Phenomenal Advancements in Transducers and Piezoelectric Composites for Non-Contact Ultrasound and Other Applications

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Abstract. Ultrasound is a well known method for non-destructive testing of materials; however, this age-old method has been stifled by direct or indirect transducer contact with the test media, generally by liquids. As a consequence, a substantial number of materials cannot be analyzed using ultrasound. While Non-Contact Ultrasound (NCU) would be highly desired, its realization calls for overcoming the natural barrier of massive acoustic impedance in air as well as Zmismatch between STP coupling air and solids. We have developed transducers to accomplish this which are capable of driving ultrasound through any material without contact utilizing relatively low energy excitation and amplification. This paper presents the acoustic characteristics of these NCU transducers, experimental evidence of their exponentially high efficiency, and applications possibilities for NDT, sensing, proximity analysis, and more. To help accomplish this, we have developed a new piezoelectric composite that is characterized by extremely high coupling, zero cross-talk, broad bandwidth, very low dielectric constant, and several other advantages. Utilizing this material, we have not only accomplished NCU, but also extremely high efficiency contact and immersion transducers, bridging the chronic frequency gap between <50kHz to 500kHz.

Introduction

The idea of dry coupling and air/gas propagation transducers has been around since 1983, however in order for Non-Contact Ultrasound (NCU) to become a reality, transducer efficiency is of paramount importance. Assuming the first medium of ultrasounic propagation is ambient air followed by a solid medium, there are two natural phenomena that defy NCU (figure 1). The first is the absorption of ultrasound in air due to the rarified nature of gasses. The second is the near-total reflection of ultrasound at the air/solid interface due to anywhere from 3 to 7 orders of magnitude of Z-mismatch between the two materials. These issues, combined with the highly inefficient transmission of ultrasound from the piezoelectric material to air, create for us a truly formidable situation. The first two are natural phenomena so there is nothing we can do to change them. This leaves us with only one alternative: improving the efficiency of the transducer design for ultrasound transduction in gaseous media. In 1997 a major breakthrough in transducer design altered our perception and the utility of ultrasound – we succeeded in creating these ultrasonic devices with frequencies between <50kHz to >5MHz which generated 10’s to 100’s of Pa/V acoustic pressure in ambient air. These new transducer materials in conjunction with improvements in the material making process and acoustic impedance matching layers warrant serious attention for the further development of non-contact ultrasound for nondestructive testing and characterization of materials.

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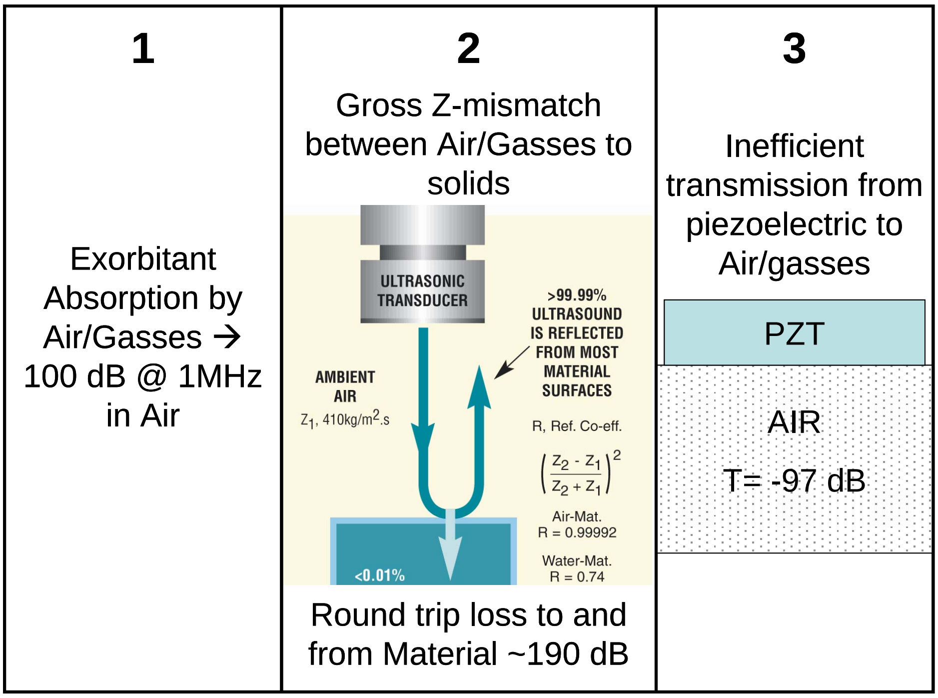

