 3 it is 9.9MHz.

Bandwidth (normally described at -6dB level) = $(F_2 - F_1)$, In the example cited, it is 11.0MHz or 110% of the bcf.

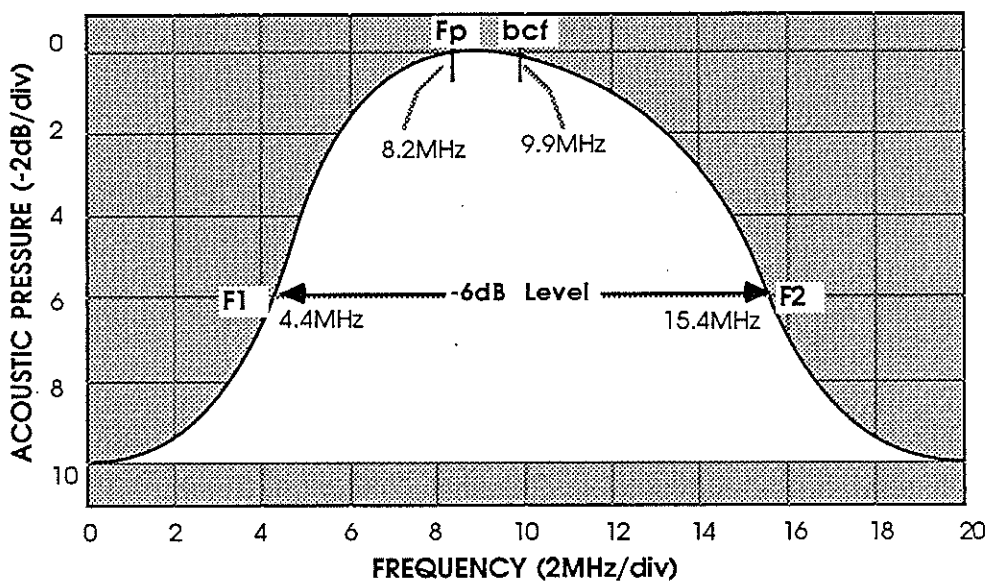

Fig. 3. An idealized frequency domain of the time domain envelope shown in Fig. 2.

Depending upon the bandwidth of a given transducer, it can also be used to investigate frequency-dependent characteristics of the test material.

ULTRASONIC PARAMETERS MEASURED IN NDC

Applications of ultrasound are dependent upon the development of relationships between the following ultrasonic measurements as functions of test material characteristics:

1. *Velocity of longitudinal waves*
2. *Velocity of shear/transverse waves*

3. *Velocity of surface/Rayleigh waves*

4. *Frequency dependence /attenuation of above waves*

5. *Phase change and phase amplitude of reflected or transmitted waves, and*

6. *Interference of polarized waves.*

Investigation of materials with longitudinal waves can be used to reveal sub-surface and bulk-body defects, thickness or corrosion measurements; and by angulating these waves transversely oriented defects can also be studied. Longitudinal and shear waves can be applied to determine elastic constants, densities, and porosities of materials. Surface waves can be used for the detection of surface-breaking defects and microstructure of shallow sub-surface regions. Investigation of the rest of the above mentioned parameters can be applied to reveal important mechanical properties of materials.

COMPREHENSIVE DEVELOPMENT OF ULTRASOUND FOR NDC

The diversity of media that can be investigated by ultrasound is extensive, as we noted earlier. Practically speaking, if ultrasound of a specific frequency and its pulse shape and size can be propagated in one material, it may not necessarily propagate through another material. For example, a 50MHz ultrasound may propagate through a dense BeO substrate easily, while making hardly any impression on a direct bonded fused SiO_2 refractory. On the other hand, a 1MHz ultrasound would adequately propagate through both of these materials, but the pulse width of the 1MHz ultrasound might be too large to allow any meaningful use on dense BeO. For the fused silica refractory, a 1MHz would be the right selection.

