LOGIC OF ULTRASONIC NONDESTRUCTIVE CHARACTERIZATION*

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ULTRAN LABORATORIES, INC.
Boalsburg, PA USA

**A handout of technical presentation delivered to Framatome Technical Center, St. Marcel, FRANCE on May 6, 1994.*

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ISSUES DISCUSSED

1. Introduction to Ultrasonic NDC
2. Resolution & Detectability
3. Frequency & Materials Dependence of Ultrasonic Attenuation
4. Why Materials Suitable Acoustics & Techniques
5. Velocity Measurements & NDC Examples
6. Ultrasonic Spectroscopy & NDC Examples
7. Limiting Factors of Ultrasonic NDC
8. Transducer Selection Guide
9. Ultrasonic Classification of Materials
10. Conclusions & Recommendations

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1. Introduction to Ultrasonic NDC

Definition
Significance
Status with respect to other materials characterization methods
Generation
Acoustics & Field Parameters

MATERIALS CHARACTERIZATION

"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."

U.S. National Research Council - 1967

NONDESTRUCTIVE CHARACTERIZATION (NDC)

also aims to achieve the same, however, without destroying or altering the original features of material during the analytical process. To this effect, ultrasound presents exciting and promising opportunities.

The ultimate goal of ultrasonic NDC is not merely to detect defects (an old NDT adage), but to prevent them from occurring. This direction is imperative for enhancing materials reliability for safety and economy in our increasingly complex world.

However, unlike conventional methods, **ultrasonic NDC methodology is still under development.** From a practical standpoint, it needs to be understood at a basic level.

SIGNIFICANCE OF ULTRASONIC NDC

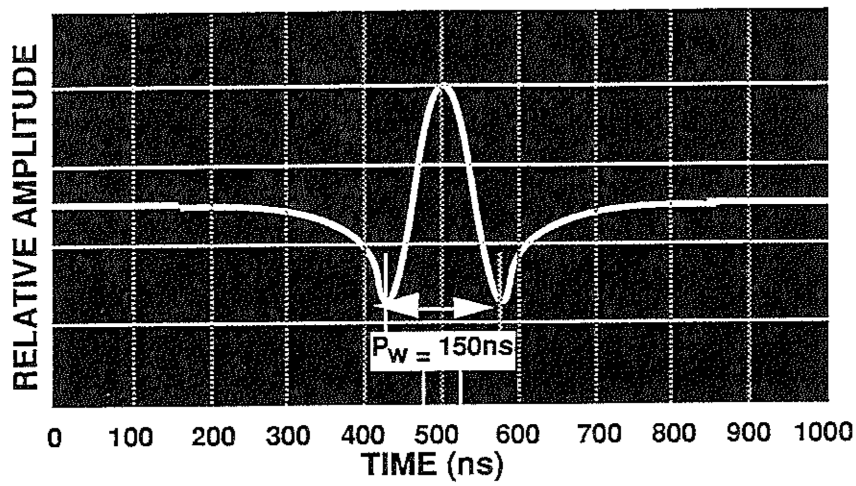
MEASUREMENT CATEGORY	MEASURED PARAMETERS	INFORMATION REVEALED & APPLICATIONS
TIME DOMAIN	Velocities of longitudinal, shear, and surface waves	Density, porosity, defect detection, elastic and mechanical properties, interface analysis, anisotropy, etc.
FREQUENCY DOMAIN	Frequency dependence of ultrasonic attenuation (Ultrasonic Spectroscopy)	Microstructure: grain size and grain boundary relationships, porosity, etc.
IMAGE DOMAIN	Time of Flight, velocity, and attenuation mapping	Surface and internal imaging of defects, microstructure, density, velocity, etc.

Measurement categories and corresponding measured parameters - significant information revealed through their correlation with materials.

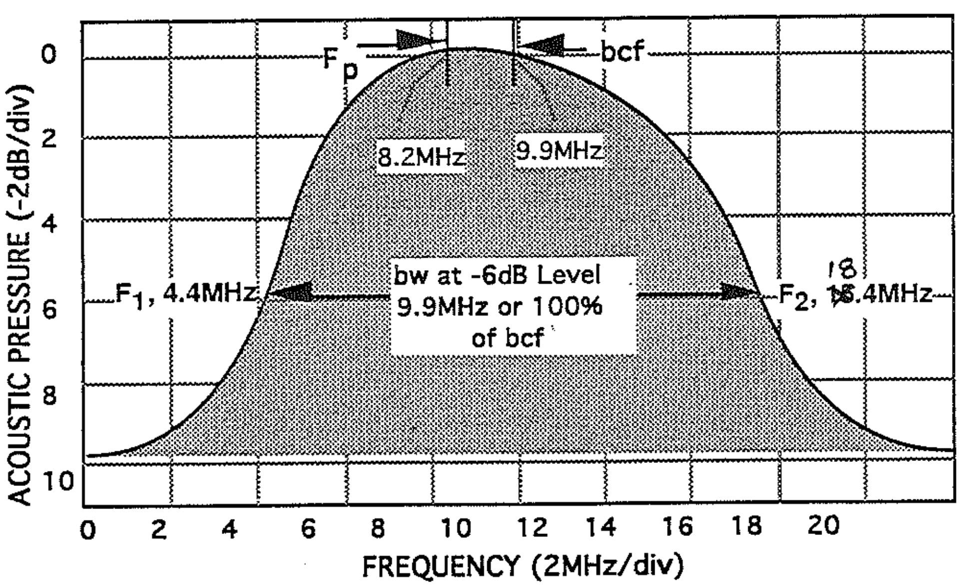
Status of Ultrasonic NDC Method, relative to some other methods - also utilizing wave as the characterizing tool

MATERIALS CHARACTERIZATION BASED UPON (evolution of instruments, techniques, and applications)	STATUS RELATIVE TO TIME		
	PAST (~50 years ago)	PRESENT (from ~25 years to present)	FUTURE
LIGHT (optical microscopy, spectroscopy, etc.)	**Magnification of objects (resolution ~20μm) Use: Limited**	**Magnification to ~1,500X Resolution <1μm Use: Widespread**	***Peaked!***
X-RAY (radiography, diffractometry, spectroscopy, etc.)	**Bone fracture detection (resolution& detectability ~1mm) Use: Limited**	**Diffraction: d-spacing resolution ~2Å Atomic structure & chemical analysis Use: Widespread**	***Saturated!***
ELECTRON BEAM (SEM, TEM, diffraction, microprobe analysis, etc.)	**Foundation of very high magnification microscopy, diffraction, spectrometry, etc.**	**Microscopy: resolution ~1Å Chemical analysis: ppb Use: Widespread**	***Saturated!***
ULTRASOUND (sonar, defects, properties, microscopy, spectroscopy, etc.)	**Range finding, overt defect detection in metals (resolution & detectability ~1mm) Crude use for concrete testing Use: Very Limited**	**Resolution: ~10ns Detectability:~5μm in metals and ~10μm in dense ceramics Elastic properties characterization: Universally feasible Mechanical & Engineering properties: Routinely not feasible, yet. Compositional analysis: None Phase transformation detection: None to very little Use: Limited**	**Needs standardization, reliability (particularly between ~50 - 300KHz and ~30 - >100MHz), and classification with respect to its widespread uses, including compositional analysis. Should be routinely used in QC/QA and materials development functions and other proven applications.**

Acoustic parameters of ultrasound



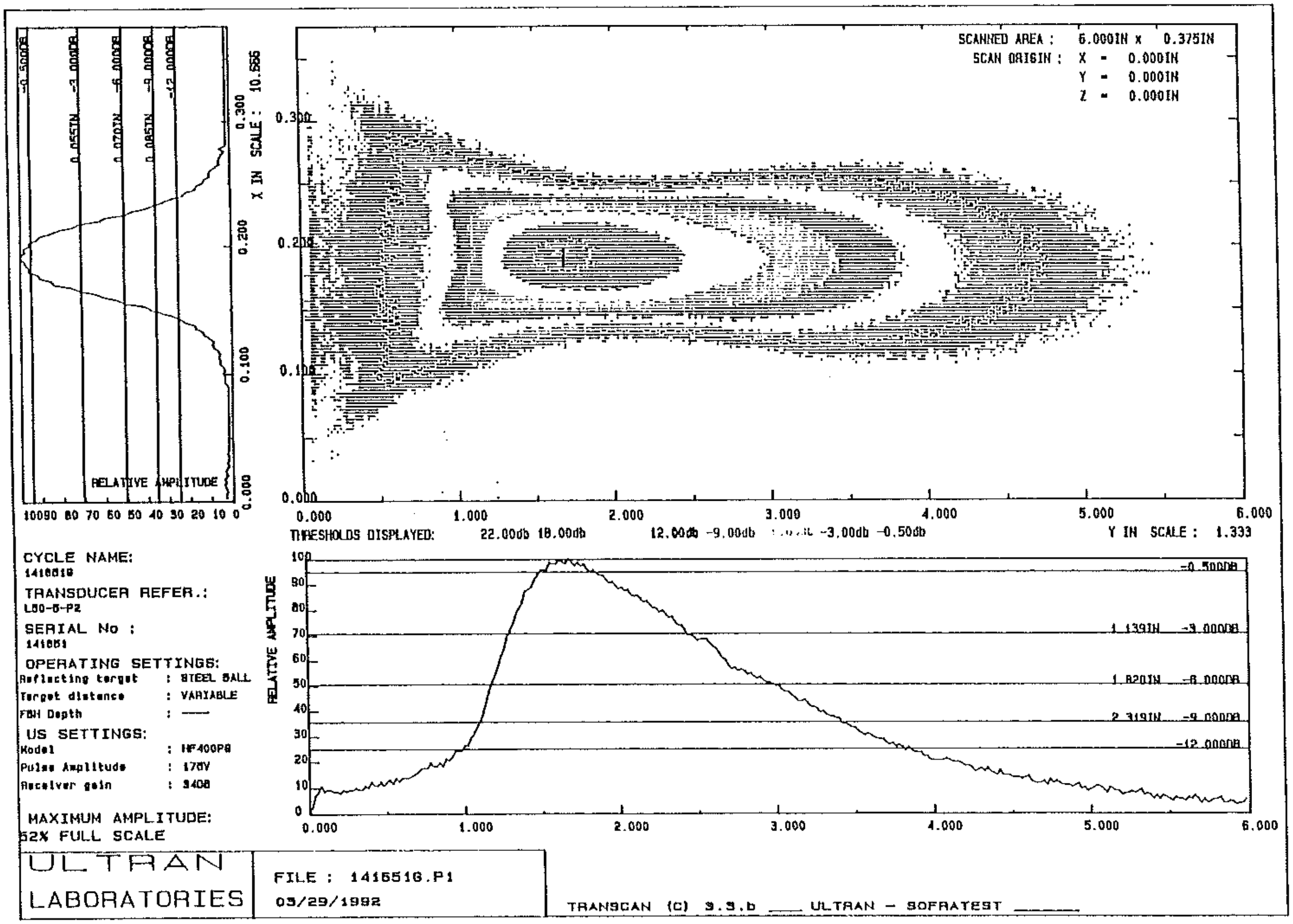
Time Domain Envelope - describing pulse shape and its size. P_W, pulse width



Frequency domain envelope - describing frequencies and their concentration in a given time domain envelope. F_p, peak frequency, bcf, bandwidth center frequency (F_1 + F_2/2), and bw, bandwidth.

