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EVOLUTION OF NON-CONTACT ULTRASONIC ANALYSIS AND ITS APPLICATIONS FOR HIDDEN OBJECTS DETECTION

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ABSTRACT

This paper describes unusual applications of ultrasound that are based upon recent advances in transduction efficiency in air and gaseous media.

Piezoelectric transducer devices -- capable of generating extremely high intensity ultrasound in ambient air up to 5MHz -- have been successfully developed and tested. Besides their obvious uses for gas analysis, remote sensing, liquid level, gap, and thickness measurement, and proximity analysis, these new generation transducers now make it possible to analyze solids and liquids not only non-destructively, but also without physically touching transducers to the test medium.

Among various applications concerning the Non-Destructive Characterization (NDC) of industrial materials, we also describe the feasibility of a forensic application. This concerns the detection of objects such as knives, guns, contraband drugs, dead bodies, etc., hidden inside false compartments or walls.

Keywords: *Ultrasound, non-destructive, characterization, evaluation, non-contact, biomedical, dry coupling, forensic.*

INTRODUCTION

Analogous to any materials characterization method that utilizes a wave as the characterizing vehicle, ultrasound can also provide significant information about the medium through which it is propagated. Reflected and transmitted ultrasonic signals can be correlated and manipulated to detect internal discontinuities, to measure physical properties and microstructure, and to generate surface and internal images of a medium, Table-I. Besides being nondestructive, the advantages of ultrasound are numerous: it does not require special sample preparation; it can be adapted to on-line manufacturing or testing environment, unlike x-ray and γ-ray methods, ultrasound is non-hazardous; the equipment involved is relatively easy to transport; and it can be used to test transparent or opaque materials. In fact, ultrasound can be used to characterize *any* medium through which it can be propagated. For example, with the exception of vacuum, all three states of matter - solid, liquid, and gas - can be analyzed by ultrasound. The only impediment is the complexity of the test material shape, which can be arduous to overcome. **In any case, the key requirement is to transmit measurable quality ultrasound through the test medium.**

MEASUREMENT CATEGORY	MEASURED PARAMETERS	INFORMATION REVEALED
Time Domain	Velocities of Longitudinal, shear, and surface waves.	Direct correlation with density, porosity, defect detection, mechanical properties, residual stress, interfacial analysis, etc.
Frequency Domain	Frequency dependence of ultrasound absorption and attenuation. (Ultrasonic Spectroscopy)	Direct correlation with atomic structure, inter-granular relationships, phase detection, etc.
Image Domain	Time of flight, attenuation, or frequency domain monitoring of ultrasonic signals by raster or multi-transducer scanning.	Planar or 3D images of surface and internal features of materials, including graphical representation of material heterogeneity in terms of microstructure, defects, and physical properties.

Table-I. Significance of Ultrasonic Analysis, modified after Vary [1].

Since its inception [2,3], ultrasonic NonDestructive Testing (NDT) has been preoccupied with overt flaw detection in primary metals [4] by either physically coupling transducers to test materials with oil and grease, or by submerging both transducers and test materials in water or like medium. Since the theory and practice of materials characterization by ultrasound have been well-established [5,6,7], it is rather disconcerting to note that this important subject has only recently begun to receive the attention of the materials community. Some thoughts on the late entry of ultrasound into materials science and engineering are given by this author elsewhere [8].

The insatiable hunger and burgeoning complexity of our crazy socio-economic world demand dirt-cheap materials and components which must withstand extreme physico-chemical environments, constant mechanical and thermal cycling in a plethora of uses: from baseball bat to steam generator tube; from household paint to diamond coatings; from bullet trains to space stations; the list is endless! . Keeping in tune with this diversity ultrasonic materials have also witnessed revolutionary developments [9,10]. Ultrasound-based techniques are now used in industrial materials testing, cleaning, joining, and fabrication. In health care, they are used for invasive and non-invasive diagnostics, fetus monitoring, therapeutics, and surgical applications.

