HIGH EFFICIENCY NON-CONTACT TRANSDUCERS AND A VERY HIGH COUPLING PIEZOELECTRIC COMPOSITE

M. C. Bhardwaj, Ultran Group, Boalsburg, PA USA

Abstract: Despite the usefulness of ultrasound for materials analysis, this age-old method has been stifled by direct or indirect transducer contact to the test media, generally by liquids. Consequently, a branch of materials that are porous, liquid-sensitive, food, pharmaceuticals, wood lumber, concrete, consolidated powders, or in early stages of formation cannot be analyzed by ultrasound without adversely affecting them. While Non-Contact Ultrasound (NCU) is highly desired, yet its realization calls for overcoming natural barrier of massive Z-mismatch between NTP coupling air and solids, which can be between <3 to >7 orders of magnitude! This is only possible if transducers are characterized by phenomenally high transduction efficiency in air. After a struggle of more than 20 years, in 1997 we finally succeeded in creating ultrasound devices between <60kHz to ~10MHz, capable of generating 10s to 100s of Pa/V acoustic pressure in air -- US and internationally patented. In practical terms, the NCU transducers are capable of driving ultrasound through any material even with relatively low energy excitation and amplification. This paper presents acoustic characteristics of NCU transducers, experimental evidence of their exceptionally high efficiency, and applications possibilities for NDT, sensing, proximity analysis, and more. Here we also introduce a new piezoelectric composite that is characterized by the highest coupling, zero cross-talk, broad bandwidth, very low dielectric constant, and several other advantages -- US and international patents pending. NCU and other transducers based upon this material are characterized by efficiency that is twice that of conventional piezoelectric composites.

Realities that defy Non-Contact Ultrasound: In order for NCU to become a reality for analytical and other applications of ultrasound, the significance of transducer efficiency cannot be over-estimated. Assuming that the first medium of ultrasound propagation is ambient air before it encounters a solid medium, two natural phenomena defy the NCU reality, Fig. 1. These are absorption of ultrasound by air and near total reflection of ultrasound at the air-solid interface. The former due to rarified nature of air/gas and the latter due to gross acoustic impedance mismatch at the interface. Add to this the in-efficient transmission of ultrasound from the piezoelectric material to air and other gases we truly have a formidable situation in our hands. Since the first two are natural phenomena, there is nothing that we can do about them. This leaves us only one alternative, i.e., to improve the efficiency of the transducer for ultrasound transduction in gaseous media. To this effect, we have been experimenting with transducer designs and materials

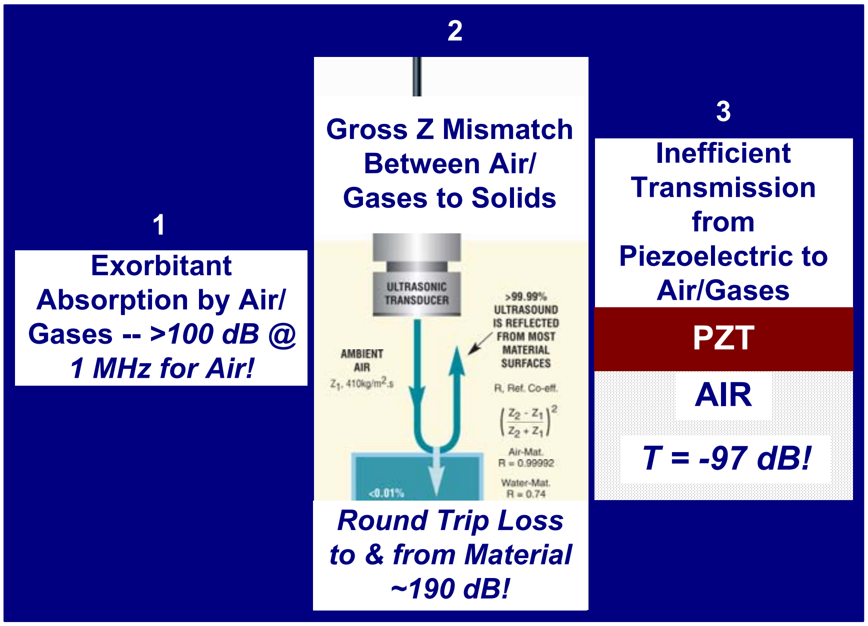

Fig. 1. Realities that defy non-contact ultrasound.

for a long time. New transducer materials in conjunction with improvements in material making process and acoustic impedance matching layers have resulted into substantial increment of ultrasound transduction in air that warrants serious attention for the development of non-contact ultrasound modality for non-destructive testing and characterization of materials.