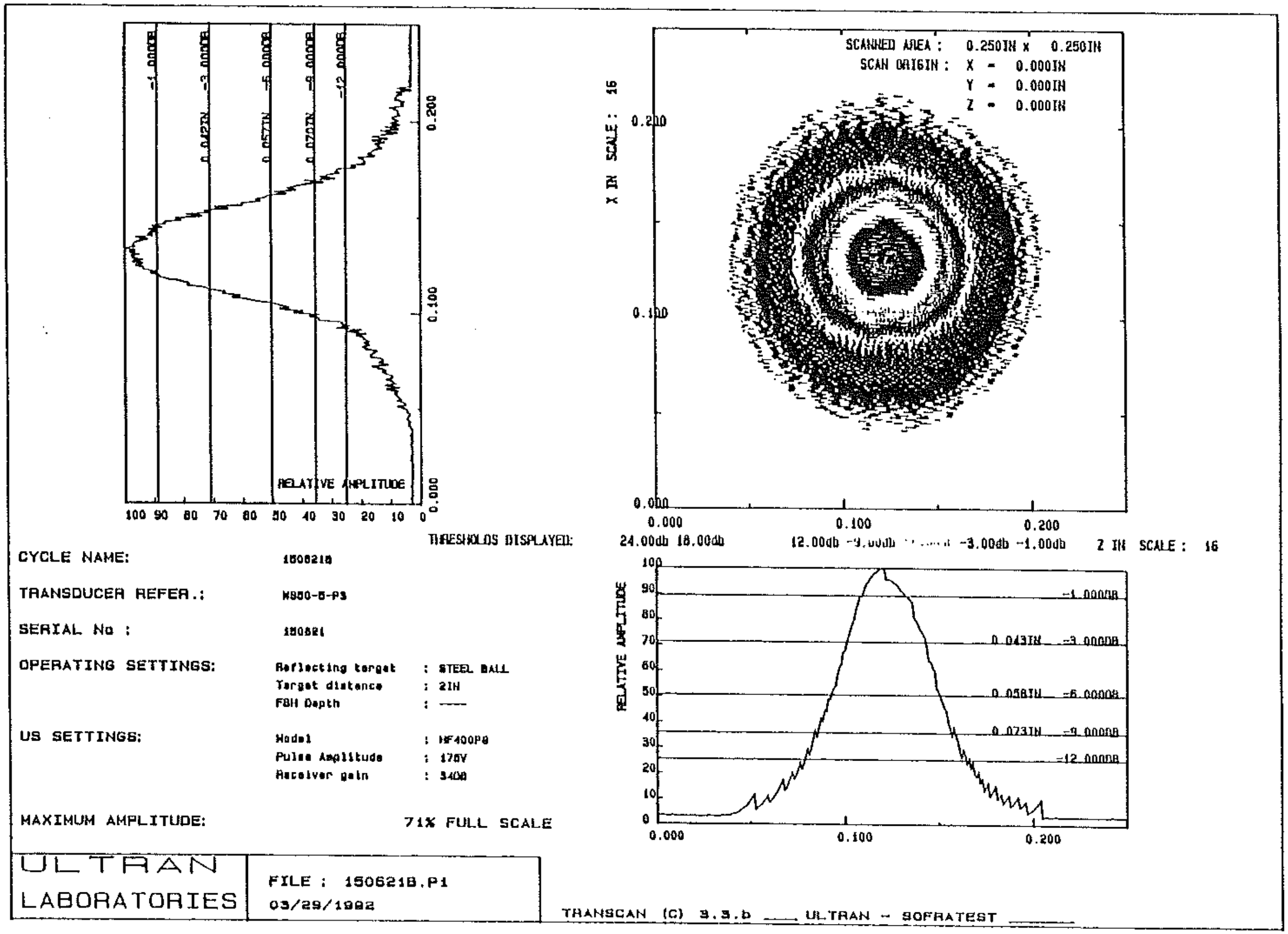
Field of ultrasound

Axial acoustic pressure distribution - along transducer face at varying distance - and its profile. Determines shape and size of ultrasonic field.

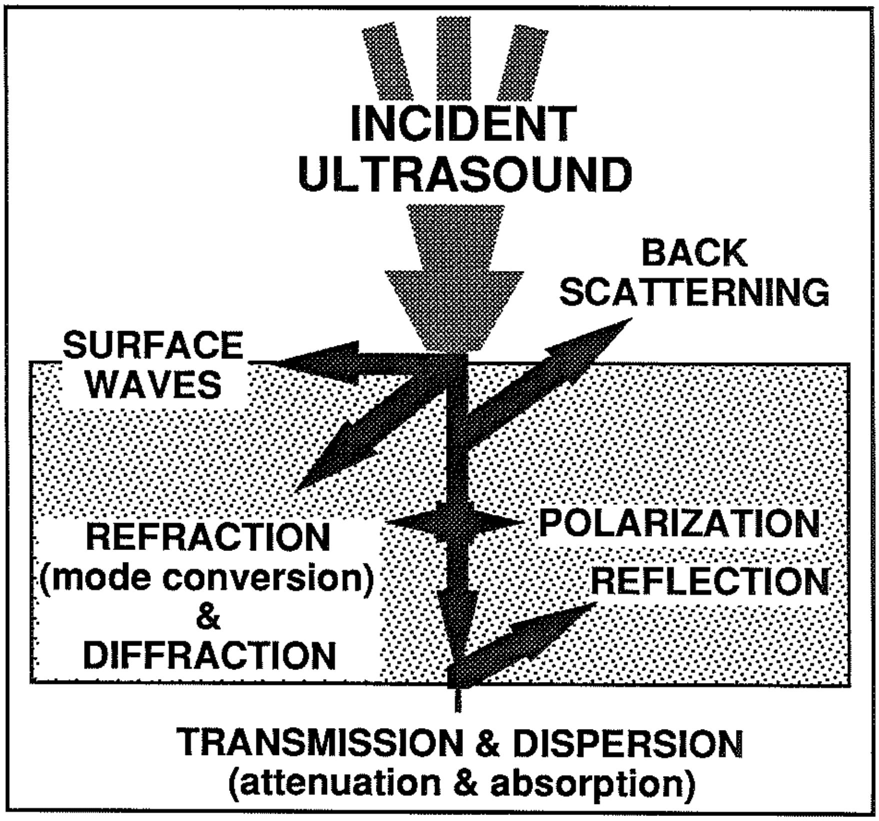


Field of ultrasound

Cross-sectional acoustic pressure distribution - across transducer face at a fixed distance - and its profile. Determines shape and size of ultrasonic field.



What happens when ultrasound "strikes" a material

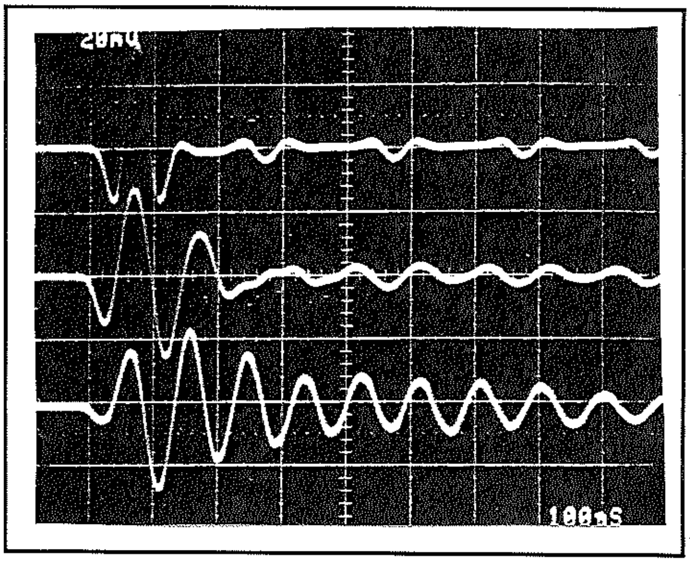


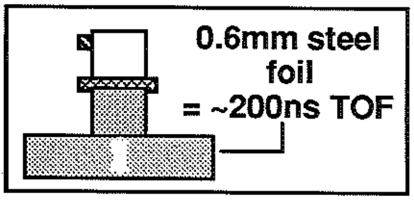
All phenomena are related to various properties and characteristics, including composition, of the material

2. Time Domain - Pulse Width & Resolution

Pulse width and resolution - more than the incident or the marked frequency, it is the pulse width of the system that defines resolution.

Pulse width and resolution





Effect of varying pulse widths on the resolution of top and bottom surfaces of a thin material section. All tests performed by direct reflection technique.

TOP TRACE: Pulse width: 100ns -100% resolution (complete separation of signals from top and bottom surfaces)
MIDDLE TRACE: Pulse width: 200ns - marginal resolution.
BOTTOM TRACE: Pulse width: 300ns - no resolution at all!

Minimum resolvable thicknesses in selected materials (defined by ultrasonic velocities) as a functions of incident pulse widths

MATERIAL CATEGORY/ VELOCITY (m/s)	d_{min} (mm)[1] Incident Frequency (10MHz)				d_{min} (mm)[1] Incident Frequency (20MHz)				d_{min} (mm)[1] Incident Frequency (50MHz)			
	Pulse width (ns)				Pulse width (ns)				Pulse width (ns)			
	0.5λ[2] (50)	1λ (100)	2λ (200)	3λ (300)	0.5λ[2] (25)	1λ (50)	2λ (100)	3λ (150)	0.5λ[3] (10)	1λ (20)	2λ (40)	3λ (60)
6,000[4]	0.15	0.3	0.6	0.9	0.075	0.15	0.3	0.45	0.03	0.06	0.12	0.18
12,000[5]	0.3	0.6	1.2	1.8	0.15	0.3	0.6	0.9	0.06	0.12	0.24	0.36

[1]Minimum thickness that can be resolved when direct reflection technique is used - TOF corresponds to "round-trip" through test material.

[2]0.5 to 0.75 wavelength pulse widths are possible from "critically" damped and acoustically matched Lambda and piezo-film transducers.

[3]Half wavelength pulse width at 50MHz and beyond is unknown.