Figure 1. Realities that defy non-contact ultrasound

1. Increasing the Efficiency of NCU Transducers

1.1 Z-Matching

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 in a large increase in transducer efficiency compared to other transducer designs which utilize other Z-matching materials (1, 2, 3.) These new transducers, known as Non-Contact Ultrasound (NCU) transducers, had their efficiency in air measured as a function of transducer to a solid reflector distance, the results of which are shown in Figure 2. When similar transducers Z-matched for water immersion are tested in water, their acoustic pressure is typically approximately 16 to 30 dB higher than for those in air.

1.2 Advancements in Piezoelectric Materials

Also crucial to the NCU transducer design is the 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 highly unusual, desirable features. For example, its thickness coupling factor rivals that of the longitudinal coupling factor of solid piezoelectric materials,]it has very low density, very low mechanical Q, zero acoustical cross-talk, and several other advantages, table 1.

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 2 shows general specifications and features of NCU transducers.

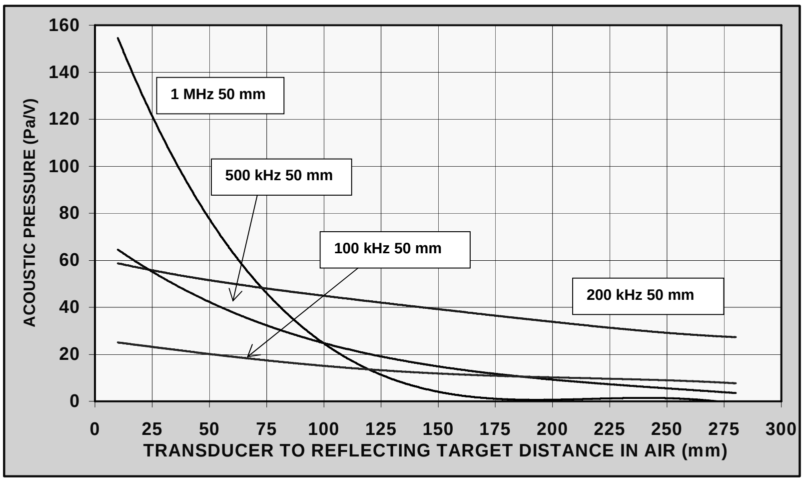

Figure 2. Pressure generated by NCU transducers in ambient air as a function of transducer to a flat target distance. Transducer frequencies and active area dimensions are given in the text boxes on the graph

Table 1. 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 Direction[4]	– 220		– 240
– $K_{33}T$ Relative Dielectric	– 1000	– 900	– 288
Constant[5]	– 0.3	– 0.03	– 0.01
– Dissipation Factor[6]	– 900		– 43
– Q_m Mechanical Quality Factor[7]	– 2100	– 1500	– 1520
– Frequency Constant[8]	– Extremely	– High	– Extremely low
– Pyroelectric Charge[9]	high	– 40	– 23
– Elastic Modulus[10]	– 72	– Extremely	– Relatively easy
– Ease of Production	– ---	difficult	
		– Very difficult	– Relatively easy
– Large Structures	– Very difficult	– High	– Nearly none
– Acoustic Cross Talk	– Very high	– High	– Very high
– Bandwidth	– Very low		

[1]g/cc, [2]longitudinal electro-mechanical coupling coefficient, [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.

Relative to its applications, it is important to note that even very high frequency NCU transducers, under ambient conditions, can be used for surface reflection investigation. However, should transmission through solids be required, frequencies beyond 4 MHz become extremely cumbersome. On the other hand, at a higher gas pressure, not only direct transmission, but also single transducer, pulse-echo operation through solids becomes increasingly easier. For example, using a 10 mm specimen of steel and a 3.0 MHz NCU transducer one can observe its thickness reflection at <7 bar air pressure (3).