Phenomenally High Efficiency NCU transducers: In our attempt to increase the air transduction efficiency of an electro-mechanical transducer a compressed fiber layer was used as the acoustic impedance (Z) matching layer. This resulted into phenomenal increment of transducer efficiency relative to any other transducer design that utilizes other Z-matching materials (1, 2, 3.) Known as NCU transducers, their efficiency in air was measured as a function of transducer to a solid reflector distance, Fig. 2. When similar transducers Z-matched for water immersion are tested in water, their acoustic pressure is approximately 16 to 30 dB higher than for those in air.

Complementing the NCU transducer design there is also a parallel advancement in the area of piezoelectric material. This concerns our Gas Matrix Piezoelectric (GMP) composite – US and international patents pending. This material is characterized by the most unusual, yet highly desirable features. For example, its thickness coupling factor rivals that of the longitudinal coupling factor of the solid piezoelectric material, very low density, very low mechanical Q, zero acoustical cross-talk, and several other advantages, Table I.

By utilizing the NCU transducer design with conventional piezoelectric and GMP materials, devices ranging in frequency from <60 kHz to ~10 MHz; and in active dimensions from 1 mm to >200 mm have been successfully produced in single and multi-element arrays in planar, point and cylindrically focused configurations, Fig. 3. It is important to note that the GMP production also facilitates the production of transducers greater than 1x1 m or conceptually any dimension of shape. Table – II shows general specifications and features of NCU transducers.

Relative to the applications of NCU, it is important to note that under ambient conditions, even very high frequency NCU transducers can be used for surface reflection investigation. However, should transmission

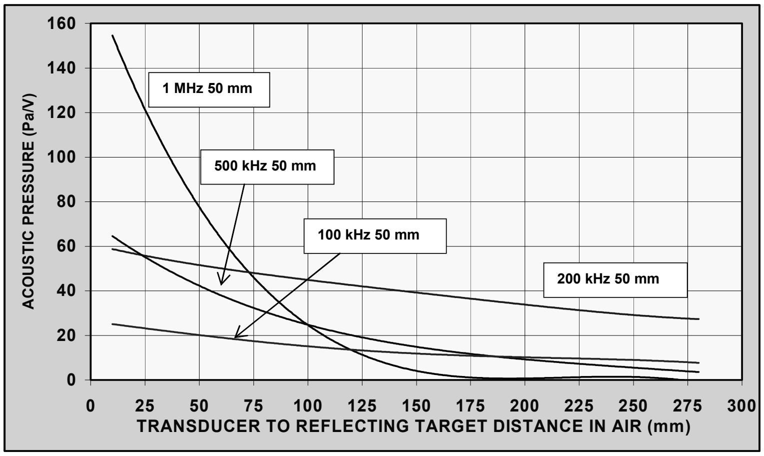

Fig. 2. Acoustic pressure generated by NCU transducers in ambient air as a function of transducer to a flat target distance. Transducer frequencies and active area dimensions are given in the text boxes of the graphs.

Table – I. Preliminary comparison of salient characteristics of Gas Matrix Piezoelectric (GMP) composite with other piezoelectric materials.

CHARACTERISTIC	Solid Piezoelectric Material	Polymer Matrix Piezoelectric	Gas Matrix Piezoelectric
Density[1]	7.6	5.3	<2.5
K_t Coupling, Thickness[2]	0.61	0.5	0.66
k_p Coupling, Planar[3]	0.51	0.3	~0
d_{33} Piezoelectric Strain in Thickness	220		240

Direction[4]			
$K_{33}T$ Relative Dielectric Constant[5]	1000	900	288
Dissipation Factor[6]	0.3	0.03	0.01
Q_m Mechanical Quality Factor[7]	900		43
Frequency Constant[8]	2100	1500	1520
Pyroelectric Charge[9]	Extremely high	High	Extremely low
Elastic Modulus[10]	72	40	23
Ease of Production	---	Extremely difficult	Relatively easy
Large Structures	Very difficult	Very difficult	Relatively easy
Acoustic Cross Talk	Very high	High	Nearly none
Bandwidth	Very low	High	Very high

[1]g/cc, [2]longitudinal electro-mechanical coupling co-efficient, [3]planar electro-mechanical coupling factor, [4]x10^{-12} m/V, [5]dielectric constant @ 1 kHz, [6]dissipation factor, [7]mechanical quality factor, [8]Hz-m, [9] frequency constant in compressional wave direction, [10]GPa.