However, modern ultrasound is also sought for unusual applications, such as forensic science. As our civilization makes strides in the areas of communication, travel, cosmic exploration, health care and longevity, there is a group of people involved in heinous activities that threaten the entire human race. Among such activities are illegal manufacture, concealment, and distribution of drugs extremely dangerous to persons of all walks of the society, particularly to our children. Based upon modern developments into ultrasound, this paper presents the feasibility for detection of contraband material, including drugs, firearms, dead bodies, etc., hidden within walls -- real or artificial. X-ray technology can provide useful information for this. But X-rays may be hazardous and non-portable for this application, besides being expensive in its deployment. Ultrasound is non-hazardous and portable. But, until recently it was not sensitive enough to propagate through various interfaces of a wall structure in order to detect materials hidden inside the wall.

This author has been developing ultrasound for nondestructive testing of materials for more than 20 years, but it is only during the last three years that phenomenal progress has been made in enhancing transduction in gaseous media. This development has opened new doors for NON-CONTACT analysis and imaging of all materials. This major advancement is at the center stage of "looking" inside walls and hidden compartments.

PRELUDE TO NON-CONTACT ULTRASONICS

Recognizing the necessity of total materials quality (including the accuracy and reliability of analyzed information), at Ultran we have advanced NDC to new heights through innovative and essential R&D into ultrasonic transducer devices with respect to modern materials characterization objectives [11]. Here we provide the background of non-contact ultrasound.

DRY COUPLING ULTRASOUND

One of our major accomplishments was the development in 1983 of dry coupling ultrasonic transducers and techniques for NDC of materials. Dry coupling ultrasound has been successfully applied for reliable determination of density, microstructure, and elastic properties of liquid-sensitive materials, electro-ceramics, superconductors, porous and green media [12,13,14,15]. Transducers and techniques based upon this work are also used for defect and property characterization of composites -- particularly those used in complex rocket motors of the space shuttle, helicopters, and aircrafts -- as well as for bio-medical applications.

PARTIAL CONTACT ULTRASOUND

Devices capable of generating and receiving ultrasound (>>100kHz) in air were the by product of dry coupling transducers. Since 1983 our AIR/GAS propagation transducers (<250kHz to ~20MHz) have been utilized mostly to satisfy the intellectual curiosity of researchers. They also discovered limited applications as high frequency receivers, non-contact surface profiling, thickness measurement, object identification, and in paper and proximity analysis. These transducers failed to produce quality ultrasound transmission in other solid materials.

However, when a partial contact technique (that is, when one side of the sample is placed on a transmitting transducer, and the scan performed by translating the receiving transducer in air) was applied, we succeeded in generating ultrasonic images of aircraft composites by utilizing frequency as high as 2.0MHz, Figure 1.

Figure 1. Partial contact ultrasonic image of an 8-ply 1.5mm thick graphite fiber plastic composite showing the central impact damaged region. Scan area: 25 x25mm.

HIGH TRANSDUCTION AND NON-CONTACT ULTRASOUND

Understanding of interfacial phenomena with respect to transmission of ultrasound from an active piezoelectric element and development of materials for efficient and high transduction finally resulted in devices suitable for non-contact materials analysis. Our initial observations indicated that transduction in ambient air was only 40dB lower than similar observations in water![1]

While the transducer designs and techniques that evolved are proprietary information, in this section we present their characterization scheme aimed at establishing received sensitivity criteria. Several industrial and bio-medical examples, and benefits of non-contact ultrasonic analysis of materials are also provided.

TRANSDUCER CHARACTERIZATION

Matching pairs of ultrasonic transducers, 250kHz, 1.0MHz, and 2.0MHz -- specially formulated to propagate and receive ultrasound through gaseous media -- were characterized to establish the transduction criteria. This was accomplished by measuring the transducer sensitivity under the scheme shown in Figure 2. Conditions of transducer excitation are shown in Table-II.