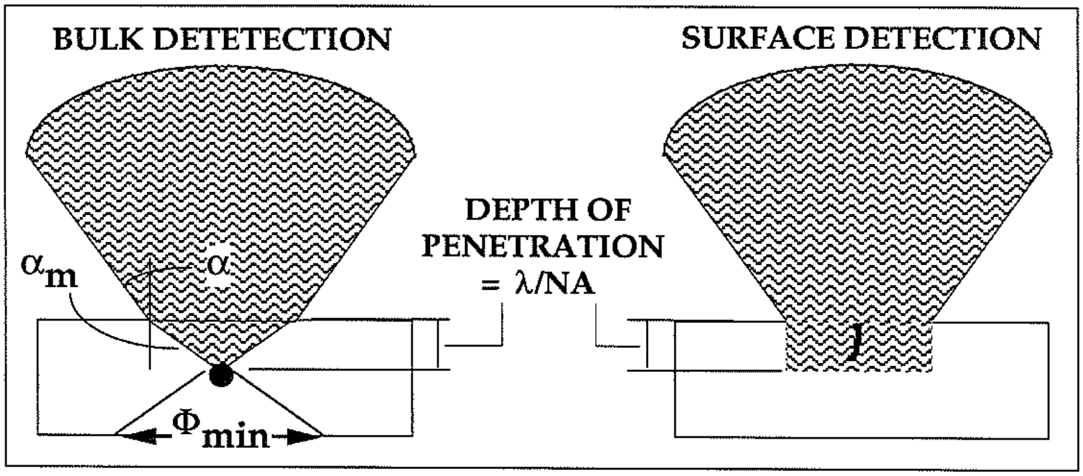
[4]Materials such as fibrous and particulate ceramic composites, powder metals, medium porosity ceramics, steels, aluminum, etc.

[5]Materials such as oxides, carbides, nitrides, and borides of metals and non-metals, diamond, sapphire. etc.

DETECTABILITY

The smallest discontinuity detected by an ultrasonic wave. It is a function of wavelength and the size of the interrogating beam.

Utilization of High Power Geometrical-Acoustics for extremely high detectability.



$$\Phi_{min} = 2K\,(0.003\lambda^2/NA)^{1/2}$$

(a semi-empirical relationship)

λ = Wavelength in test material, or medium of propagation

K = Proportionality Constant, >1

N.A. (Numerical Aperture)

= 2 sinα_m for bulk detection, and

= 2 sinα for surface detection

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DETECTABILITY LIMITS

Utilization of High Power Geometrical-Acoustics for extremely high detectability.

FREQUENCY (MHz)	BULK DETECTABILITY[1] Φ_{min} (µm)				SURFACE DETECTABILITY[4] Φ_{min} (µm)	
	MATERIALS OF VELOCITY 6,000m/s[2]		MATERIALS OF VELOCITY 12,000m/s[3]			
	Max	Realistic	Max	Realistic	Max	Realistic
25	25	50	50	100	6	10
50	13	25	25	50	3	5
75	9	18	18	36	2	3
100	6	12	12	25	1.5	2
150	5	10	10	20	1	1.5

1. Based on NA = 1.
2. Example Materials: Metals, Alloys, glasses, alumino-silicates, etc.
3. Example Materials: Dense Oxides, carbides, nitrides, and their composites.
4. Based upon NA = 1 and water as medium of propagation.

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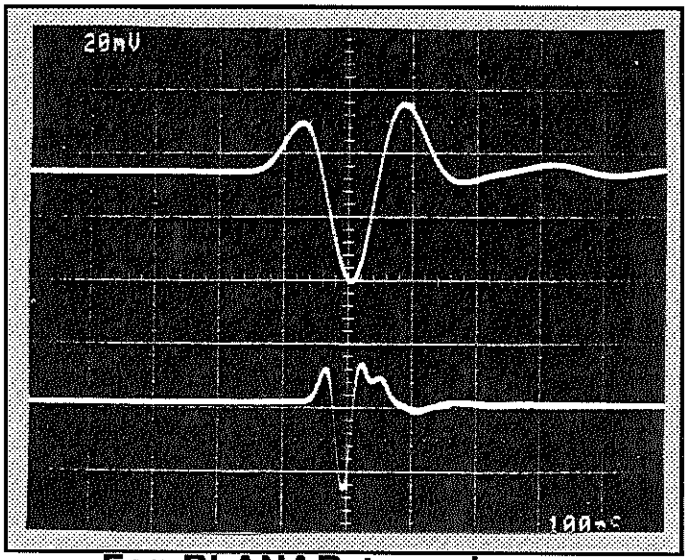
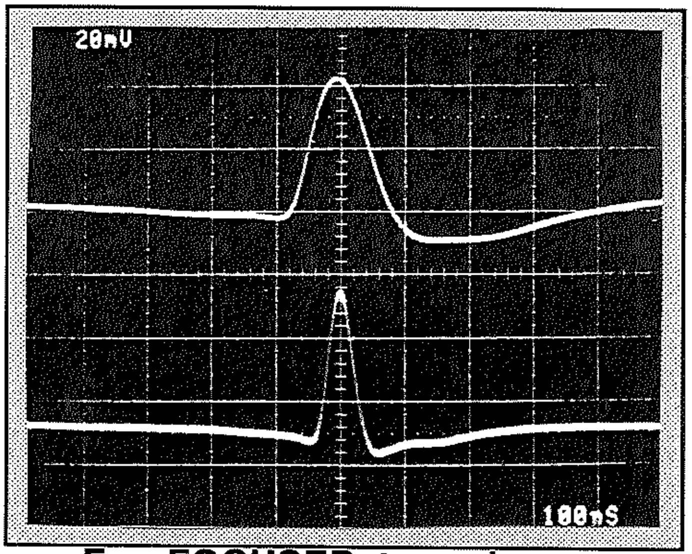
Examples of "shortest possible pulse widths



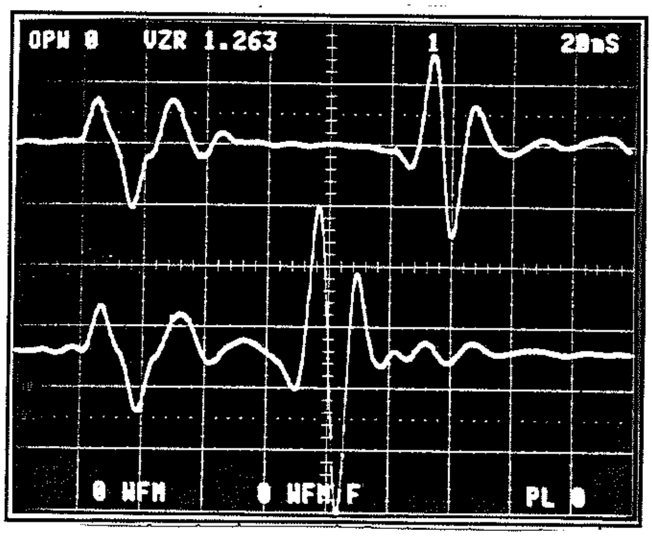
For PLANAR transducers
TOP TRACE: Nominal frequency - 5MHz, Pulse width - ~160ns
BOTTOM TRACE: Nominal frequency - 10MHz, Pulse width - ~70ns



For FOCUSED transducers
TOP TRACE: Nominal frequency - 5MHz, Focal length - 63mm, Pulse width - ~150ns.
BOOTM TRACE: Nominal frequency - 10MHz, Focal length: 19mm, Pulse width - ~55ns.

GENERATION OF SURFACE WAVES BY HIGH POWER (HIGH NA) AND VERY HIGH FREQUENCY ULTRASONIC TRANSDUCERS

TRANSDUCER DESCRIPTION: MDS12-100-N1.2: A NOMINAL 100MHz IMMERSION TRANSDUCER WITH 3.2mm ACTIVE AREA DIAMETER AND 1.2NA THROUGH ~4μs OPTICAL QUALITY CFQ.



Top Trace: Longitudinal (left) and Surface (right) waves in a dense Al_2O_3 plate.

Bottom Trace: Longitudinal (left) and Surface (right) waves in a dense Si_3N_4 plate.

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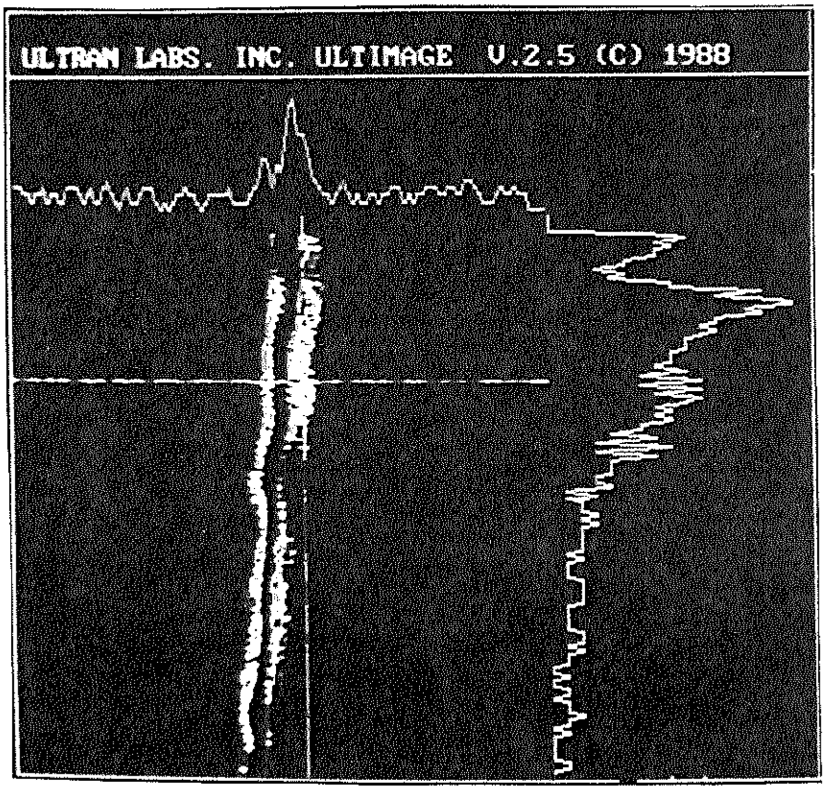
SURFACE DETECTABILITY BY HIGH POWER (HIGH NA) AND VERY HIGH FREQUENCY ULTRASONIC TRANSDUCERS

TRANSDUCER DESCRIPTION: GA25-25-N1: A NOMINAL 25MHz GEOMETRICAL-ACOUSTICS IMMERSION TRANSDUCER WITH 6.3mm ACTIVE AREA DIAMETER AND 1.0NA THROUGH DIRECT FOCUSING



Detection of ~10μm surface-breaking crack in a dense BeO electronic substrate.

