AIR-COUPLED PIEZOELECTRIC ARRAY TRANSDUCERS FOR NDT APPLICATIONS

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Abstract: Air coupled ultrasonic NDT using single transducers is growing in interest. The goal remains in the design of transducers sensitive enough to perform standard test protocols. Piezoelectric transducers specially adapted to air coupling have shown good performances at frequencies up to 5 MHz. Different labs and companies have started using these transducers for standard NDT. Nevertheless very little work has been made to extend the air-coupled testing with linear or phase array configurations.

A novel piezoelectric array transducer design for air coupling has been designed, developed and tested. The array works at 0.8 Mhz central frequency with 39% bandwidth. The array has 32 active elements – 15x1mm^2 -and has concave geometry with 35 mm radius. The transducer has two matching layers specially adapted to air loading and low impedance backing.

The concave configuration permits different type of inspections. Lamb waves can be generated selecting a number of transducer channels and a delay configuration without rotating or moving the transducer. This design permits beam steering without alteration of the acoustic wave impact point. Focusing capabilities can also be tailored changing the aperture and the acoustic focal distance to adapt the inspection to different materials and geometries.

Introduction: Air coupled NDT using single transducers is still growing in interest. Since Massa published a pioneer work(1) the evolution of the air-coupled transducers started with the initial proximity sensors made of capacitive transducers. During the last two decades, a big effort has been made to adapt the standard piezoelectric transducer technology to air medium, looking for materials having low density and mechanical losses to be used in the well known one-quarter wavelength matching layers design (2)(3). At the present, piezoelectric transducers coupled to air having two-way insertion losses as low as 30 dB at 1 MHz as been reported (4,5). The capability of capacitive ultrasonic transducers to be used in ultrasonic non-destructive testing has also been studied and demonstrated (6,7). The goal remains in the design of transducers sensitive enough to perform standard test protocols. Companies as QMI and Ultran commercialise piezoelectric transducers with very good sensitivity up to 5 MHz. Nevertheless very little work has been made to extend the air-coupled testing with single transducers to linear or phase array transducer configurations. Only multi-channel configurations of single transducers have been tested to increase the scanning speed of large structures (8).

Concerning inspection techniques through- transmission tests to scan structures looking for defects as dis-bonds in carbon-fibre composites or thickness gauging using longitudinal or transversal bulk waves have demonstrated the possibilities of air-coupling but ,normally, air-coupled ultrasound is related to the excitation and detection of plate waves (9).

The excitation technique consists of launching a plane wave to the surface of the plate with an angle such as to maximize the efficiency of the plate wave excitation. The angle is a simple function of the sound speed in air and the plate mode velocity, $sen\theta_i = \frac{Cair}{Cplate}$. After the angle is reached, if the medium and plate material velocities remain unchanged, no adjustment of the transducer angle is needed and the plate mode is excited with maximum efficiency. Nevertheless, there are applications where the temperature or humidity changes in the surrounding air and/or the material under test, decrease the efficiency of the plate wave generation. Moreover in some on-line applications, the thickness of the tested material can varies, which implies a change on the plate mode velocity and , consequently, the transducer angle must be adjusted to continue exciting efficiently the plate mode.

The above considerations have been the motivations to develop an ultrasonic system able to self-adapt the transducer incident angle without any mechanical action. It consists of a couple of air-coupled transducer arrays working in pitch-catch configuration with concave geometry and array electronics to control the incident angle. The system has been tested for paper inspection, choosing a frequency of 800 kHz, close to known Lamb modes in common paper sheets.

System description: Figure 1 depicts a block diagram of the developed system. The heart of the procedure is the use of a couple of concave lineal arrays specially adapted to work efficiency in air. The system works in pitch-catch configuration. The concave array geometry permits to steer the acoustic emitted and received beams by simply choosing the physical aperture which central radius forms the desired angle with the normal of the plate surface. If the plate is placed at the geometrical focus, all the acoustic beams from the different array sub-apertures will impinge at he same plate zone. Only the incident angle will vary between +/- 15º.