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[1]*This development in 1993 was so startling that we had to wait for six months before sharing it with our close professional associates. We wanted to make sure that what we had witnessed was real, and not just a figment of wild imagination.*

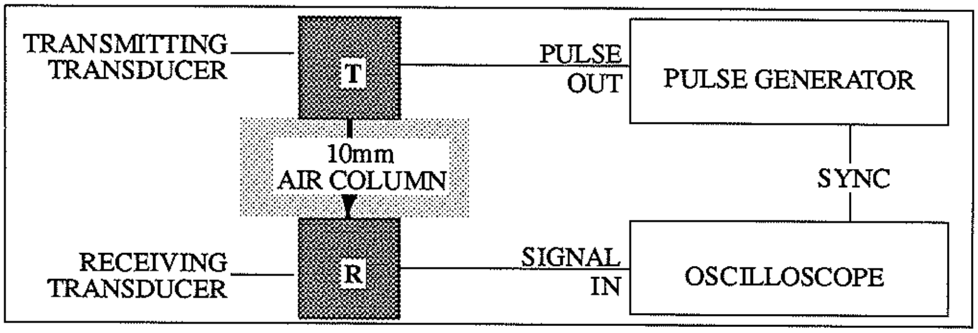

Figure 2. Scheme of non-contact transducer sensitivity characterization.

EXCITATION PULSE				FREQUENCY	RECEIVED SIGNAL
Shape	Volts	Burst	Duty Cycle		
Sine	16.0	1	10%	Adjusted to yield maximum signal amplitude	Measured directly from oscilloscope

Table-II. Transducer excitation parameters and measurement of received signal.

From this the transduction sensitivity was calculated according to,

Sensitivity (dB) = - 20 Log V_x/V_o **(1)**

where V_x is the received signal in volts, and V_o the excitation volts, i.e., 16V in this case.

Figures 3, 4, and 5, respectively show rf A-scans of transmitted signals (under conditions described above) for 250kHz, 1.0MHz, and 2.0MHz frequency transducers in air at ~50% relative humidity in Central Pennsylvania.[2] Table-III provides the summary of transducers and their sensitivities.

FREQUENCY		ACTIVE AREA DIAMETER (mm)	SENSITIVITY (dB)	
Nominal	Actual		Air	Water*
250kHz	220kHz	51mm	-54	-14
1.0MHz	0.95MHz	51mm	-62	-18
2.0MHz	1.7MHz	25mm	-66	-20

Provided as approximate value for comparison.

TABLE-III. Salient characteristics of transducers and their transmitted sensitivities.

[2]*4 to 6 dB loss was observed while working in the open fields of Utah in Summer. As a "thumb rule," the higher the humidity and lower the sea level, the higher is the sensitivity of ultrasound in air. Of course, for optimum performance the environment can be controlled.*

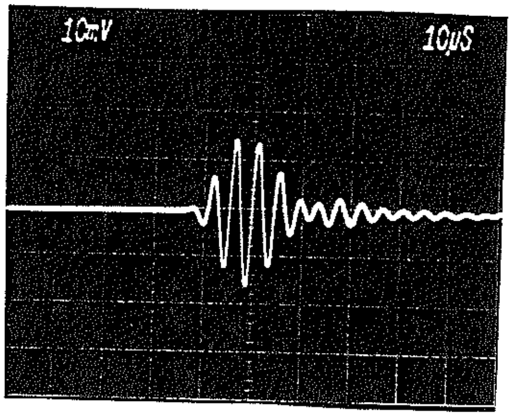

Figure 3. 250kHz transducers.
Received signal: 0.032V.

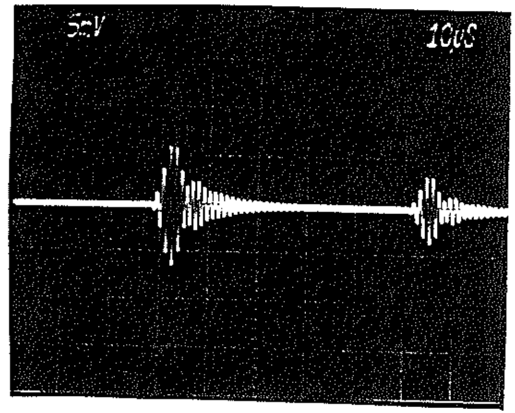

Figure 4. 1.0MHz transducers.
Received signal: 0.013V.