Figure 3. Non-Contact Transducers produced utilizing z-matching techniques and GMP materials

Table 2. 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

Evidence of Phenomenal Efficiency

2.1 Observations Using NCU Transducers

A large amount of data and observations have already been taken using these new non-contact ultrasound transducers showing their high sensitivity and applicability in a variety of situations. Figures 4, 5, 6, and 7 show typical time and frequency domain measurements as well as sensitivity observations from 100 kHz, 200 kHz, 500 kHz, and 1.0 MHz NCU transducers obtained in direct transmission from a transmitting transducer to a receiving one through ambient air, located at a distance from one another specified in each of the figure captions.

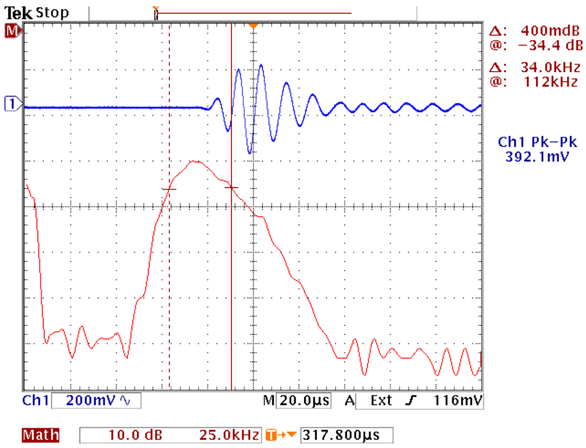

Figure 4. 100 kHz, 50x50 mm, Sensitivity: -38 dB Distance in Ambient Air: 100mm

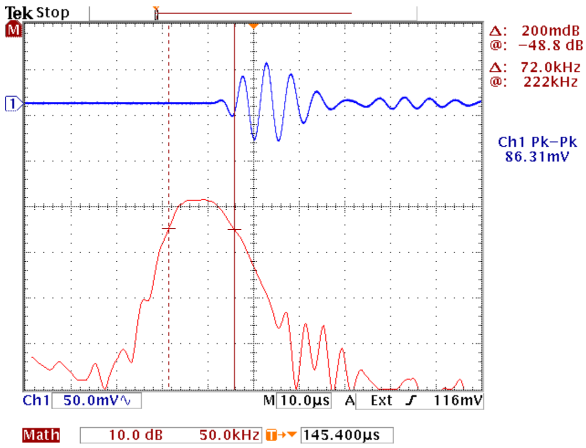

Figure 5. 200 kHz, 25x25 mm. Sensitivity: -50 dB Distance in Ambient Air: 50 mm

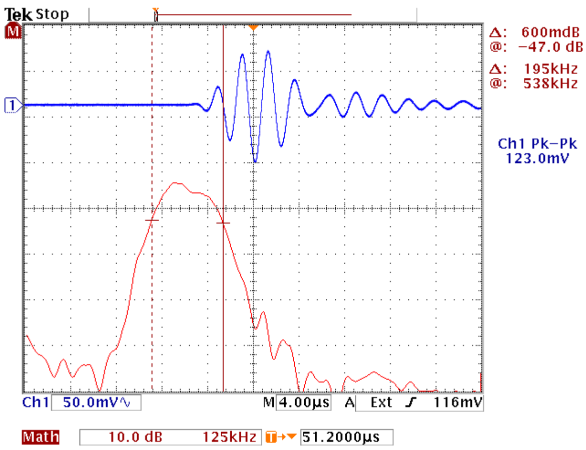

Figure 6. 500 kHz, 19x19 mm, Sensitivity: -48 dB dB Distance in Ambient Air: 20mm