The electronic architecture corresponds to a typical linear array scheme. The excitation stage consists of a delay generator that permits to introduce steering laws into the pulser stage, consisting on 32 independent pulser channels with amplitude selection. The pulser can syntethise arbitrary delayed unipolar pulses up to 500V. The minimum delay for each channel can be independently programmed from 40 ns. to 10,2 µs., in 40 ns increments. The interface between the delay generation and the array transducer is made through an UP2 card – ALTERA-.

The reception at the present design is made with a 32 channels multiplexer and an A/D 12 bits 100 Msps PCI card. A dedicated preamplifier for each reception array element is used before multiplexing.

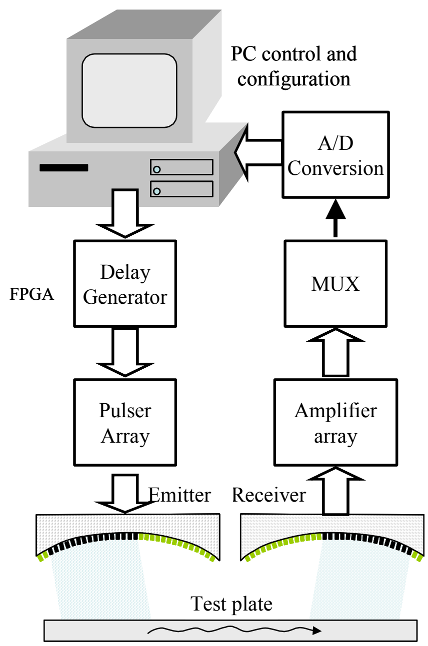


Figure1.- Block diagram of the air-coupled ultrasonic array system.

Transducer fabrication and test: The array transducers have linear configuration. Their construction has five steps. First, a flexible cooper circuit is soldered to the back face of a pz27 1 MHz piezoceramic – Ferroperm- using low temperature soldering pastes. The cooper has defined the electric terminals of the array electrical elements. Then, the plate is diced leaving two acoustic elements in parallel for each electrical channel. A special technique is used to cut completely the plate maintaining its integrity and flexibility. After cutting, the array elements are tested visually and electrically. The second step is the bonding of the array to a concave shape previously synthesised by moulding. This shape acts as backing and has as constituent polyurethane and air micro spheres. The specific acoustic impedance is 1 Mrayl. The glue is the same polyurethane used to make the shape. Pre-curing is made to increase the polymer viscosity. The next stage is to stick on the two matching layers. Both of them are synthesised before being glued to the array. The first one is made of polyurethane – 2.2 Mrayl- and the second one is made of a micro porous material (10) In both cases, the same pre-curing technique is used to avoid that the glue comes into the piezoceramic slabs and to avoid impregnation of the porous matching material. Figure 2 shows a 32 array transducer at a early fabrication stage when the ceramic plate is bonded to the backing after been diced. The array has a curvature radius of 35mm. The array width is 15 mm and the total length is 32mm because the acoustic pith is 1mm and each electrical element has two piezoceramics in parallel. Figure 3 shows the picture of a 32 elements array mounted with the connector and the pulser array electronic stage.

Figure 2.- Picture of the diced piezoelectric plate with the flexible circuit and the backing shape.

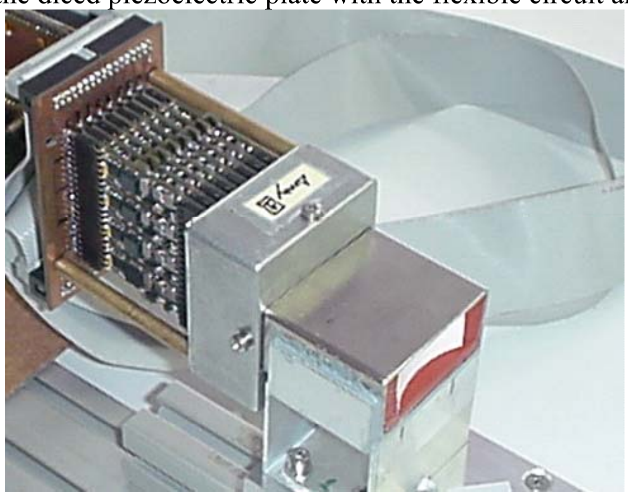
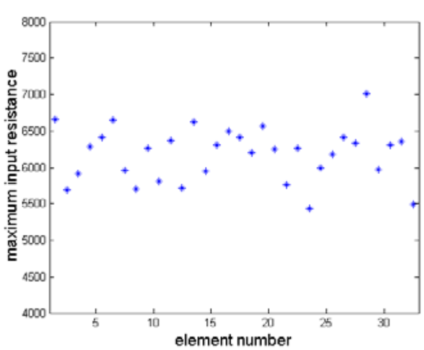