Among all known materials, those based upon ceramics, powder metals, and polymers are characterized by extreme compositional and microstructural diversities. Such variations cause corresponding variations in ultrasonic measurements. For example,

1. *"Lowest"* ultrasonic velocity: 580m/s - $Al_2O_3 + SiO_2$ foam

2. *"Highest"* ultrasonic velocity: 18,500m/s - Diamond

Leaving aside the diversity of materials in general, ceramics alone dictate that a number of ultrasonic sources or transducers be designed for making a wide range of NDC a reality. Modern piezoelectric materials in conjunction with several acoustically active and passive materials developed in our laboratory, have resulted in the formation of a broad range of NDC transducers. Known as *"six basic acoustic series of NDC transducers,"* Table 1 shows their general characteristics and applications. These transducers, spanning in frequency range from <100KHz to >100MHz and in pulse widths from a theoretical minimum of 0.5λ to $>6\lambda$ have been developed and optimized in our laboratory during the last 10 years of ultrasonic applications research.

Those well-versed in the art and practice of ultrasonic NDC are aware that while "controlled" acoustics transducers in frequency range of 500KHz to 20MHz can be relatively easily designed and reproduced. Fabrication of "extremely" low and high frequency devices present their own specific problems. Here, we show examples of a few NDC transducers representing extremes in frequencies. The terms Very Low Frequency (VLF) and Very High Frequency (VHF) are used in an aribitrary manner. We are congnizant of the fact that one involved in the testing of concretes may not necessarily consider 250KHz as being "VLF." Similarly, one working into frequency dependence or microscopy of materials such as sapphire, diamonds, etc., may not consider 75MHz as being "VHF."

Very Low Frequency (VLF) ultrasound

Fig. 4 depicts the time and frequency domain analysis of a wideband 50KHz transducer. The pulsewidth of this device is approximately 2.5λ and bandwidth at -6dB is 60% of the center frequency 50KHz. Fig.5 shows a similar photograph for a 100KHz wideband transducer. Here the pulse width is approximately 2.0λ and bandwidth at -6dB is 66% of the center frequency 100KHz. Figures 6 and 7, respectively show the time and frequency domain analyses of 250KHz broadband and narrowband NDC transducers. Compare the pulse widths - 2.5λ for broadband and ~7λ for

Table 1. General characteristics and applications of six "basic acoustic series" of NDC transducers derived from modern piezoelectric materials and several acoustically active and passive materials surrounding the active piezoelectric elements.

SERIES	FREQUENCY RANGE	BANDWIDTH (% at -6dB)	PULSE WIDTH (λ)	SENSITIVITY (RELATIVE)	APPLICATIONS (GENERAL)
W	<100KHz to >25MHz	50 - 100	1 - 2	MOD-LO	Resolution & velocity
P	<500KHz to >25MHz	40 - 70	2 - 4	MOD-HI	General purpose
K	<100KHz to >20MHz	20 - 50	3 - 6	VERY HI	Deep penetration
M	<100MHz to >100MHz	30 - 100	1 - 6	MOD-HI	VHF
λ	<500KHz to 30MHz	100 - 300	0.5 - 1	LO-MOD	VH resolution & spectroscopy
GA	<1MHz to 100MHz	100 - 200	0.5 - 1.	V. LO	Surface characterization & other uses

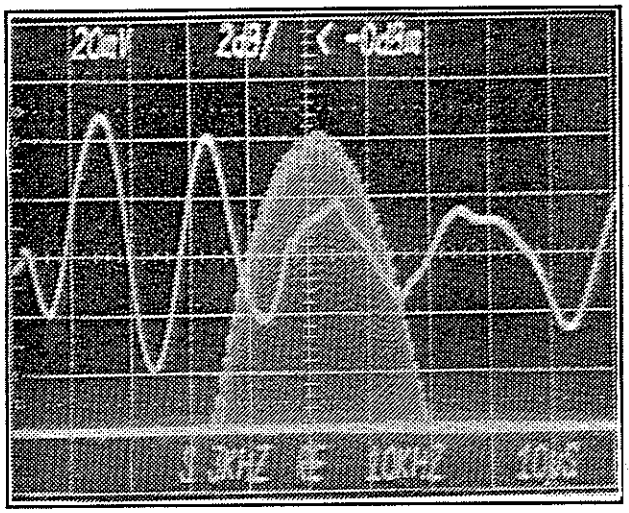

Fig. 4. Time and Frequency domain analysis of a Very Low Frequency (VLF) NDC transducer. Example shown is for a relatively broadband 50KHz ultrasound.
BcF = 50KHz, bandwidth = 60%,
pulse width = 2.5 λor 50μs.