Fig. 3. Non-contact transducers

Table-II. General specifications, features, and other aspects of non-contact transducers.

FEATURE	DESCRIPTION
Frequency range	50kHz to >10MHz. Under ambient conditions it is extremely arduous to handle frequencies >4.0 MHz if NCU transmission in solids is required.
Sensitivity	16 to 30dB lower than contact or water immersion transducers
Bandwidth	Broad and narrow band
Dimension	<1mm to >100mm – >1x1 m are also possible.

Field geometry	Planar, point and cylindrically focused
Elemental configuration	Single and multi-element arrays
Optimum distance in air	Approximately, <5 to >50 wavelengths in air
Minimum usable dimension	Approximately between <4 to 6 wavelengths in air
Pulse-echo operation	Extremely difficult under NTP conditions, very easy under high gas pressure
Construction	Robust and factory suitable

through solids be required, frequencies beyond 4 MHz are extremely cumbersome under such conditions. On the other hand, at high gas pressure, not only direct transmission, but also single transducer, pulse-echo operation through solids is relatively easy. For example, with a 10 mm specimen of steel and a 3.0 MHz NCU transducer one observes its thickness reflection at <7 bar air pressure (3.)

Figures 4, 5, 6, and 7 show typical time and frequency domain and sensitivity observations from 100 kHz, 500 kHz, 1.0 MHz, and 3 .0 MHz NCU transducers obtained by round-trip reflection in ambient air from a flat steel reflector, located at a distance from transducer specified in the figure captions.

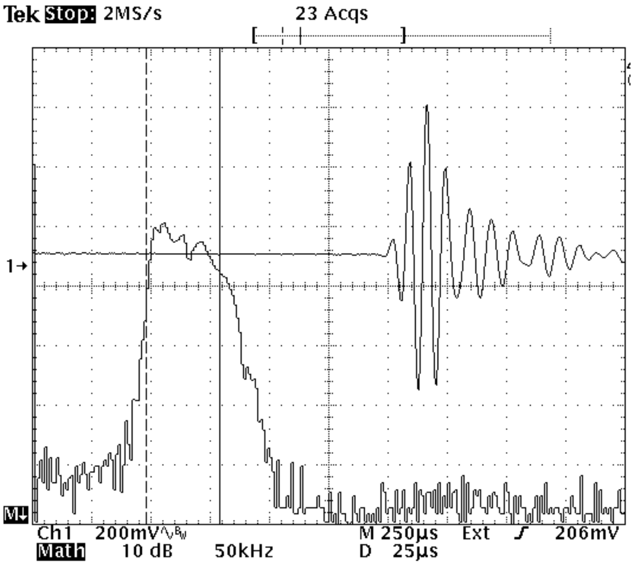

Fig. 4. 100 kHz, 50x50 mm. Sensitivity: -46 dB. Distance in ambient air: 100 mm.

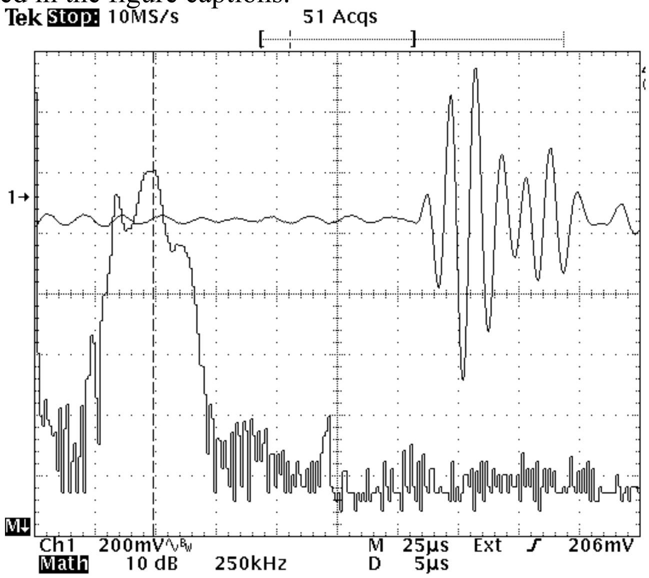

Fig. 5. 500 kHz, 19x19 mm. Sensitivity: -50 dB. Distance in ambient air: 20 mm.