Figure 3.- 32 elements array prototype with the pulser stage.

Transducers test: Electrical impedance and acoustic field tests were performed to characterise the transducers. A HP 4294A Impedance Analyser was used to measure the input electrical impedance of the single array elements. Figure 4 shows the plot of the maximum input electrical resistance of all the elements of a 32 elements prototype. The maximum resistance at the centre of the frequency band – 800 kHz- is 6.12 +/- 0.5 kΩ . The lack of homogeneity – less than a 10%- is typical in piezoelectric array prototypes before establishing a repetitive construction protocol with dedicated mechanical tools.
Figure 5 shows the emission impulse response of a 16 elements array aperture at the geometrical focus- 35mm- . The signal was recorded with a PVDF needle hydrophone with 0.5mm active diameter– SONDA-.



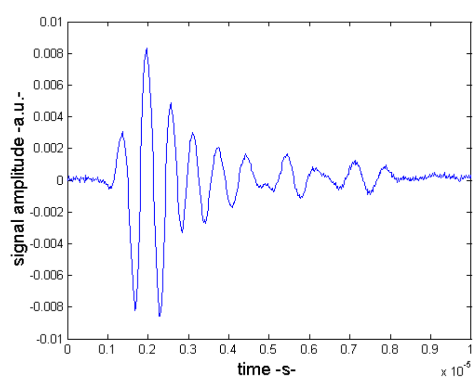


Figure 4.- Input resistance maximum of an array sub aperture of 32 elements.	Figure 5.- Emission impulse response of an array sub aperture of 32 elements measured at the geometrical focus – 35mm

The first acoustic characterisation test was the study of the arrival time of all the array elements at the geometrical focus. This study is necessary because the wave length in air is only 452 µm at 800 kHz and the exciting electronics must be able to correct the delay errors to conform well the steering and defocalisation of the array acoustic aperture . The relative delays recorded at the focus are depicted in figure 6. A maximum deviation of 200ns is observed. This deviation can be corrected by the excitation electronics because the minimum delay step is 40ns.

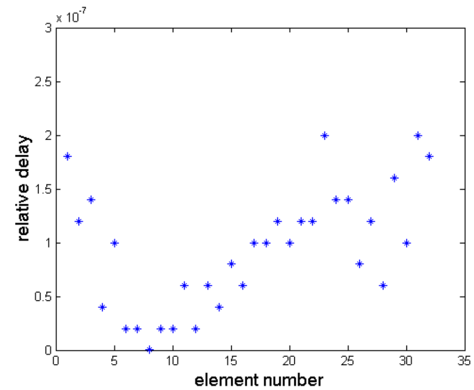


Figure 6.- Relative delay of the individual impulse responses of the 32 array sub-aperture measured at the geometrical focus.

To ascertain the influence of these phase inhomogeneities, the acoustic field of the array was simulated and measured. A 3D acoustic field model based on the Stepanishen approach was used (11) to calculate the field at different propagation planes. Figure 7 depicts the calculated transversal beam profile at the focal zone and the corresponding measured field. The scan was performed with a 3D computer controlled XYZ movement system with 20 µm precision Microcontrole stages. The agreement is quite good indicating that the delay inhomogeneities are not important. The apparent bias of the experimental measures is due to the level threshold of the peak detector used – Panametrics UA5052-.