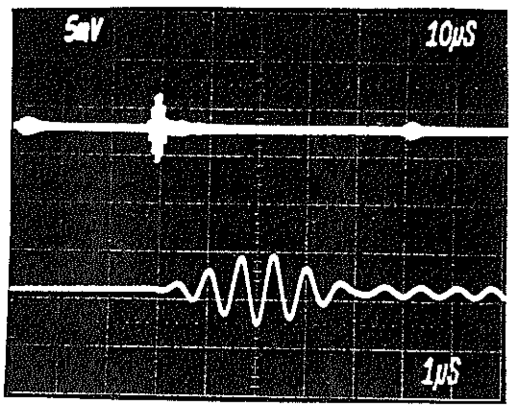

Figure 5. 2.0MHz transducers.
Received signal: 0.0075V.

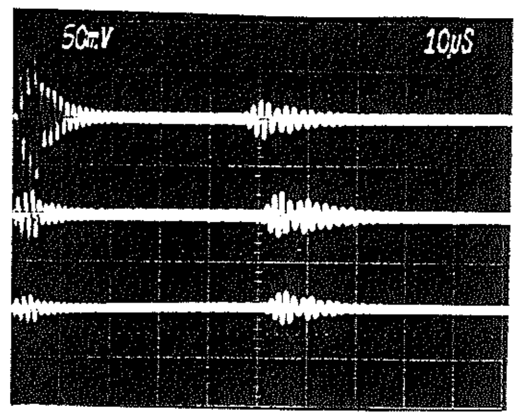

Figure 6. Transmission of 1.0MHz non-contact ultrasound through 12.7mm thick dense Al_2O_3 (top trace), aluminum (middle trace) and steel (bottom trace).

TRANSMISSION THROUGH CERAMICS AND METALS

By utilizing new transducers, we have successfully demonstrated that ultrasound -- between <250kHz to >2.0MHz -- can be transmitted in all materials, including even dense ceramics and metals. Figures 6 shows transmitted ultrasound signals through alumina, aluminum, and steel produced in RTP air environment.

Considering the fact that air is an exorbitantly attenuative medium and that acoustic impedance mismatch between air and these materials is more than five orders of magnitude,

the feat of non-contact ultrasound transmission defies ordinary logic. It is almost like piercing a Helium-filled rubber balloon through a steel wall!

NON-CONTACT IMAGING OF COMPOSITES

Figures 7 and 8 are non-contact 250kHz transmission images of a 5-ply 20mm thick plywood and 51mm thick rubber composite sample containing hidden objects.[3]

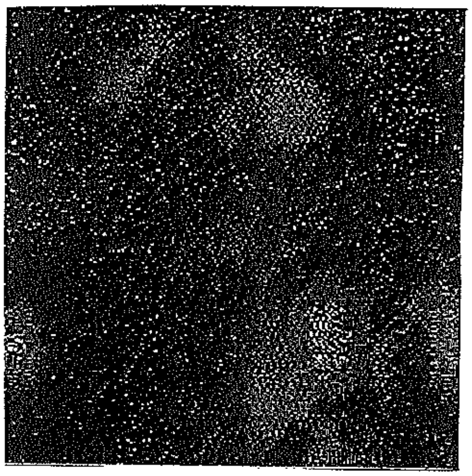

Figure 7. Non-contact ultrasonic image of 5-ply 20mm thick plywood, showing knotted and disbond regions. Scan area: ~150x150mm.

