PIEZOELECTRIC TRANSDUCERS FOR AIR-COUPLED OPERATION IN THE FREQUENCY RANGE 0.3-2.5 MHZ.

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ABSTRACT.

Use of non-contact techniques to produce and sense acoustic vibrations in the megaherzt frequency range are increasing. Higher frequencies provide higher spatial resolution while non-contact operation is an important improvement for rapid NDE scanning, analysis of materials that can not be wetted or touched, "in-situ" NDE appplications, etc. The approach we present in this paper is based on the use of piezoelectric transducers for both signal generation and reception. It is based on the use of a stack of quarter-wavelength matching layers to improve both the efficiency and the frequency band. To this end it is extremely important to find materials having: very low attenuation, very low acoustic impedance and the thickness requiered for the working frequency of the transducer. Piezoceramics and 1-3 connectivity piezocomposites are studied and compared. Plane and focused transducers are presented.

PRINCIPLES FOR AIR-COUPLED ULTRASOUND.

Air-coupled ultrasound in the megahertz frequency range is becoming a real posibility for some particular applications like: NDT and materials characterization.[1, 2, 3] Main problems of using air-coupled ultrasonic energy are the great acoustic impedance mismatch between air and solid materials, the enormous difference of sound wave velocity between air and any solid material, and the very high attenuation of ultrasonic waves in air. Impedance mismatch give rise to a very high reflection coefficient which produces: low sensitivity and SNR, and a strong influence of multiple reverberations inside samples and transducers. This means very narrow frequency distribution of transducers response and samples transfer function. On the other hand, the difference between velocities of sound in air and solid materials implies strong refraction at the interface, in other words, very low values for the angle for total reflection. To this scenario it must be added the high attenuation of ultrasonic waves in air at ultrasonic frequencies.

<u>High Reflection Coefficient at any Soild/Air Interface.</u>

Reflection and transmission coefficients at a plane discontinuity between two media are given by:

$$T = \frac{4Z_1 Z_2}{\left(Z_1 + Z_2\right)^2} \qquad (1)$$

where Z is the acoustic impedance. Acoustic impedance of the air is about 410 Rayl while for most solids Z is in the range 1-50 MRayl. This is an energy loss between 55 and 88 dB at any solid/air interface. That is, most of the energy is reflected and any solid-air interface is always a problem.

In this sense, the first problem is the interface between the transducer surface and the air. Transducers must be designed so that they can radiate efficiently acoustic energy into the air over a significant frequency band. Possible solutions are the use of low impedance piezoelectric materials (composites, PVDF, etc),[4] and/or the use of a stack of matching layers for piezoelectric transducers.[5, 6 7] An alternative solution is the use of non-piezoelectric transducers like electrostatic transducers.[2, 8, 9] The solution we have developed and we used for the work shown this paper is the use of piezoceramics with a stack of matching layer where the outer one is made of a low-impedance, low-loss, and flexible porous polymer sheet.[5, 7] The second problem appears at the interface between the air and the sample under test. To enhance the amount of energy transferred through the sample some techniques have been intended: excite sample resonances (e.g. thickness resonances in plates),[10] use of Lamb waves,[11] and attaching matching layers to the sample.[7] An alternative is the use of laser generated ultrasound.[12] The third problem that must be considered in this sense is that once the energy is put into a solid it is strongly confined within it. In other words, multiple reverberations inside solid materials are very important. For the transducer it is important because the frequency band response is very narrow. For solid samples having simple geometries (eg. plates) , this is important because the amount of energy that can be transmitted through the sample depends very much on the posibility to excite any mode of vibration of the sample (eigenmode). This depends strongly on the samples dimensions, velocity of sound in the sample and frequency band of the transducer. Nothing similar (in magnitude) is observed in water immersion tests, so results obtained by air-coupled techniques may appear whimsical at a first sight.