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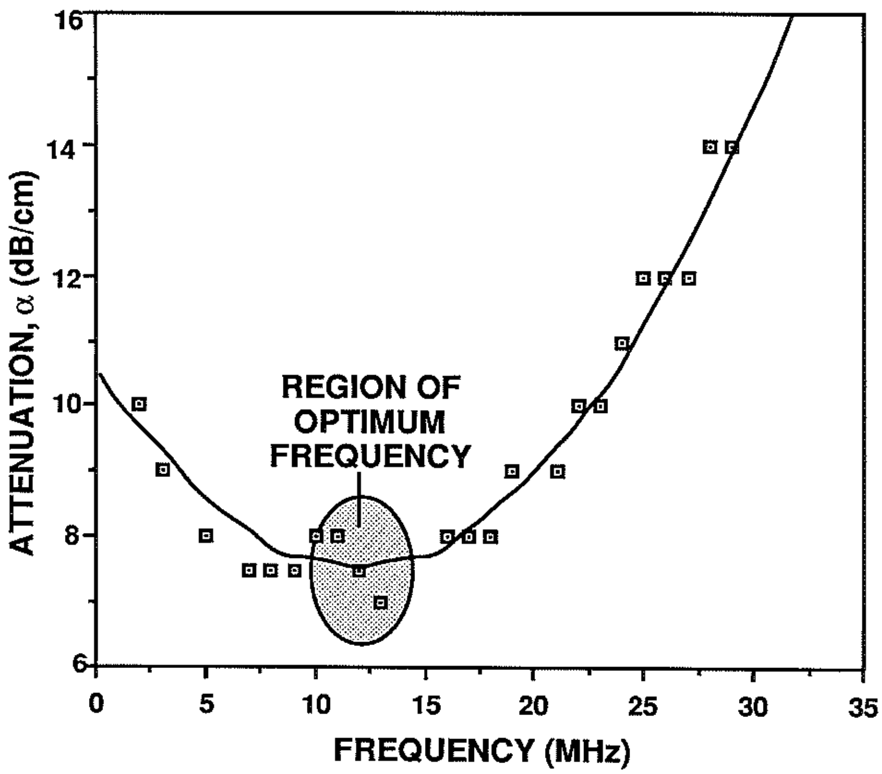
3. Frequency & Materials Dependence of Ultrasonic Attenuation

Frequency dependence - attenuation as a function of frequency

Materials dependence - attenuation of a given frequency by different materials

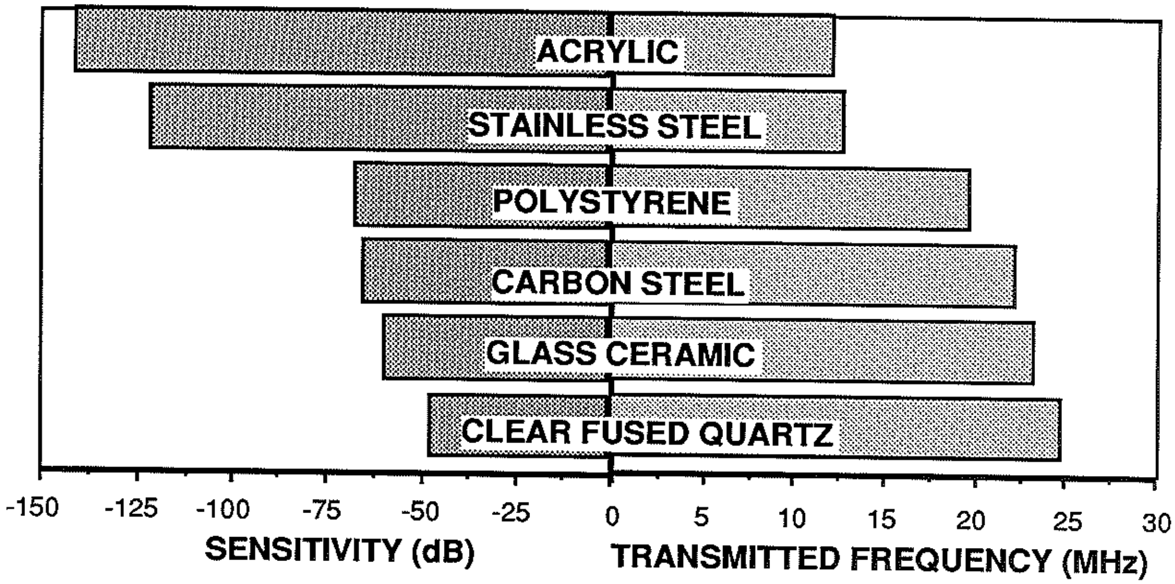
Useful relations for ultrasonic NDC

Frequency-Dependence of Ultrasonic Attenuation



Frequency-dependence of attenuation and determination of "optimum" frequency. Example shown is for a microstructurally complex stainless steel. The shaded region shows the frequency range suitable for the evaluation of this material on account of its "minimum" attenuation.

Material-Dependence of Frequency Attenuation



Effect of 25MHz input frequency into various materials. All samples are 1.0cm thick. Note as the transmitted frequency decreases, so does its sensitivity (output).

4. Why Materials Suitable Acoustics and Techniques?

Acoustics diversity of materials - as the composition, microstructure, and state of material (which modern ultrasound is capable of analyzing) vary so is the necessity of suitable acoustics and technique - both important from the standpoint of NDC reliability and accuracy.

Acoustic Diversity of selected materials as a function of composition and microstructure*

MATERIAL	PREPARATION CONDITION	POROSITY %	LONGITUDINAL VELOCITY (m/s)	ACOUSTIC IMPEDANCE ($x10^5 g/cm^2 \cdot s$)	FREQUENCY ATTENUATION (Relative)
Al_2O_3 (dense)	Green	<1	1,600	2.4	V. High
	Sintered		10,600	43.0	V. Low
Al_2O_3 (porous)	Green	30	1,300	1.7	V. High
	Sintered		7,100	19.9	Low
Fused Silica (refractory)	Sintered	20	4,100	10.25	V. High
ZrO_2 (refractory)	Green	15	2,900	11.0	V. High
	Sintered		5,500	35.5	High
Ceramic Ferrite	Green	2	1,100	2.0	V. High
	Sintered		6,800	37.0	High
WC	Green	<1	1,400	2.8	V. High
	Sintered		9,500	114.0	Low
YBC Superconductor	Green	<10	1,100	1.9	V. High
	Sintered		4,500	29.0	High
SiC (single phase)	Sintered	<1	12,000	37.5	V. Low
SiC (composite)	Sintered	<5	7,500	18.0	Low
Si_3N_4 (single phase)	Sintered	<1	11,000	33.5	V. Low
Si_3N_4 (composite)	Sintered	<5	6,500	15.3	Low
Rigid Porous Ceramic	Sintered	>80	400	0.04	V. High
AZS (refractory-skin)	Fusion-cast	~5	7,100	46.0	Low
AZS (refractory-int.)	Fusion-cast	~7	6,700	43.5	High
Diamond	?	0	18,500	64.7	V. Low
Isotropic graphite	Graphitized	<2	2,900	4.9	Low
2D C-C composite (along planes)	Graphitized	~15	7,300	12.6	Low
2D composite (across planes)	Graphitized	~15	2,200	3.7	V. High
Pyrolytic graphite (a-b)	CVD	--	4,815	10.6	High
Pyrolytic graphite (c-c)	CVD	--	3,350	7.4	Low
Roadway Concrete	Chem. Bonded	~30	4,000	8.0	V. High

*Reliable NDC requires applications of acoustic parameters that are suitable to the physical characteristics and compositions of test materials.

Materials suitable acoustics -

explained by "suitability" and "unsuitability" of selected ultrasonic characteristics as functions of two compositionally and microstructurally varying materials.

EXAMPLE MATERIAL	PARTICLE SIZE	THICKNESS (mm)	VELOCITY (m/s)	SAMPLE TOF[1]	SELECTED ULTRASONIC CHARACTERISTICS			
					1MHz (PW - 1μs)[2]		20MHz (PW - 50ns)[2]	
					λ[3]	SUITABILITY	λ[3]	SUITABILITY
Fused Silica (direct-bonded)	50μm - >1mm	19	4,100	9.3 μs	4.1mm	**OK[4]**	0.205mm	**NO[6]**
SiC (dense)	sub-micron	1	12,000	170ns	12.0mm	**NO[5]**	0.6mm	**OK[7]**

[1]TOF - Round Trip Time-Of-Flight when DIRECT REFLECTION technique is applied.

[2]PW - Pulse Width, assumed one period at the specified frequency.

[3]λ - Wavelength in example material at the specified frequency. v/f.

[4]At 1MHz PW is small enough for resolution and accurate TOF measurement, besides at this frequency there is no significant attenuation by this material.

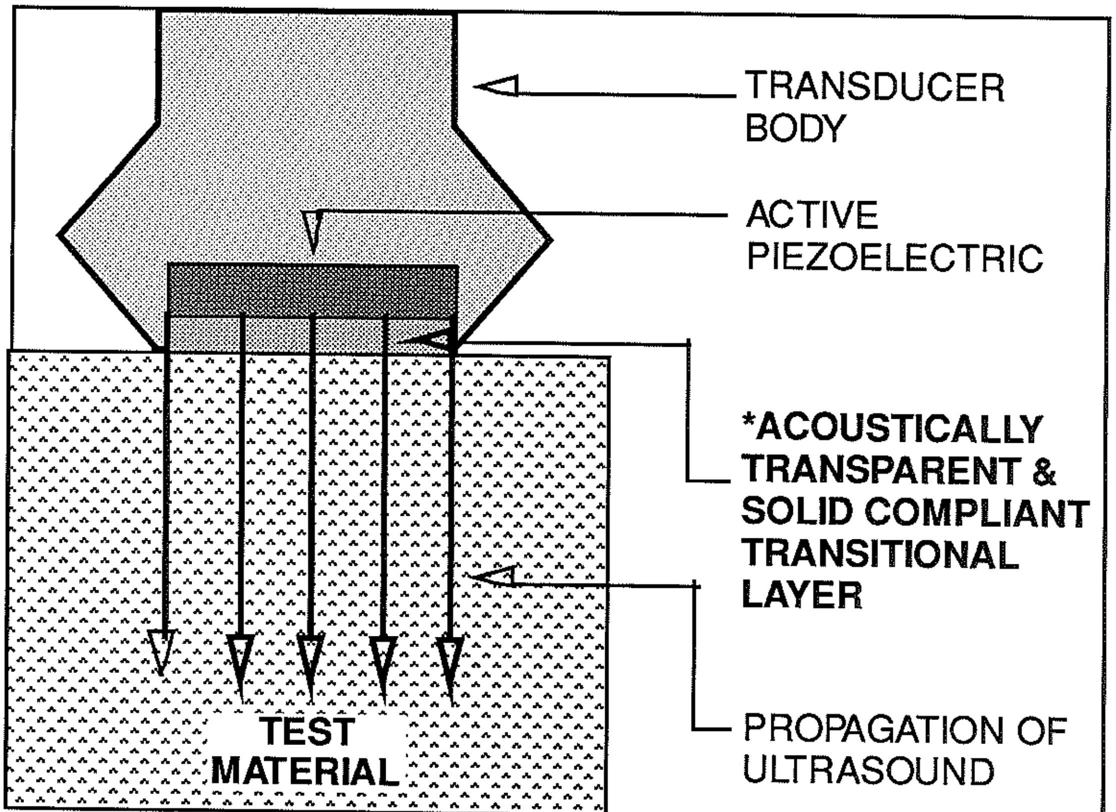
[5]At 1MHz PW (1μs) is too large to interrogate this material, the TOF of which is only 170ns.

[6]The coarse-grained texture of this material will almost completely attenuate 20MHz frequency.

[7]At 20MHz PW (50ns) is small enough for resolution and accurate TOF measurement of this material.

Materials suitable technique

provided by the elimination of liquids as ultrasound coupling media



*This matching layer efficiently transfers ultrasound from the active piezoelectric into the test material without liquid coupling. Longitudinal and shear wave devices based upon this concept have been successfully produced from <100KHz to >25MHz. DRY COUPLING is the logical route for the NDC of GREEN, POROUS, & LIQUID-SENSITIVE MATERIALS.