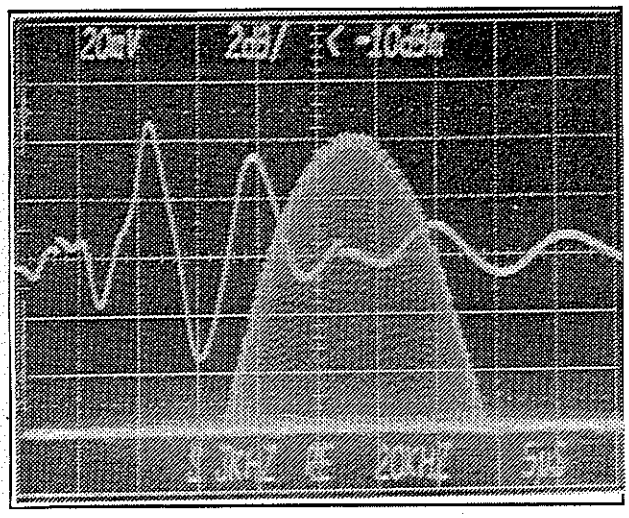

Fig. 5. Another example of VLF Ultrasound. Bcf = 100KHz, bandwidth = 66%, pulse width = ~2.0λ or 20μs.

the narrowband 250KHz device. The bandwidth of the former is 60% and of the latter 25%. It is important to note that the sensitivity of the narrowband (Fig. 7) is approximately 20dB higher than its broadband counterpart (Fig. 6). In very strict practical terms, if a material showed optimum frequency response in the neighborhood of 250KHz, then the narrowband 250KHz transducer would have the highest penetrating power in that material. On the other hand, if high resolution in the same material was required, then the broadband transducer due to its shorter pulse width

would be preferable, but, at the expense of deeper penetration of ultrasound. Very Low Frequency (VLF) transducers are more suitable in the investigation of coarse-grained and attenuative media such as large grain refractories , concretes, C-C and other similar composites.

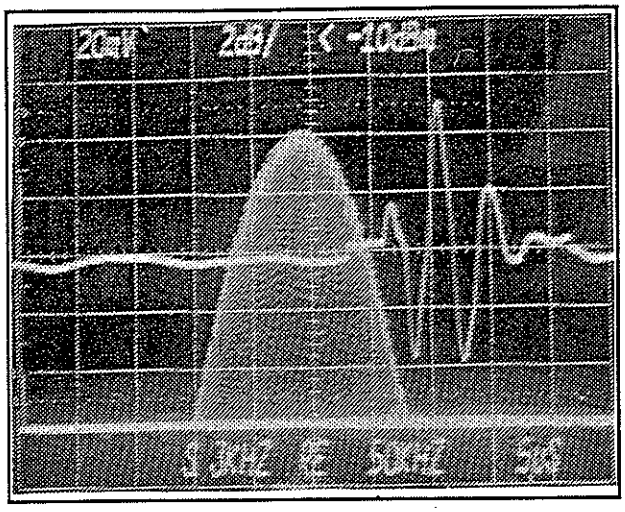

Fig. 6. Time and Frequency domain analysis of a Very Low Frequency (VLF) NDC transducer. bandwidth = Example shown is for a relatively broadband 250KHz ultrasound BcF = 240KHz, bandwidth = 60%, pulse width = 2.5 λor 10μs.

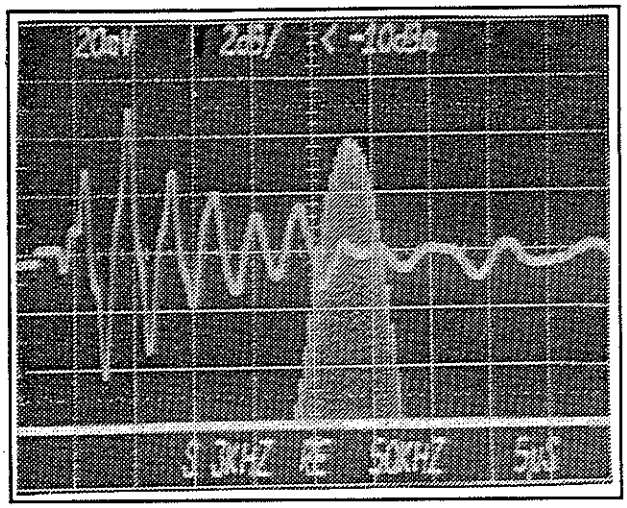

Fig. 7. Example of VLF narrowband Ultrasound 250KHz. Bcf = 270KHz, bandwidth = 25%, pulse width = ~7.0λ or 28μs.