<u>Strong Refraction Effects at any Soild/Air Interface.</u>

As a consequence of the extremely high difference between velocities of sound propagation in air and solid materials, the angle of incidence of the acoustic radiation on the solid surface that provides total reflection (limit angle) is very low. This angle is calculated from the Snell's law:

$$\frac{\sin q_1}{v_1} = \frac{\sin q_2}{v_2} \qquad (2)$$

where v is the phase-velocity of sound and q the angle. If wave is travelling from 1 to 2, q_1 is the angle of incidence and q_2 is the angle of refraction. It is clear that refraction depends only on the ratio of velocities of the two media involved. For example: for an air/polymer interface it is about 9º, and less than 4º for most air/metal interfaces. This fact has very important consequences when samples having rough or curved surfaces are to be inspected and for the design of focused transducers for through transmission operation.

Situation is illustrated in Fig 1: Transducer “a” has a very short focal distance. Much of the acoustic radiation impignes on the sample surface at an angle of incidence larger than the limit angle and is completely reflected back..Only a smal portion of energy at the center of the transducer is able to go through the interface. Due to a strong refraction at the interface (Snell’s law) the beam becomes strongly focused within the sample and afterwards diverges swiftly. Therefore, the energy flux at the end of the sample is extremely low. In addition surface waves may be generated at sample surface. On the contrary, transducer “b” in Fig.1 presents a much larger focal distance. All the energy emitted by the transducer impignes on the sample at an angle of incidence lower than the limit angle. Total reflection is avoided. Once again, the strong refraction effects at the interface has a very strong influence on focusing the acoustic beam. In this case, much more energy is transmitted through the solid plate. In both cases, the acoustic energy is slighly defocused due to the appearance of two different waves in the sample propagating at different velocities: longitudinal and shear waves.

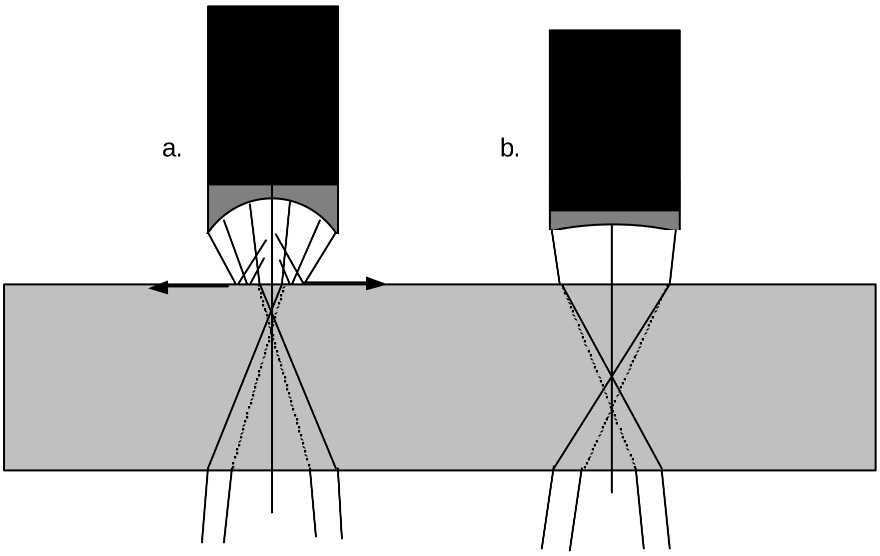


Figure 1. Refraction at the surfaces of a plate in a through transmission test for two differen focused transducers. Solid and dashed lines in the sample represent longitudinal transverse waves respectively.

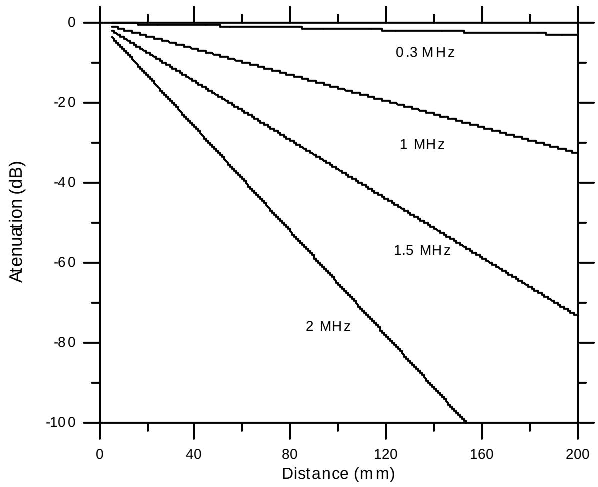


Figure 2. Attenuation of ultrasonic waves in air at normal conditions for 0.3, 1, 1.5, and 2 MHz versus distance travelled in the air.