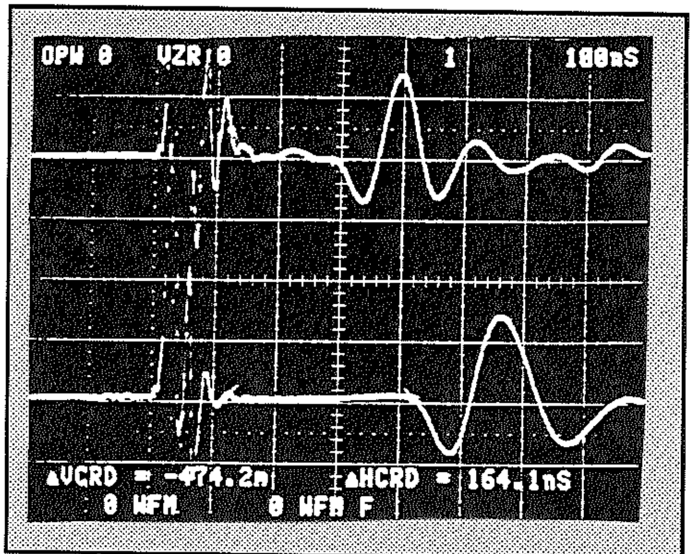
Transducer coupling methodology as a function of test materials characteristics

TEST MATERIALS & THEIR CHARACTERISTICS	TRANSDUCER COUPLING SUITABILITY
All impervious, closed porosity, and liquid-insensitive materials (dense ceramics, metals, single crystals, glasses, and other like materials.	***WET or DRY***
All open porosity, green, and liquid-sensitive materials. (porous ceramics, ceramic electrolytes, porous composites, and other liquid-sensitive materials.	***DRY***

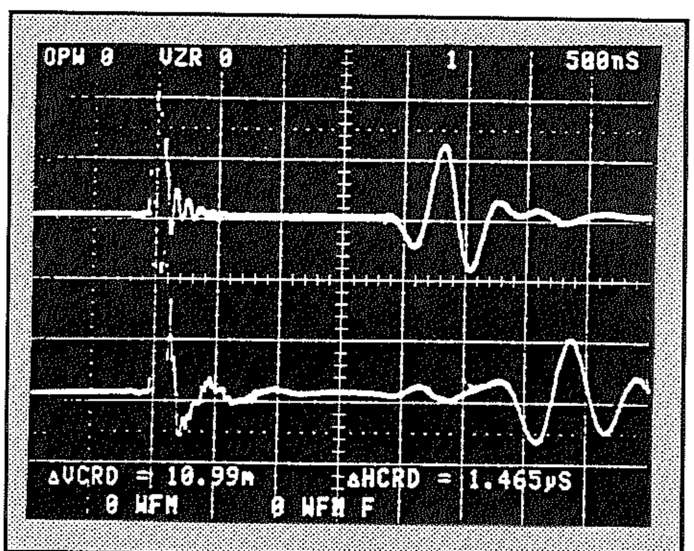
5. NDC Examples From Velocities Measurements

Measurement of Longitudinal& shear wave velocities
NDC of microstructurally diverse sintered materials
NDC of green materials
Numerous examples of ceramics, including composites, superconductors, and other materials for elastic properties characterization

Propagation of longitudinal & shear waves and measurement of their velocities



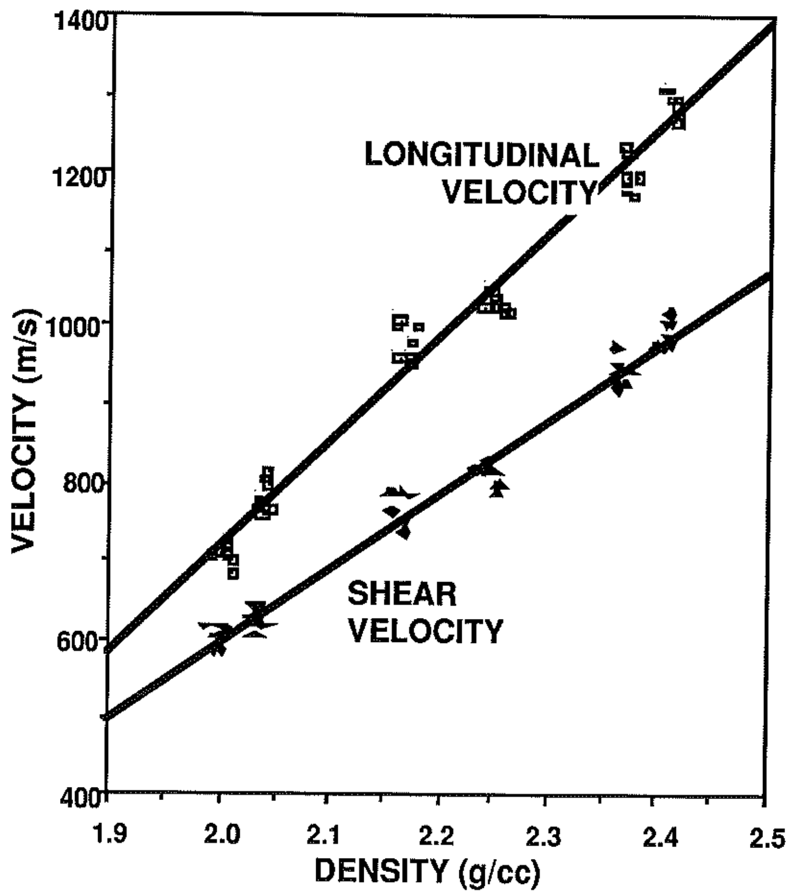
Sintered material example: dense BeO substrate, 2.16mm
TOP TRACE: Longitudinal wave velocity: 13,160m/s
BOTTOM TRACE: Shear wave velocity: 7,200m/s



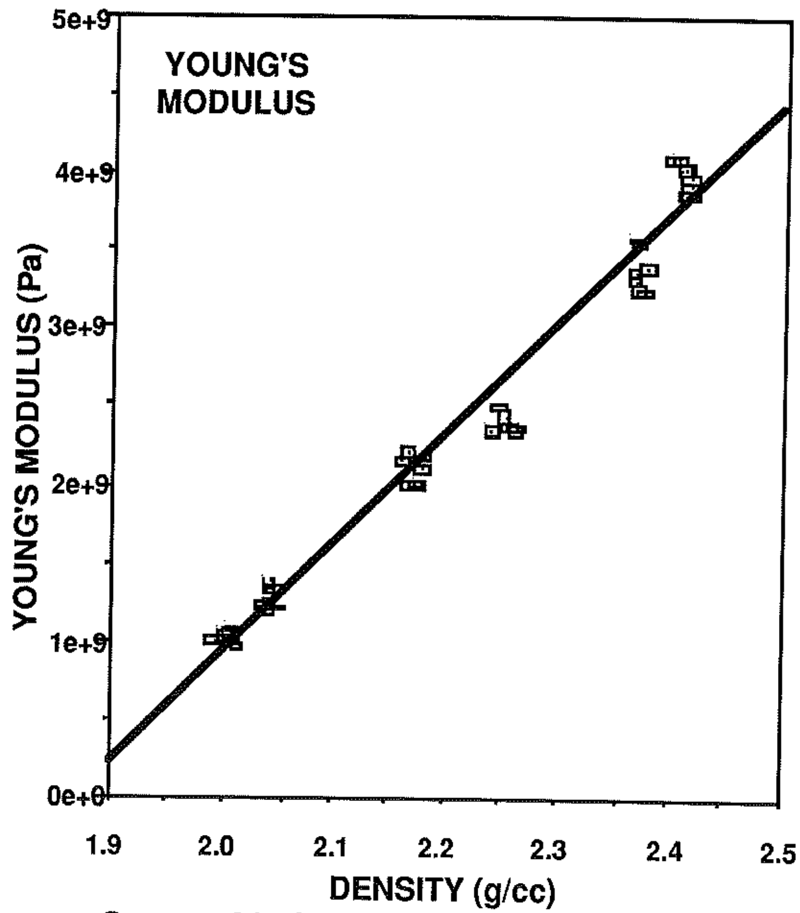
Green material example: Al_2O_3 substrate, 2.28mm
TOP TRACE: Longitudinal wave velocity: 1,565m/s
BOTTOM TRACE: Shear wave velocity: 1,140m/s

Green material NDC

From measurement of ultrasonic velocities



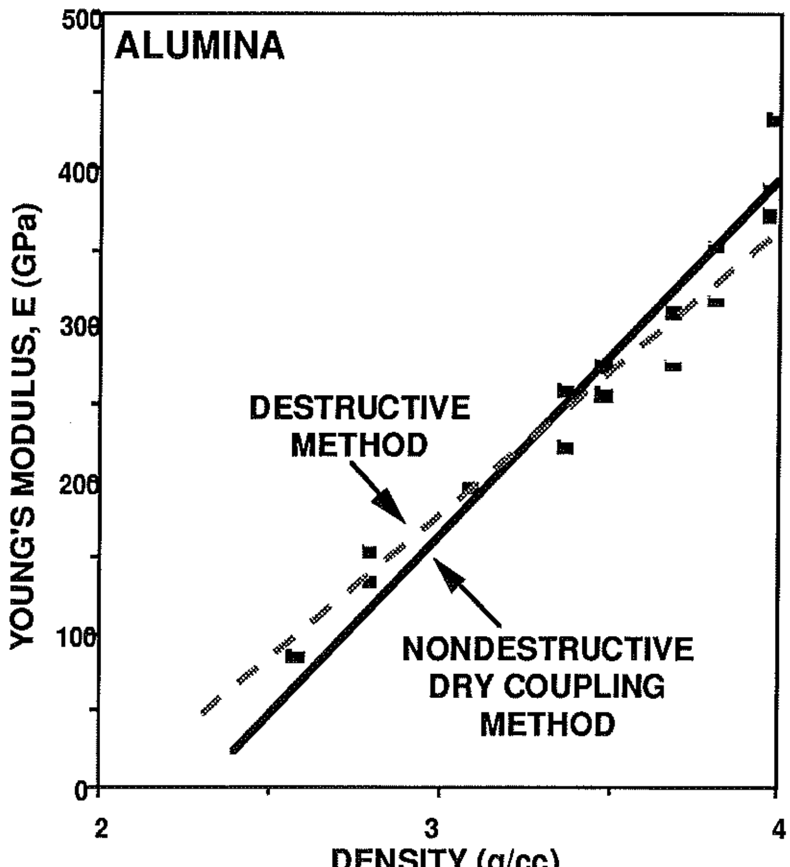
Green Al_2O_3 - density vs. longitudinal and shear wave velocities relationships.