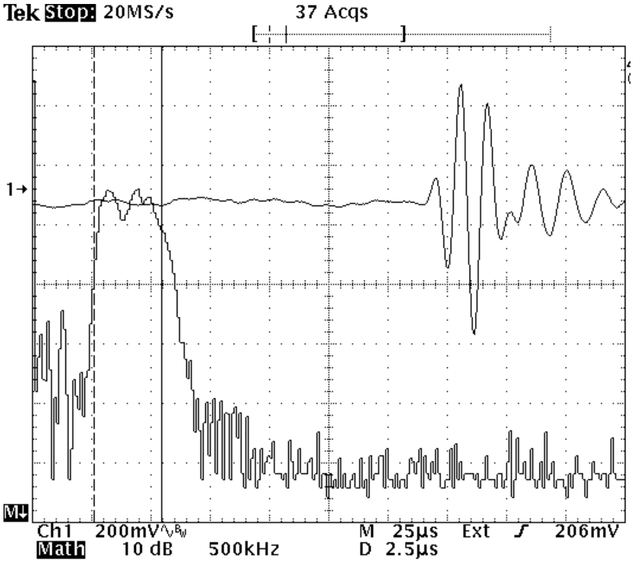

Fig. 6. 1.0 MHz 12.5 mm dia. Sensitivity: -50 dB. Distance in ambient air: 10 mm.

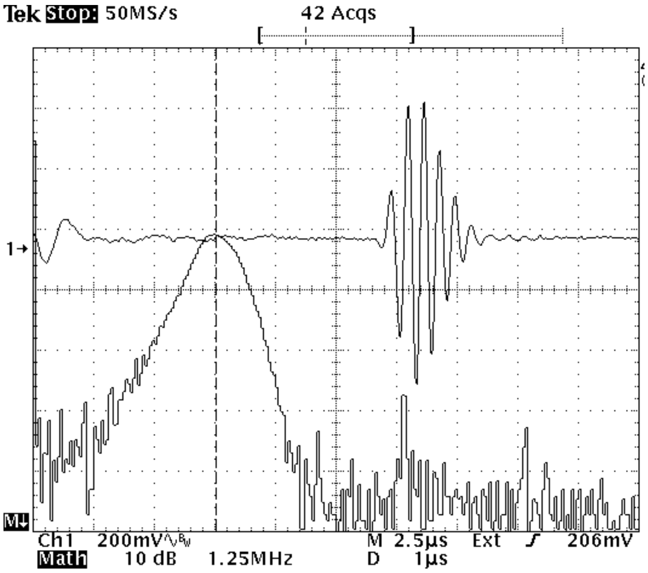

Fig. 7. 3.0 MHz, 12.5 mm dia. Sensitivity: -60 dB. Distance in ambient air: 5 mm.

Evidence of Phenomenal Efficiency: In order to demonstrate the high efficiency of NCU transducers in megahertz frequency regime an unusual experiment was performed in direct transmission mode. 1.0 and 3.0 MHz NCU transducers, respectively 12.5 mm and 6.3 mm active area diameter, were excited with a 16 volt single sinusoidal pulse. The received signal from the receiving transducers in both cases was amplified by 64 dB gain. For 1 0 MHz the transducers were separated by approximately 10 mm ambient air and for 3.0 MHz, by 6 mm. Flat samples of aluminum (3.2 mm), Carbon Fiber Re-enforced Plastic (CFRP – 5.0 mm)) composite, and PMMA (acrylic – 3.2 mm) were individually placed between the transmitting and receiving transducers. Fig. 8. shows transmitted signals at 1.0 MHz, and Fig. 9, at 3.0 MHz. The signal to noise ratio in these observations were enhanced by signal averaging.