<u>High attenuation of ultrasonic waves in the air.</u>

Ultrasonic waves are highly attenuated in the air. It is possible to reduce the attenuation of ultrsonic waves in air by increasing the pressure, but this is normally not possible. The only one solution left is to reduce as much as possible the dimension of the airgap. An approximate expresion for the attenuation of ultrasonic waves in air at normal conditions is given by:

$$a = 1.88 f^2 \times 10^{-11} \, Np/m \tag{3}$$

To illustrate the effect of the attenuation of ultrasonic waves in air for frequencies in the megahertz range, figure 2 shows some pratical results worked out from Eq. (4).

TRANSDUCER DESING, CONSTRUCTION, AND CHARACTERISATION.

Two kind of transducers were designed: plane and focused.

Plane Transducers

Efficient air-coupled operation (high sensitivity and high SNR) is achieved by attaching a stack of 2 layers to the piezoceramic surface. In all cases, the first is a λ/4 layer of PMMA, the second is a low-impedance, low-loss, and microporous λ/4 polymer sheet specially designed for this application. (see references [5] ,[7]). Table I shows the acoustic impedance and attenuation of the microporous polymer sheet used as the outter matching layer.

Table I. Acoustic properties of the microporous polymer sheet used as matching layer.

Acoustic Impedance (MRayl)	Attenuation @ f_r (Np/m)	λ/4 frequency f_r (MHz)
0.1	310	0.5
0.22	220	1
0.38	600	1.5