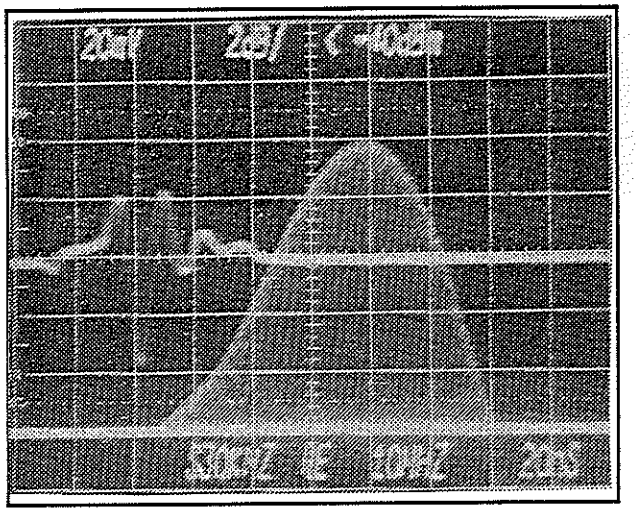

Fig. 8. Time and frequency domain analysis of a Very High Frequency (VHF) NDC transducer. Bcf = 57MHz, bandwidth = 60%, pulse width = 1.5λ or 25ns.

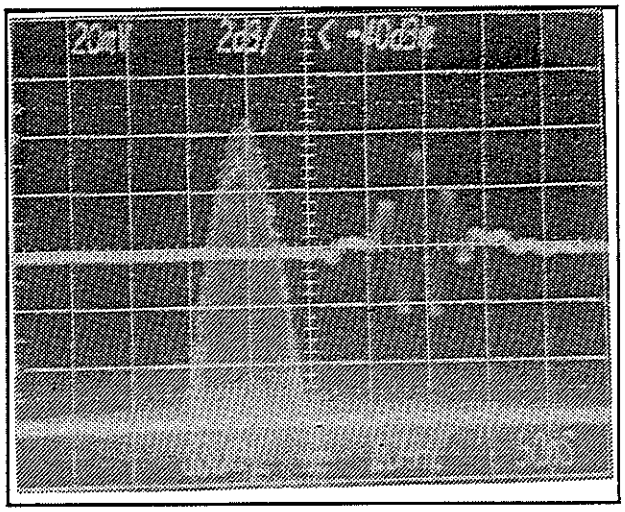

Fig. 9. Example of a relatively narrowband VHF ultrasound. Bcf = 39MHz, bandwidth = 40%, pulse width = 2.0λ or 80ns.

Very High Frequency (VHF) ultrasound

Very high frequency extremes are shown in Figures 8 and 9. Fig. 8 is a real time and frequency domain analysis of a nominally 75MHz device. Here we observe that the pulse width is approximately 1.5λ and bandwidth at -6dB is in the neighborhood of 60% of the observed 57MHz center frequency of this transducer. Fig 9 is a similar photograph for a nominal 50MHz device. The pulse width of this transducer is 2 to 3λ, and bandwidth nearly 40% of the observed 39MHz center frequency. Once again we find that the sensitivity of the shorter pulse width transducer, (Fig. 8) is about 10dB less than the slightly larger pulse width transducer, (Fig.9). VHF and short pulse width devices are suitable for the characterization of dense and relatively thinner materials sections.

Examples cited in this section clearly show that a variety of ultrasonic devices - varying in frequencies, bandwidths, pulse widths, and sensitivities - are now feasible. Since modern industrial materials are based upon diverse combinations of composition and microstructure, recent developments in ultrasound can be gainfully applied for their nondestructive characterization.

CONCLUSIONS

We have defined ultrasonic NDC in light of the guidelines established by the National Research Council (1967) on the characterization of materials. Important elements of ultrasound have been described for the analysis of a wide range of industrial materials. Significance of practical concepts presented here will be undoubtedly determined by their applications into the development and manufacture of materials and components.

ACKNOWLEDGEMENTS

This work was supported by the on-going ultrasonic NDC R&D at Ultran Laboratories.

REFERENCES

1. National Research Council, "Characterization of Materials," U.S. Department of Commerce, National Bureau of Standards, Institute of Applied Technology, Pub. No. MAB-229-M (1967).