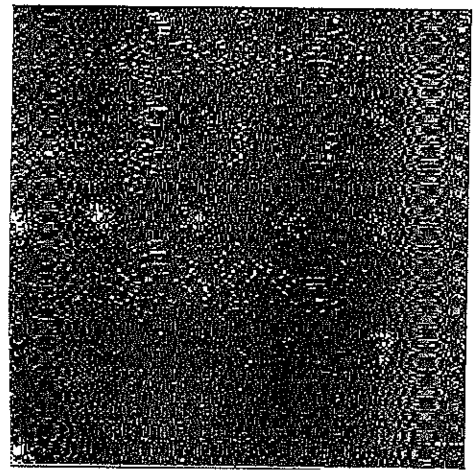

Figure 8. Non-contact ultrasonic image of 51mm thick rubber composite with embedded foreign objects, indicated by circular shaded regions. Scan area: ~150x150mm

DETECTION OF FOREIGN MATERIALS IN LIQUIDS

Figure 9 shows detection of a foreign object hidden in a plastic milk bottle, i.e., when transducers are not in contact with the bottle. It is interesting to note that ultrasound in this mode is capable of traversing through various interfaces several times. These observations were produced by using 250kHz transducers, although higher frequencies were also successful.

TRANSMISSION THROUGH HUMAN BODY

Figure 10 shows non-contact 250kHz ultrasound transmission through the human hand and forearm. In both cases ultrasound not only travels through the tissue, but also goes through bones. This feasibility should pave the way for diagnostic ultrasonography without

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[3]*Space shuttle rocket motor insulation, furnished by Thiokol Corporation, Space Operations, Brigham City, UT.*

discomforting the patient with the transducer load and wet coupling. Non-contact medical diagnostics is highly desirable when examining patients with burnt, excematic, or cancerous skin conditions.

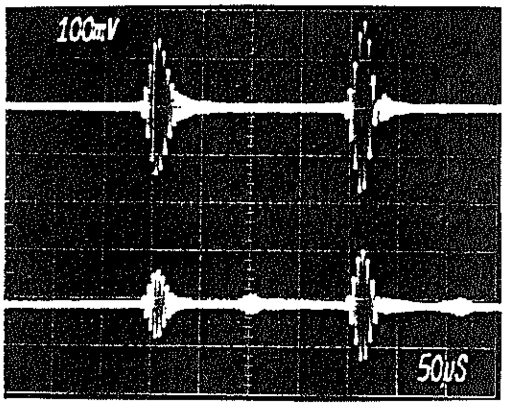

Figure 9. Detection of objects in liquids by non-contact ultrasound. Top Trace: Transmitted and reflected signal from a plastic milk bottle. Distance traveled: 150mm. Bottom Trace: Same as top trace, except when a metal rod (20mm diameter) is inserted in the bottle. Appearance of its signal is obvious in the trace center.

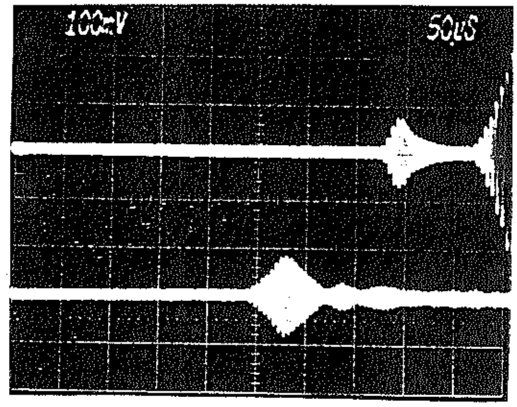

Figure 10. Transmission of non-contact ultrasound through a healthy human being. Top Trace: Palm, ~25mm. Bottom Trace: Forearm: ~80mm.

OTHER ADVANTAGES OF NON-CONTACT ULTRASOUND

One of the most frequently measured ultrasonic parameters is the longitudinal wave velocity of materials. Longitudinal velocity is directly related to material density, microstructure, and elastic properties. It is a matter of common sense that conventional techniques utilizing wet transducer coupling would contaminate while investigating porous materials, thus generating erroneous observations.

Even dry coupling has been found to generate inaccurate data from porous and visco-elastic materials because the technique is pressure sensitive. If similar observations are made by non-contact technique described in this paper, the ensuing values of velocities will correspond to the true nature of test material. Table-IV provides a comparison of velocities measured by various ultrasonic techniques on selected materials.