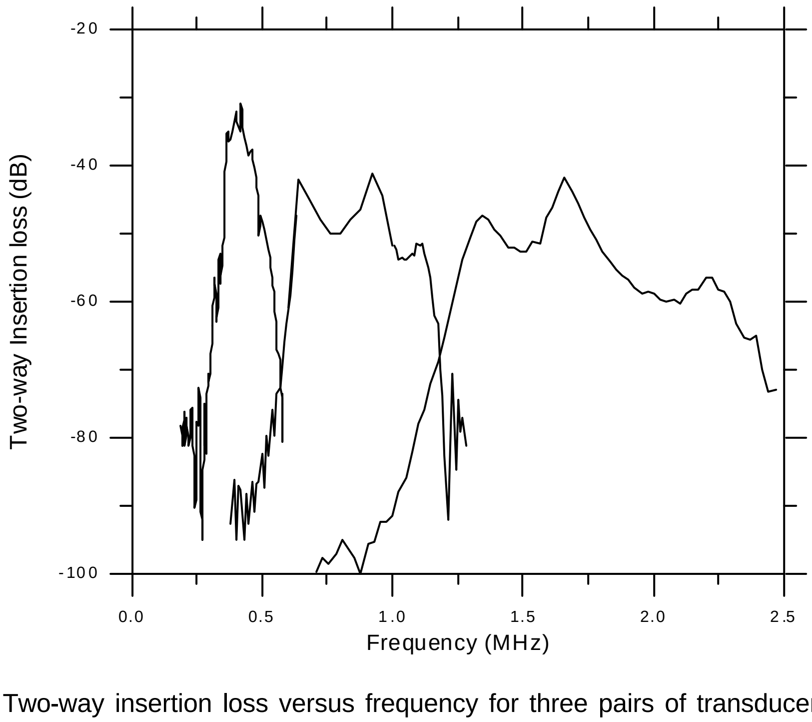


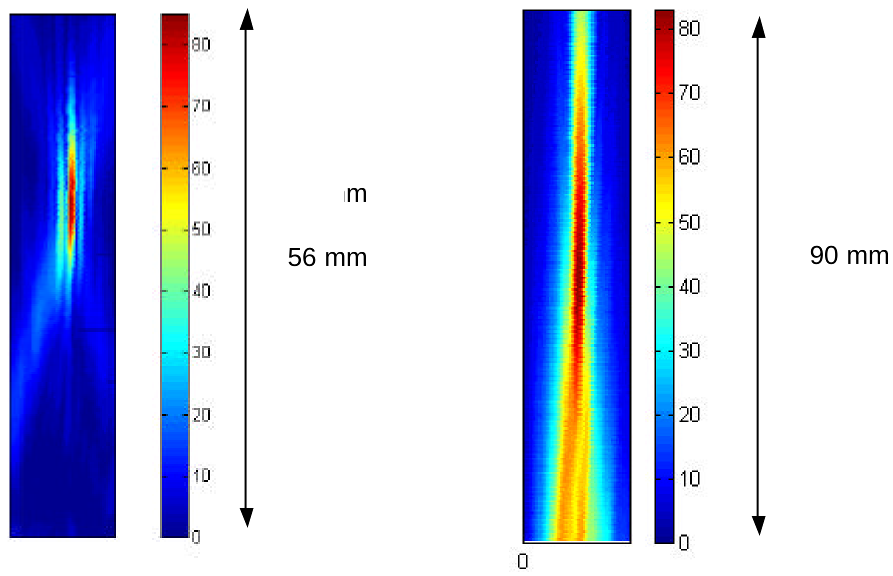
Figure 3. Two-way insertion loss versus frequency for three pairs of transducers: 0.5, 1, 1.5 MHz. Pitch-catch operation.

Three plane transducers wer designed and produced. Centre frequency is 0.5, 0.8 and 1.5 MHz respectively. For 0.5 MHz transducers Ferroperm PZ-27 ceramic disk was used. For 0.8 and 1.5 MHz transducers 1-3 composites made of PZ-26 and epoxy resin were used. Figure 3 shows the insertion loss calculated from the frequency response. It was measured using two identical transducers operation in through-transmission mode; separation between transducers was 1cm. Transmitter transducer was driven by a broad band pulse generated by a HP 811A. Received signal was displayed on an oscilloscope (Tektronix 2432 A), digitized and transferred to a PC for FFT transform. Time domain waveform of the pulse applied to the transmitter transducer was also digitized, stored on the computer and FFT calculated. Attenuation in the air is taken into account by Eq. (4).

Values around 1 MHz are comparable to those reported by Yano et. al for 1 MHz piezoelectric transducers with two matching layers: polymer and microporous polyolefin.[2]

<u>Focused Transducers</u>

For the focused transducer a silicone rubber spherical lens (central thickness of λ/4) was located in between the PMMA and the porous polymer sheet. 1 MHz, PZ 26 ceramic disks (Ferroperm) were used.



4.a

4.b

Figure 4. Acoustic field of the focused transducer (located at the bottom of the image radiating upwards).

Two focused transducers were produced. Focal distance is: 3 cm and 7 cm respectively. Figure 4 shows the longitudinal acoustic field distribution for both transducers operating in air. Lateral resolution at the focal point is about 0.3 mm and 2 mm respectively. The first is used for surface analysis,[6, 13] while the second is used for through transmission NDE at high spatial resolution.

CONCLUSIONS.

Main problems of air-coupled ultrasound have been discused. For air-coupled piezoelectric transducers the main problem is the low sensitivity and the narrow frequency band response. A technique to produce air-coupled piezoelectric transducers having high sensitivity but also a significant frequency band operation is presented. It is based on the use of two quarter wavelength matching layers; for the higher frequencies 1-3 piezocomposites were used. Plane transducers covering the frequency range 0.3-2.5 MHz were produced and characterized. Two kind of focused transducers (centre frequency 1 MHz) were also produced and characterized.

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