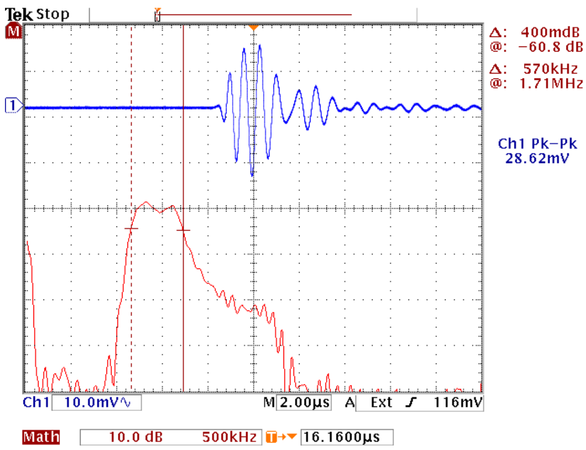

Figure 7. 1.0 MHz, 12.5x12.5 mm. Sensitivity: -60 Distance in Ambient Air: 5 mm

In order to demonstrate the extremely high efficiency of NCU transducers in the megahertz frequency regime an unusual experiment was performed in direct transmission mode. NCU transducers with characteristic frequencies of 1.0 and 3.0 MHz, with 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 using 64 dB gain. The 1.0 MHz the transducers were separated by approximately 10 mm ambient air and the 3.0 MHz, by 6 mm. Flat samples of aluminium (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. Figure 8 shows transmitted signals at 1.0 MHz, and figure 9, at 3.0 MHz. The signal to noise ratio in these observations were enhanced by signal averaging. Considering high frequency and variability in the acoustic impedance of materials reported here, it is quite surprising that one can expect to see NCU transmission through them with mere 16 volt sine wave excitation. This is a testimonial to extremely high efficiency of NCU transducers, however, from a practical standpoint it is not our recommendation that such low voltage excitation be used since higher excitations dramatically improve the signal to noise ratio. This does demonstrate, however, the extremely high sensitivity of these NCU transducers.

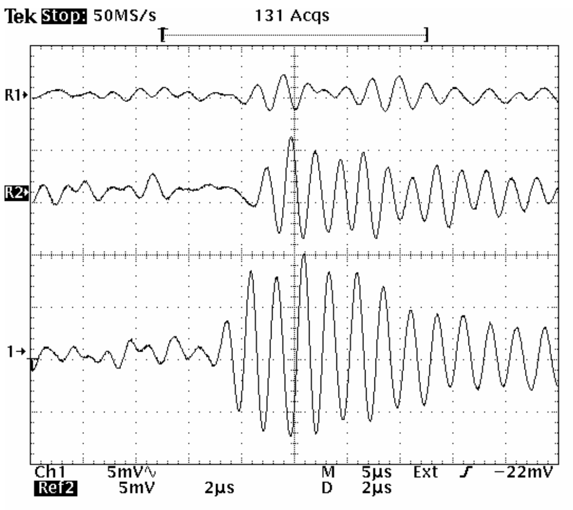

Figure 8. NCU transmission at 1.0 MHz. Top trace: 3.2 mm aluminium. Middle trace: 5mm CFRP. Bottom trace: 3.2 mm PMMA.

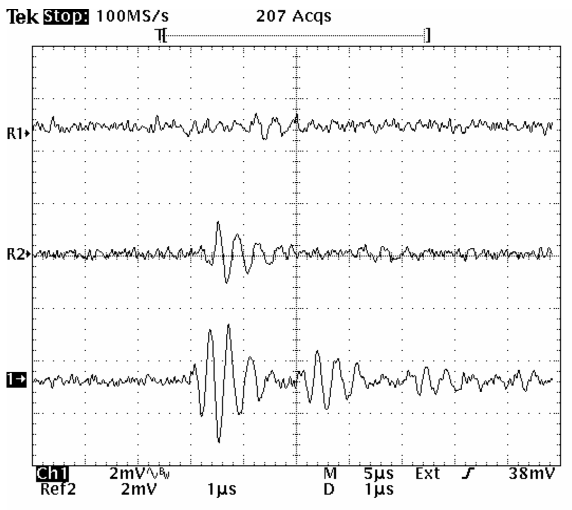

Figure 9. NCU transmission at 3.0 MHz. Top trace: 3.2 mm aluminium. Middle trace: 5 mm CFRP. Bottom trace: 3.2 mm PMMA. Observed thickness resolution in CFRP and PMMA

2.2 Applications and Future Work

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 for that transducer which is characterized by exceptional properties. Together they have elevated the status of ultrasound well beyond conventional wisdom. Besides a myriad of valuable applications in the 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 other entirely unexpected high power related applications. Included is 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 may well rival the discovery of 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 imaginations of thinkers and researchers.

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