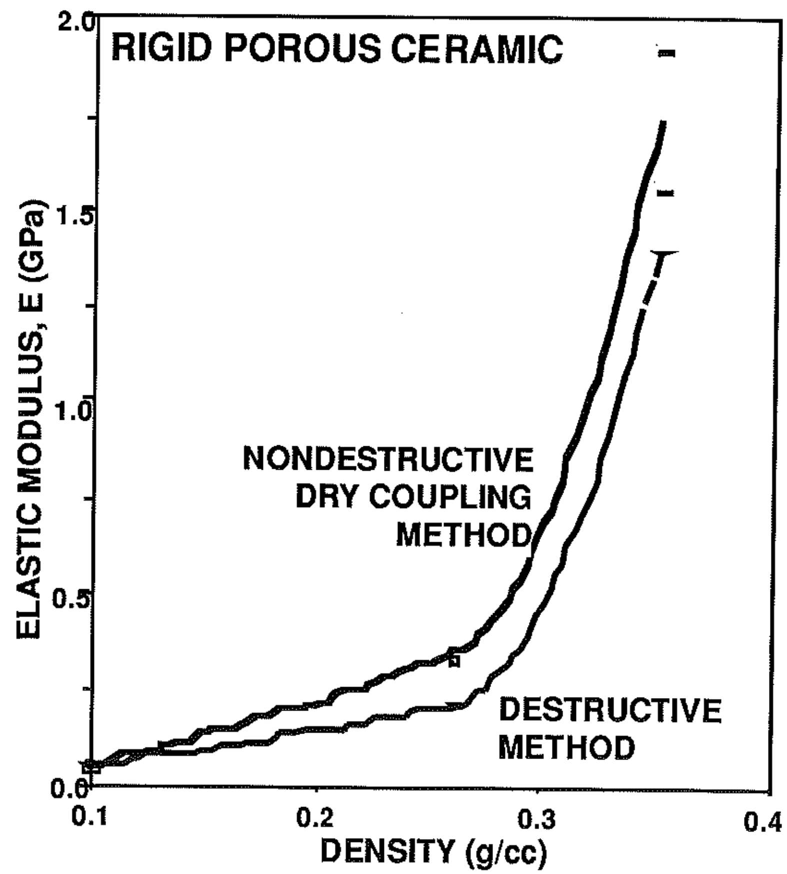


Green Al_2O_3 - determination of Young's Modulus from left hand figure data.

Sintered materials' NDC

From measurement of ultrasonic velocities





Comparison of destructively (4-point bending method) and nondestructively (DRY COUPLING ultrasonic method) determined modulus of DENSE and POROUS ceramics.

Sintered Al_2O_3 varying from ~70 to 100% theoretical density.

"Ultra" porous ceramic preforms with 50 to >80% porosity.

Elastic properties of single and multiphase SiC and Si_3N_4

Obtained from the measurement of ultrasonic velocities

MATERIAL	DENSITY (g/cc)	VELOCITY (m/s) LONGITUDINAL	SHEAR	ELASTIC MODULI (GPa) E	G	K	POISSON'S RATIO σ
SiC - Single Phase	3.01	11,500	7,320	374	161	184	0.161
	3.09	11,800	7,530	406	175	198	0.159
	3.15	12,050	7,700	431	186	210	0.157
SiC - Composite*	2.37	7,480	4,640	121	51.1	64.8	0.186
	2.40	7,540	4,750	126	54.0	64.2	0.172
Si_3N_4 - Single Phase	3.05	11,050	6,225	299	118	215	0.268
Si_3N_4 - Composite*	2.30	6,390	4,010	86.6	36.9	44.3	0.174
	2.35	6,540	4,020	90.8	38.0	50.0	0.196

*Second phase, presumably amorphous.

Elastic properties of single and multi-phase YBCO superconductors

Obtained by measurement of ultrasonic velocities.

SAMPLE	VELOCITY Longitudinal m/s	Shear m/s	ρ kg/m3	E GPa	G GPa	K GPa	σ
YBC-2 *(single phase Tc: 93K)*	4590	2540	5,580	92.0	36.0	69.0	0.279
YBC-3 *(single phase Tc: 87K)*	4490	2660	5,370	93.0	38.0	58.0	0.231
YBC-4 *(multi-phase superconducting)*	3290	1960	4,150	39.0	16.0	23.5	0.224
YBC-5 *(multi-phase poor superconductor)*	3770	2210	4,980	60.0	24.0	38.0	0.237
COPPER	4690	2240	8,710	118.0	44.0	133.0	0.351

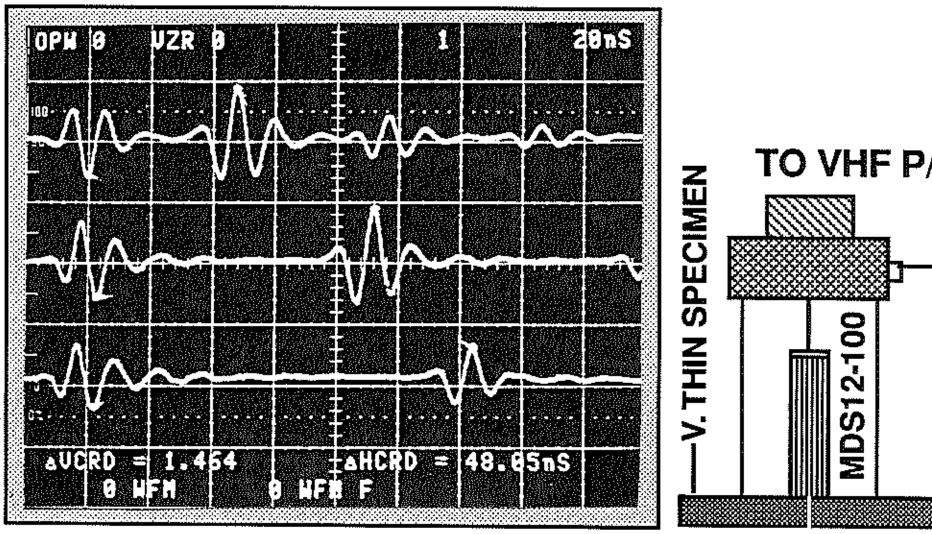
ρ, Density; E, Young's modulus; G, Shear modulus; K, Bulk modulus; σ, Poisson's Ratio

Ultrasonically Characterized Properties of Selected Porous, Dense, & Anisotropic Materials

MATERIAL	VELOCITIES TRANSDUCER (m/s) LONG.	SHEAR	MODULUS (GPa) YOUNG	SHEAR	BULK	POISSON'S RATIO σ	FREQUENCY (MHz) LONG.	SHEAR
SiC (Dense)	11,820	7,500	397	180	200	0.170	20	10
SiO_2 (Slip Cast Refractory)		4,140	2,740	30	13	13	0.110	1 1
Float Glass	5,815	3,460	72	30	44	0.230	10	10
BeO (Dense)	12,190	7,360	396	162	227	0.210	20	10
$Al_2O_3+ZrO_2+SiO_2$ (Refractory)	6,880		4,210	158	65	88	0.200	2 1
Graphite (Isotropic)	3,075	1,610	12.5	4.8	10	0.290	5	2
C-C (2D Carbon-Carbon Comp.) Along fibers		7,500	---	100	---	---	---	2 1
C-C (2D Carbon-Carbon Comp.) Across fibers		1,750	---	8.0	---	---	---	1 0.5
Diamond (Ind.)	18,770	12,100	1,176	514	551	0.144	50	20

NDC of "very thin and very high velocity" materials

Obtained by the application of VHF (~100MHz) - controlled pulse width ultrasound



TOP TRACE: 0.44mm industrial diamond

Velocity: 18,500m/s

MIDDLE TRACE: 0.39mm Si wafer

Velocity: 8,640m/s

BOTTOM TRACE: 0.64mm Al_2O_3 Substrate

Velocity: 10,535m/s

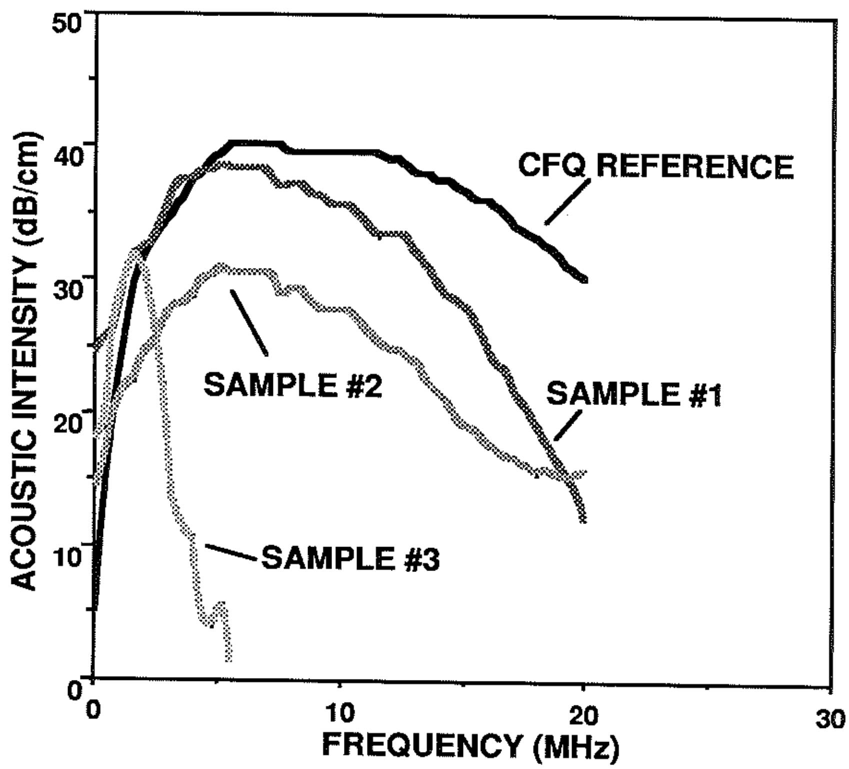
(Extreme left signal in all traces corresponds to transducer-material interface.)