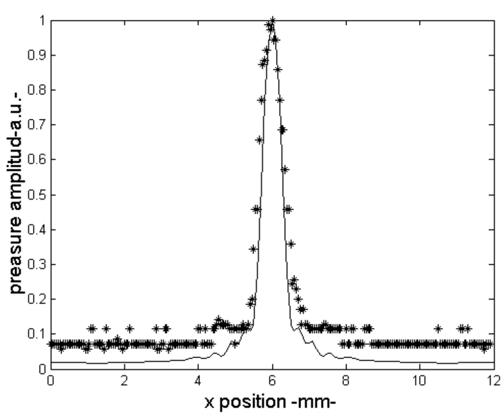


Figure 7.- Calculated – continuous line- and experimental - *- transversal beam profiles of the 32 sub-aperture at the geometrical focus.

Finally the capability of the pulse array electronics to defocus the array geometry was demonstrated .An aperture of 32 elements was used introducing a delay set to acoustically flatten it. The delays are shown in Table I. A delay set to correct the delay inhomogeneities measured during the array characterisation and shown in figure 6 was also added.

Table I.- Delays used to acoustically flatten an array sub-aperture of 16 elements

Element	Delay (ns)	Element	Delay (ns)
1	2600	8	40
2	1960	10	160
3	1440	11	320
4	960	12	600
5	600	13	960
6	320	14	1440
7	160	15	1960
8	40	16	2600

The results can be appreciated in Figure 8 where xz scans before- 8a - and after –8b- introducing the defocusing delays are shown. The figures show the phase of the pressure in function of the xz coordinates.

The curvature on the phase after and before the geometrical focus is evident in figure 8a whereas in figure 8b the on-phase plane wave corresponding to a piston in the near-field region appears. It must be underlined that the delays introduced to correct the phase inhomogeneities affect very little to the final results .

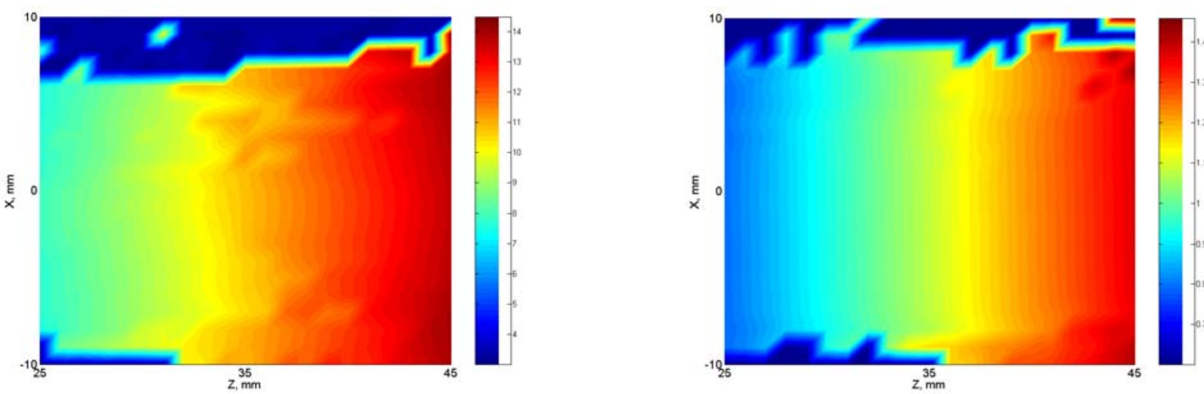


Figure 8.- XZ experimental acoustic field phase scan of a 32 sub-aperture before defocusing – a)- and after introducing delays to create a piston-like emission – b)-.

Conclusions: An array ultrasonic system has been proposed to perform NDT evaluation of plate shaped materials using plate waves in air. The linear array transducers has a cylindrical concave shape which permits to change the angle beam incident to the test plate but without changing the incident zone . The array electronics also permits to vary the acoustic aperture.

The array construction is simple and low-cost. The array transducer has good bandwidth and sensitivity.

The electrical an acoustic tests permits to calibrate the array elements in amplitude and delay excitation. The use of a “defocusing” delay set permits to use this concave array structure as a virtual flat linear array with steering capabilities between +/- 15º without the well known limitations related to standard phase-array designs.

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