2. McMaster, R.C., "Nondestructive Testing Handbook," Vol. I and II, The Ronald Press Co., New York (1963).

3. Vary, A., "Nondestructive Evaluation Techniques' Guide," National Aeronautics Space Agency, Special Pub. No. SP-3079 (1973).

4. Kinsler, L.E., Frey, A.S., Coppens, A.B., and Sanders, J.V., "Fundamentals of Acoustics," John Wiley & Sons, Inc., New York (1982).

5. Bhardwaj, M.C., "Principles and Methods of Ultrasonic Characterization of Materials," *Adv. Cer. Mat.*, Vol. 1, No. 4 (1986).

6. Richardson, L.F., "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.

7. Muhlhauser, O., "Verfahren zur Zustandbestimung von Werkstoffen, besonders zur Ermittlung von Fehlren darin," German Patent Specification 569, 598 January 10, 1931.

8. Bhatia, A.B., "Ultrasonic Absorption, an Introduction to the Theory of Sound Absorption and Dispersion in Gases, Liquids, and Solids," Dover Publication, Inc., New York (1967).

9. Varadan, V.K., Ma, Y., and Varadan, V.V., "A Multiple Scattering Theory for Elastic Wave Propagation in Discrete Random Media," *J.Acous.Soc.A.*, Vol 77, pp 375-85 (1985).

10. McGonnagle, W.J., "Nondestructive Testing," McGraw-Hill Book Company, Inc. New York, (1961).

11. Blitz, J., "Fundamentals of Ultrasonics," Buttersworth, London (1963).

12. Nozdreva, V.F., "Soviet Progress in Applied Ultrasonics," Vol 1, Ultrasound in Industrial Processing and Control, English Translation, Consultants Bureau, New York (1964).

13. Filipczynski, L., Pawlowski, Z., and Wehr, J., "Ultrasonic Methods of Testing Materials,"English translation by Schlachter, K.R. and Blitz, J., Buttersworth, London (1966).

14. Papadakias, E.P., in "Physical Acoustics: Principles and Methods," Vol. XI, Academic Press, New York (1975).

15. Vary, A., "Ultrasonic Measurements of Materials Properties," in Research Techniques in Nondestructive Testing, Vol. IV, Academic Press, New York (1980).

16. Baab, K.A. and Kraner, M.H., "Sonic Method for Determining Young's Modulus of Elasticity," *J.Am.Cer.Soc.*, Vol. 31, No. 11 (1948).

17. Crosby, D.P., "Nondestructive Testing of Fireclay Nozzles by Sonic Technique," *J.Am.Cerm.Soc.*, Vol. 47, No. 7 (1968).

18. Baudran, A. and Deplus, C., "Controle non destructif de la texture des produits refractaires," *Silicates Industriels*, Vol 23 (1958).

19. Ueda, M., "Ultrasonic Testing of Refractories," *The Refractories Journal*, Dec. 1963.

20. Davis, W.R. and Brough, R., "Ultrasonic Techniques in Ceramic Research and Testing," *Ultrasonics*, May 1972.

21. Matveev, V.I., Kozlov, V.P., Paveliev, V.A., Budov, V.M., Seskutov, Yu.V., and Yakupov, V.Sh., "Check of the Thickness of Refractory Brickwork on operating Glass Furnaces," Research Institute of Introscopy; Salvat Technical Glass Plant. Translated from *Stelco i Keramika*, No. 5 (1970), Consultants Bureau, New York.

22. Bhardwaj, M.C., "Determination of the Strength of Refractories by Nondestructive Ultrasonic Methods," A PPG Industries' Research Report No. IP-1102-100 (1976).

23. Oron, I.R.M., Pesach, J., and Rosen, M., "Determination of Grain Size in Uranium-Chromium Alloys by Ultrasonic Attenuation," *J.Mat.Sci.*, Vol. 9 (1974).

24. Gopinathan, K.K. and Padmini, A.R.K.L., "Ultrasonic Studies on Bismuth-Tin Alloys," *J.Phys.Chem.Solids.*, Vol. 35, (1974).

25. Rehwald, W. and Lang, G.K., "Ultrasonic Studies of Phase Transitions in the Tin Telluride-Germanium Telluride System SnxGe1-xTe," *J.Phys.C: Solid State Phys.*, Vol. 8 (1975).

26. Muller, O. and Roy, R., "The Major Ternary Structural Families," Crystal Chemistry of Non-Metallic Materials, Vol. 4, Springer-Verlag, New York (1974).