Developments in the field of non-contact ultrasound using piezoelectric and electro-strictive transducers have also been reported by other researchers [16,17]. LASER induced ultrasound has been developed for non-contact testing of materials [18,19]. However, in strict sense, this method is not entirely non-destructive, since high power pulsed LASER can adversely affect the test material.

MATERIAL	VELOCITY (m/s) Analytical Technique		
	Wet Coupling	Dry Coupling	Non-contact
CERAMIC FOAM (Space Shuttle Tile*)			
Sample #1	600	420	405
Sample #2	640	440	425
2D C-C DISC BRAKE	2,100 (?)	2,055 (?)	1,910
ACRLYIC (PMMA)	2,700	2,760	2,725
RUBBER	1,530	1,540	1,520
TEFLON	1,350	1,365	1,335

**Samples furnished by Lockheed Corporation, Sunnyvale, CA.*

Table-IV. Comparison of longitudinal wave velocities of selected materials determined by various ultrasonic techniques.

REQUIREMENTS FOR ULTRASOUND TRANSMISSION THROUGH GROSSLY MIS-MATCHED LAYERED MEDIA, SUCH AS A WALL STRUCTURE

While we have ample evidence of non-contact ultrasonic NDC and imaging of materials in various configurations, we need to develop similar practical methodology for the analysis of a complex structure, such as a wall. Considering the number and complexity of interfaces in such a structure, this task is by no means simple. When we impose the necessity of examining it from one side, problems are further exacerbated.

By way of transmission co-efficients and relative estimation of interfacial and bulk media attenuation, Fig. 11 provides an illustration of problems we must solve. Ultrasonically, the most critical parameter is the acoustic impedance of the medium of ultrasound propagation:

$$Z(\mathrm{MRayl}) = \rho \times V, \qquad (2)$$

where, $\rho(\mathrm{kg/m^3})$ is medium density, and $V(\mathrm{m/s})$ is its velocity. Transmission co-efficient, defining the efficiency of ultrasound propagation at two interfaces, is given by

$$T = 4Z_1 Z_2/(Z_1 + Z_2)^2 \qquad (3)$$

where, Z_1 and Z_2, respectively, are acoustic impedances of the first and second medium of ultrasound propagation. Transmission co-efficients at various interfaces, Fig. 11, are shown in Table-V with the attenuation estimate and the practical outcome.

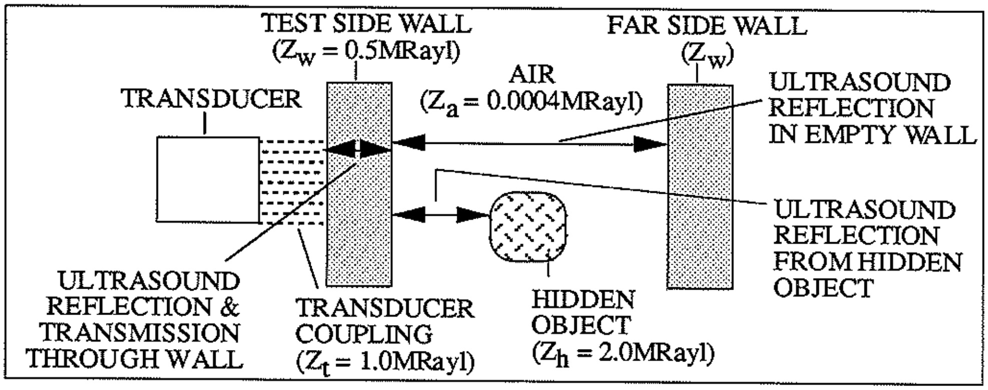

Figure 11. Structure of a wall with respect to critical interfaces and their acoustic impedances that ultrasound must overcome for hidden objects detection.