6. NDC Examples of Ultrasonic Spectroscopy

Wideband ultrasonic spectroscopy method
Examples of particle, phase, microstructure, and anisotropy characterization in various single and multi phase materials

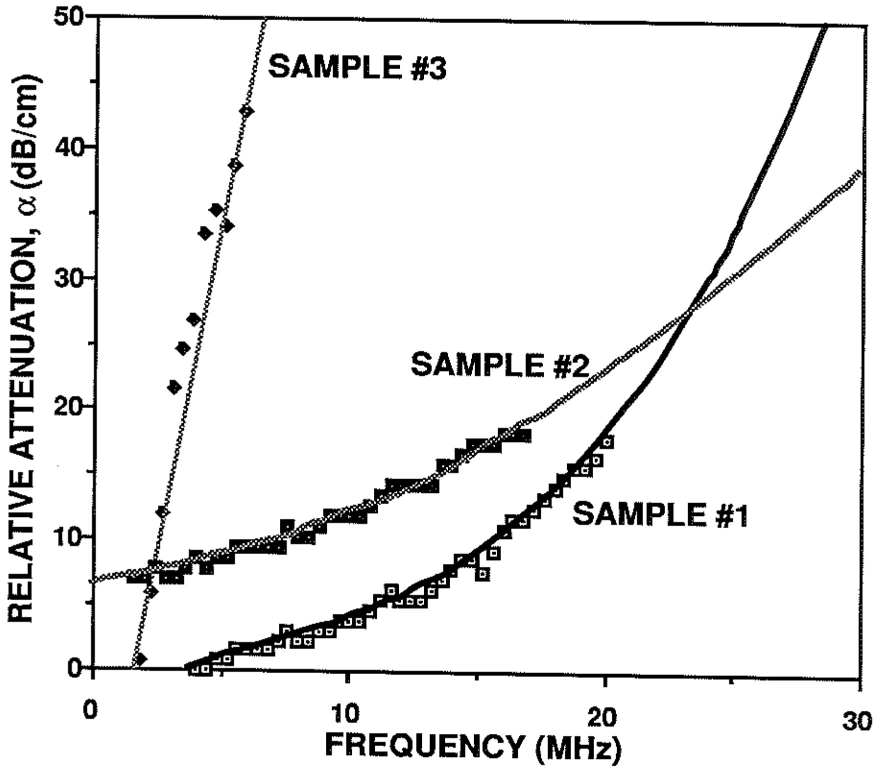
Frequency domain analysis

Wideband Ultrasonic Spectroscopy of materials, relative to optical grade Clear Fused Quartz



Frequency dependence of ultrasonic attenuation

Obtained by subtracting sample spectra from that of reference clear fused quartz



Microstructure characterization of single phase YBCO superconductors

Obtained by Wideband Ultrasonic Spectroscopy

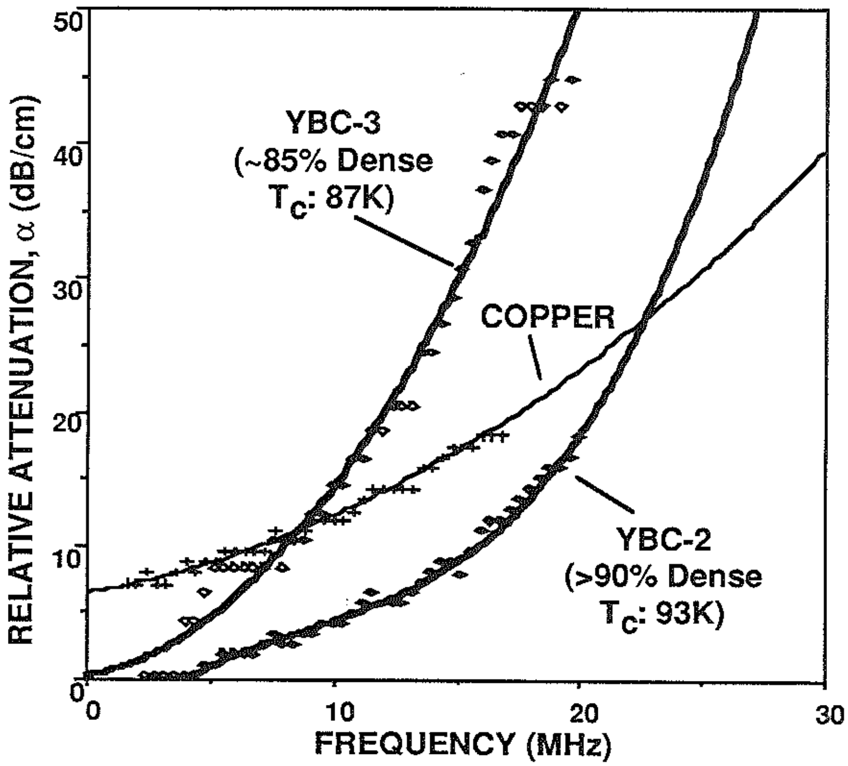
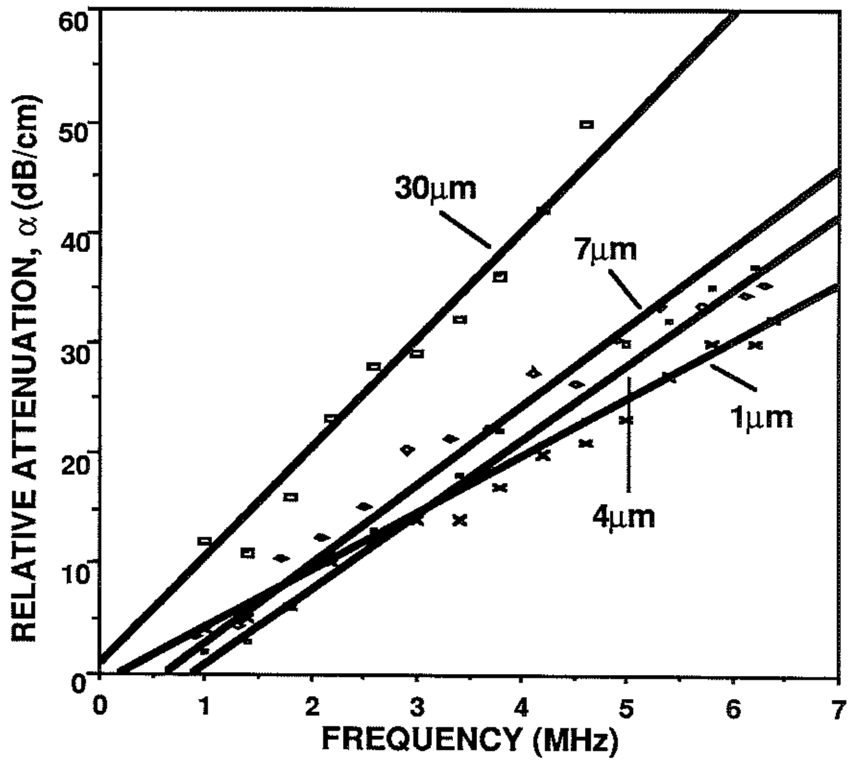


Fig. 10. Microstructure characterization of single phase YBCO superconductors obtained by Wideband Ultrasonic Spectroscopy. Spectra of copper is shown for reference only.

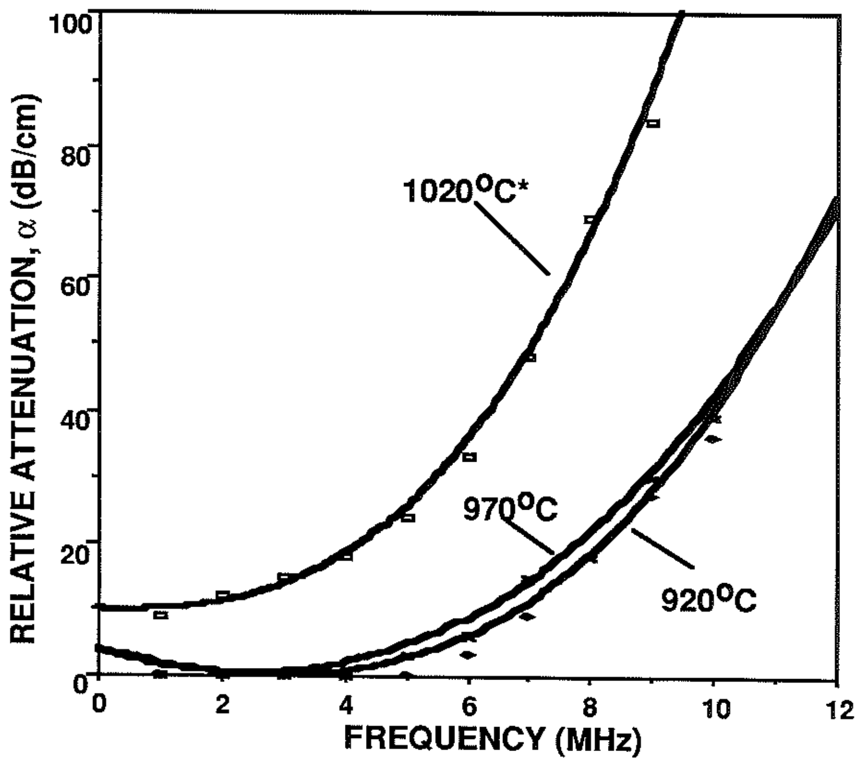
Particle size characterization in tungsten-polymer composite

Obtained by Wideband Ultrasonic Spectroscopy



Microstructure and phase characterization of polycrystalline silica as a function of temperature

Obtained by Wideband Ultrasonic Spectroscopy



***Higher attenuation at 1020°C is presumably caused by grain growth and cristobalite formation.**

ultran
redefining the limits of ultrasound

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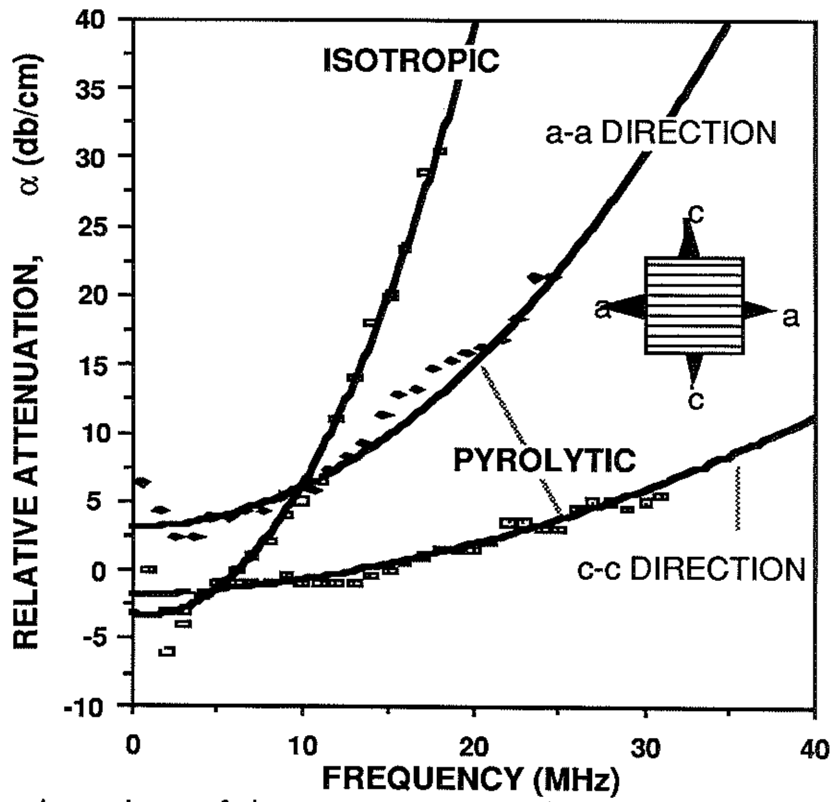
Anisotropy characterization of pyrolytic graphite

Ultrasonic Spectroscopy and velocity domain analyses



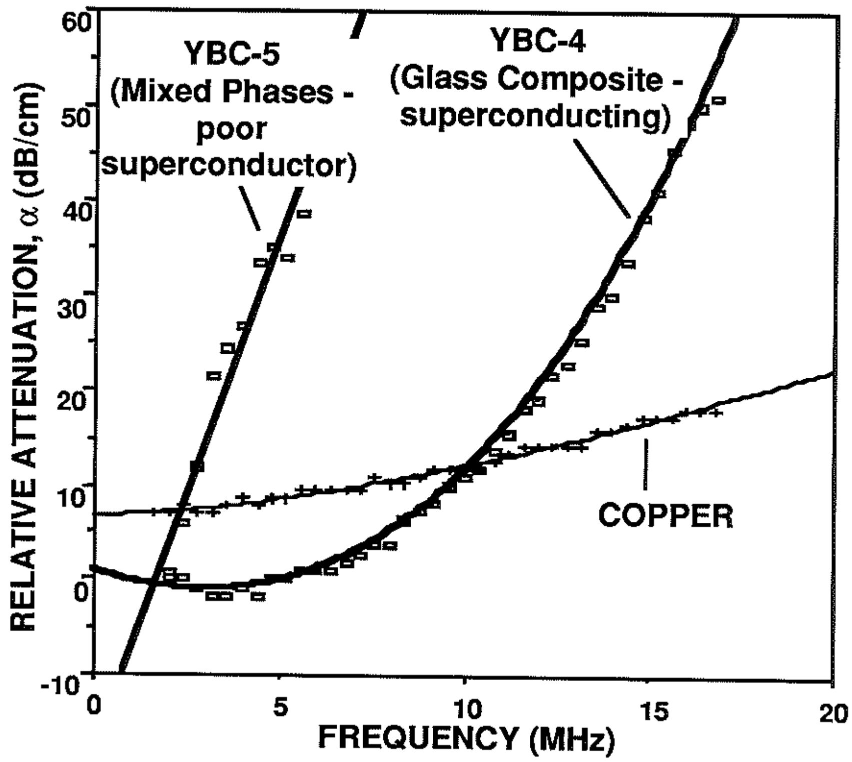
Frequency-dependence of ultrasonic attenuation of isotropic and pyrolytic graphite as a function of graphite platelet orientation - Compare more properties in the following table.