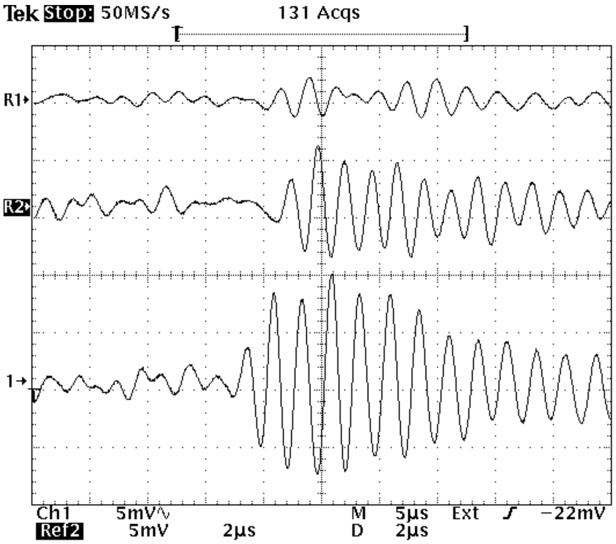

Fig. 8. NCU transmission at 1.0 MHz. Top trace: 3.2 mm aluminum. Middle trace: 5 mm CFRP. Bottom trace: 3.2 mm PMMA.

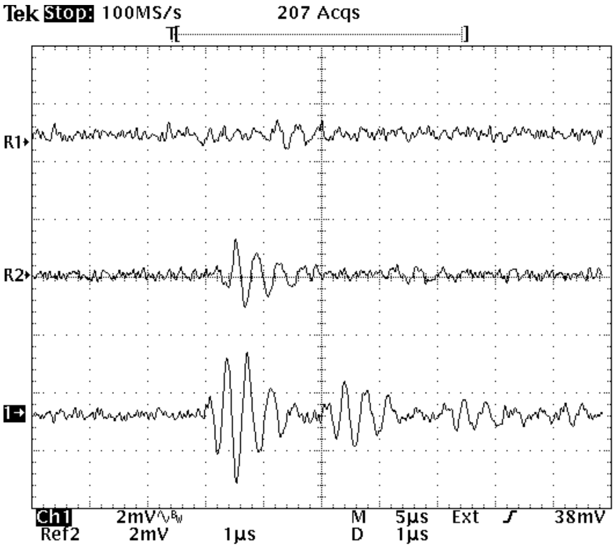

Fig. 9. NCU transmission at 3.0 MHz. Top trace: 3.2 mm aluminum. Middle trace: 5 mm CFRP. Bottom trace: 3.2 mm PMMA. Observe thickness resolution in CFRP and PMMA,

Considering high frequency and variability in the acoustic impedance of materials reported here, it is rather quite surprising that one can expect NCU transmission through them with mere 16 volt sine wave excitation. While this is a testimonial to extremely high efficiency of NCU transducers, yet from a practical standpoint it is not our recommendation that such low voltage excitation be used. The purpose of this exercise is to emphasize unusual nature of NCU transducers, the subject of this paper.

Applications and Future: In this paper we have introduced two significant advancements in ultrasound. One with respect to a transducer design that exhibits phenomenal transduction of ultrasound in air and the other related to the development of a piezoelectric composite that is characterized by exceptional properties. Together they have elevated the status of ultrasound beyond conventional wisdom. Besides a myriad of applications of value in materials, food, bio-medical, and pharmaceutical industries (4, 5, 6, 7, 8, 9, 10, 11, 12, 13), these new generation advancements in ultrasound have also been successful for an entirely unexpected high power related application. This concerns the destruction of an anthrax-type bacterial spores under NTP conditions without any contact with the material irradiated (14), US and international patents pending. It is therefore, fair to conclude that the work reported in this paper represents a phenomenal advancement in ultrasound that rivals the discovery of the x-rays and the invention of the Laser. Judging from the history of the scientific revolutions, we believe these new developments in ultrasound will not only help our complex socio-technical world, but will also enliven the imagination of thinkers and researchers.

Acknowledgements: We gratefully acknowledge the contributions of Prof. Bernard Hosten and Christianne Bateau, Universite Bordeaux, France for characterizing the transducers, and Dr. Albert Teitsma, Gas Technology Institute, USA for supporting our effort in the area of high gas pressure research.

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