TRANSMISSION CO-EFFIC. **(as a function of interface)**	**RELATIVE ATTENUATION**	**OUTCOME**
Transducer coupling into wall Z_t to Z_w = 0.88	Very Low	Ultrasound will propagate in wood, dry wall, etc.
Wall into air **Z_w to Z_a = 0.00084**	**High**	**Relatively small amount of ultrasound will transmit in air.**
Air into wall Z_a to Z_w = 0.00084	High	Ultrasound will be reflected from the far side wall.
Air into hidden object* **Z_a to Z_h = 0.0002**	**Very High**	**Ultrasound will be reflected from the surface of hidden object.**

****Assumed as a low Z material, such as a plastic bag containing sugar.***

TABLE-V. Transmission co-efficients and relative attenuation of ultrasound at various interfaces and materials in a wooden wall structure.

PROOF OF HIDDEN OBJECTS DETECTION IN WALLS

WOODEN WALL

Despite extremely poor transmission co-efficients, Table-V, we have been successful in propagating and receiving measurable quality ultrasonic signals from wall-type configurations. Figures 12 and 13, respectively show transmitted and reflected signals through a wooden wall, ~95mm apart. The hidden object is a plastic bag containing sugar.

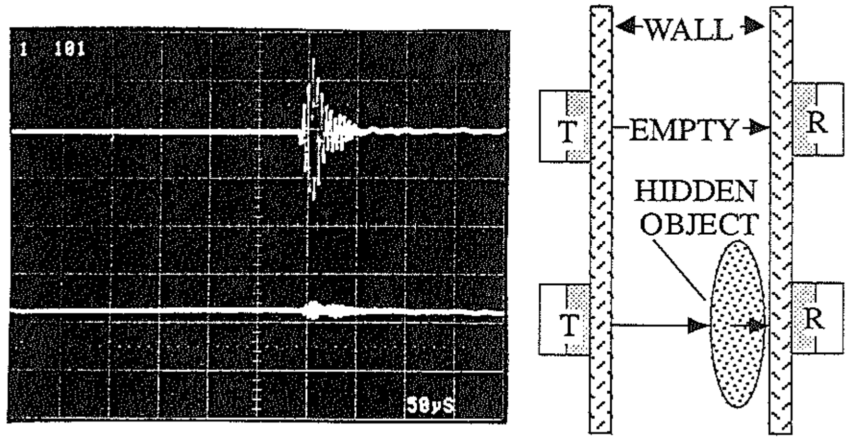

Figure 12. Wooden Wall. Transmission technique (when both sides are available). Top trace: Empty wall. Bottom Trace: With hidden object. When an object falls between the path of ultrasound, it creates a "shadow" effect, thus reducing (or eliminating) the received signal.

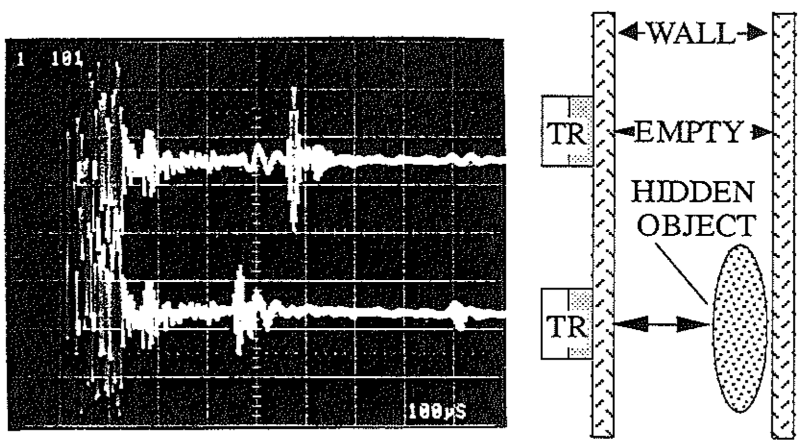

Figure 13. Wooden Wall. Reflection technique (when one side is available). Top trace: Empty wall. Bottom trace: With hidden object. Ultrasound is reflected from the surface of the object, thus reducing the time of its arrival. In empty wall it is 560µs, while with hidden object, it is 460µs. From air velocity, 342m/s, the depth of hidden object comes to ~78mm.