MATERIAL	ELECTRICAL RESISTIVITY (mΩ - cm)	LONG VEL (m/s)	SHEAR VEL (m/s)	ACOUSTIC IMPEDANCE ($g/cm^2 s \times 10^5$)	FREQUENCY ATTENUATION (relative)
ISOTROPIC	2,000	2785	1585	5.0	Very High
PYROLYTIC					
c-c direction	**500,000**	**3350**	**820**	**7.4**	**Very Low**
a-a direction	**700**	**4815**	**2455**	**10.6**	**Very High**

November 26, 1992
MCB: cbm

Microstructure characterization of multi phase YBCO superconductors

Obtained by Wideband Ultrasonic Spectroscopy



7. Limiting Factors of Ultrasonic NDC
8. Transducer Selection Guide
9. Ultrasonic Classification of Materials

Ultrasonic NDC of wide range of materials at various stages of their formation and processing is feasible. However, for reliability, repeatability, and accuracy of nondestructively characterized information, it is imperative that we mitigate the limiting factors and understand materials in ultrasonic terms.

Limiting factors of ultrasonic NDC

MATERIALS PARAMETERS	INSTRUMENTATION & TECHNIQUE/S	HUMAN FACTORS
Composition, microstructure, test environment, shape & size of test materials & components.	Wrong choice of transducers and/ or excitation, amplification, measurement, or other systems. Wrong or inadequate measurement technique/s.	Insufficient or lack of knowledge into characterization in general, or non familiarity with the basics of ultrasonic NDC and wave-material relationships.
SOLUTION	SOLUTION	SOLUTION
None **- materials or test environment parameters cannot be changed - their characterization is the aim of NDC.**	**Determine "materials suitable acoustics and techniques" before performing a particular NDC task, or investment into transducers and/or systems.**	**Formal education, training, and/or research into materials characterization, specifically relative to non-destructive methods.**

For reliable and accurate NDC, knowledge of these factors is important, lest wrong conclusions about materials/components be drawn. It is also important to develop and treat ultrasonic NDC methodology analogous to other characterizing methods, which also utilize waves as characterizing tools.

Transducer selection guide

MATERIALS CATEGORY (including gases)	APPLICABLE TRANSDUCER CHARACTERISTICS	
	FREQUENCY RANGE	PULSE WIDTH* (wavelengths)
Super-hard, & super-dense oxides, nitrides, carbides, & borides of metals & non-metals, their composites; high silica glasses, single crystals, and some liquids.	<5 to >50MHz	0.5 to 3λ
Non-porous fibrous & particulate composites, dense ceramics, medium -grained materials, metals, powder metals, glasses, liquids, and colloidal suspensions.	<2 to >20MHz	0.5 to 3λ
Refractories,(granular & porous), concretes, porous fiber & particulate composites, lumber & wood products, visco-elastic materials, and viscous liquids, slurries, etc.	<100KHz to 5MHz	2 to 6λ
Gases	<10MHz	3 to several λ

*Pulse width is defined by the number of wavelengths (λ) or cycles contained in a time domain envelope of a given frequency.

MECHANISM OF TRANSDUCER COUPLING

Quality of ultrasonic signals is greatly influenced by the effectiveness and mechanism by which a transducer is physically coupled to the test material. Transducer coupling and acoustic impedance matching at the interface of transducer and test material surface become quite significant while using dry coupling, 0^{o} incident shear wave, and VHF transducers.

The following table identifies variety of suggested coupling media with respect to transducer types, and interfaces coupled. As a general rule, for contact transducers when liquids are used as coupling media, their amounts should be kept to bare minimum at the transducer-material interface. This is particularly true when using shear wave and VHF transducers.

TRANSDUCER TYPE	COUPLING MEDIUM	INTERFACES COUPLED[1]
DIRECT CONTACT		
Standard	Light motor oil, propylene glycol, grease, etc.	T-Ms
Dry	None	T-Ms
Lambda	Propylene glycol, soap + glycol mixture, etc.	T-Ms
VHF	Light hair shampoo + glycol[3]	T-Ms
VLF	Grease, heavy motor oil, etc.	T-Ms
High Temperature	High vacuum grease, low melting glasses, etc.	T-Ms
0^{o} Incident Shear Wave	Ordinary honey, molasses, etc. Dry - None	T-Ms[2]
DELAY LINE CONTACT		
Replaceable delay		
Standard	Light motor oil, propylene glycol, grease, etc.	T-D & Dt-Ms
Dry	None[3]	T-D & Dt-Ms
Lambda	Propylene glycol, soap + glycol mixture, etc.	T-D & Dt-Ms
VLF	Grease, heavy motor oil, etc.	T-D & Dt-Ms
High Temperature	High vacuum grease, low melting glasses, etc.	T-D & Dt-Ms
0^{o} Incident Shear Wave	Ordinary honey, molasses, etc. Dry - None	T-D & Dt-Ms[2]
Fixed delay		
Standard	Light motor oil, propylene glycol, grease, etc.	Dt-Ms
Dry	None	Dt-Ms
Lambda	Propylene glycol, soap + glycol mixture, etc.	Dt-Ms
VHF	Light hair shampoo + glycol[3]	Dt-Ms
VLF	Grease, heavy motor oil, etc.	Dt-Ms
High Temperature	High vacuum grease, low melting glasses, etc.	Dt-Ms
0^{o} Incident Shear Wave	Ordinary honey, molasses, etc. Dry - None	Dt-Ms
IMMERSION	Normally water; for VHF: mixture of water and propylene glycol, or hair shampoo and water, etc.	T-W & W-Ms
AIR/GAS PROPAGATION	None	T-A & A-Ms

[1]T-Ms: Transducer-material surface
T-D: Transducer-delay
Dt-Ms: Delay tip-material surface
T-W: Transducer-water
W-Ms: Water material surface
T-A: Transducer-air
A--Ms: Air-material surface.
[2]It is important to use only "very" thin layer of couplant.
[3]Couplant needed between T-D.

Ultrasonic classification of materials

MATERIALS CATEGORY	VELOCITY RANGE (m/s)	EXAMPLE MATERIAL		ULTRASONIC CLASSIFICATION
		Velocity (m/s)	Wavelength* (mm)	
Super-hard, & super-dense oxides, nitrides, carbides, & borides of metals & non-metals and their composites.	~7,000 to >18,000	***Diamond*** 18,500	18.5	LONG WAVELENGTH MATERIALS
Non-porous fibrous & particulate composites, dense ceramics, medium -grained materials, metals, powder metals, and glasses.	~4,000 to 7,000	***Float Glass*** 5,820	5.8	MEDIUM WAVELENGTH MATERIALS
Refractories,(granular & porous), concretes, porous fiber & particulate composites, lumber & wood products, visco-elastic materials, and liquids, slurries, etc.	<400 to 4,000	***Rigid Ceramic Preform*** 400	0.4	SHORT WAVELENGTH MATERIALS

*All wavelengths (V/F) are functions of 1.0MHz.

10. CONCLUSIONS & RECOMMENDATIONS

1. Compared to other methods, ultrasonic NDC has more widespread applications in materials manufacture and R&D.

2. For reliable results and error-free conclusions, establish test "materials suitable acoustics and techniques" first.

3. It would be helpful if ultrasonic NDC was perceived as analogous to other methods that also utilize waves as characterizing tools.

4. Despite a long and confusing history, ultrasonic NDC is still a new arrival in the materials community at large. Therefore, the need for education, training, and research into this subject cannot be over-emphasized.

ultran

ULTRAN
a short resume

redefining the limits of ultrasound

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What is Ultran?

Ultran is a team of scientists, engineers, skilled technicians, and clients dedicated to materials reliability and health improvement through innovative uses of modern ultrasound. From a modest beginning in a garage in 1978 in Slippery Rock, PA, the company is now internationally recognized for playing a leadership role in the development of NonDestructive Characterization (NDC) of materials and advanced medical diagnostics and therapeutics.

What are our products?

Led by a host of standard transducers, our company is well-known for its unique designs. As an example, novel transducers such as dry coupling, unipolar λ–series, air/gas propagation, HF (~500KHz to 30MHz), VHF (~30 to ~200MHz), VLF (~50 to ~250KHz), and VHT (>1,000^{o}C) for longitudinal, shear, and surface wave propagation, and for very high power generation constitute the essence of Ultran. We also offer an advanced, fully computer-controlled ultrasonic system HPN-5000 - capable of providing diagnostic and power ultrasound from ~50KHz to ~20MHz.

What can you gain from Ultran?

Together with ultrasonics know-how and characterization, Ultran has developed unique techniques for materials QC/QA, process control, and R&D functions. These techniques are suitable for characterizing defects, microstructure, and properties in any material and practically at any stage of a material's manufacture - green or sintered, liquid or polymerized, hot or cold, and so on.

What do we sell and market?

Reinforced by an R&D laboratory, Ultran sells and markets transducers, analytical, and R&D services to conventional and advanced materials, aircraft/aerospace, nuclear, chemical & petro-chemical, automotive, electronics, and medical industries, and research institutions all over the world. Based upon its strength in ultrasound and in materials, the company has begun marketing its new developments and licensing of special applications and systems technologies to materials and instrumentation companies.

What' makes Ultran special?

Armed by comprehensive and practical ultrasonic know-how, several critical developments in ultrasound and the resulting applications have come from the company's on-going R&D. This hands'-on experience is transferred to clients in the form of dedicated solutions and specialized ultrasonic products for the advancement of industry and health care.

Epilogue

Notwithstanding our own commitments, in the matters of quality and reliability, Ultran will continue its old-fashioned philosophy of providing scientifically optimum products and services. We feel an urgent sense of responsibility to our increasingly complex world.