GYPSUM-FILLED DRY WALL

Figures 14 and 15 show observations by the transmission and reflection techniques through a gypsum-filled dry wall, ~95mm apart, with and without the hidden object.

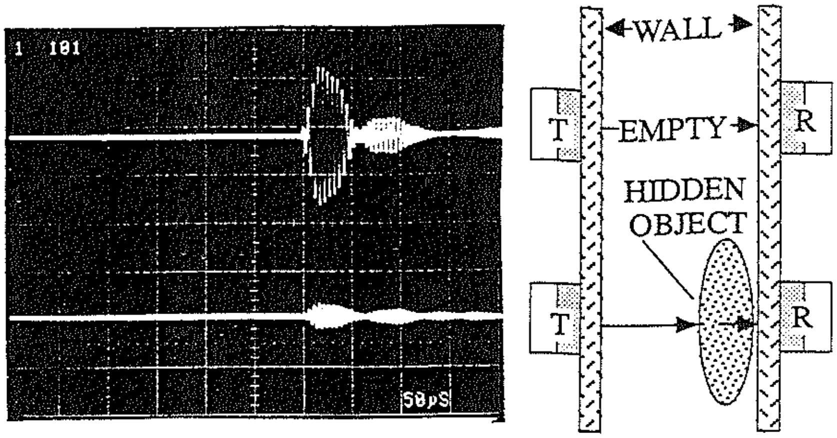

Figure 14. Dry Wall. Transmission technique. Top trace: Empty wall. Bottom Trace: With hidden object. When an object falls between the path of ultrasound, it creates a "shadow" effect, thus reducing (or eliminating) the received signal.

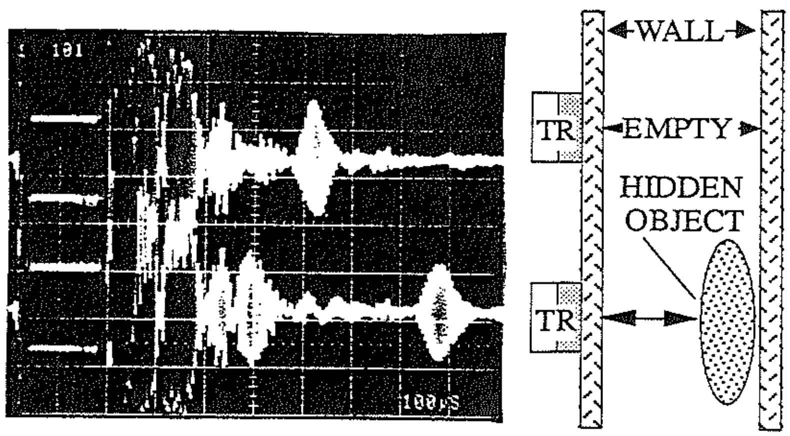

Figure 15. Dry Wall. Reflection technique Top trace: Empty wall. Bottom trace: With hidden object. Ultrasound is reflected from the surface of the object, thus reducing the time of its arrival. In empty wall it is 580µs, while with hidden object, it is 470µs. From air velocity, 342m/s, the depth of hidden object comes to ~80mm.

The successful interrogation of a wall structure is attributed to an extremely high transmission co-efficient, 0.88, at the critical transducer-wall interface in conjunction with exceptionally high transduction sensitivity, -40dB, of the piezoelectric transducer. These observations were produced by our prototype 250kHz transducers. Due to very high attenuation and interfacial problems in the structure of a wall, this frequency is considered rather high for this application. Therefore, observations reported here are considered very encouraging for future developments.

CONCLUSIONS

We have demonstrated that ultrasonic transducers, characterized by extremely high transduction in air or gaseous media, can be applied for non-contact analysis of solids or liquids and biomedical conditions. It has also been shown that these transducers can be used to "look into" hidden objects within the complexity of a wall structure for forensic studies. We have reasons to believe that besides the commercial merit of this advancement in ultrasound, researchers will also find many innovative uses of practical value.

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