Cylindrical and Quasi-Cylindrical Focalization of Air-Coupled Single Element and Linear Array Transducers.

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***Abstract*—This paper describes the design, fabrication, characterization and test of cylindrically focused air-coupled piezoelectric monolithic and linear-array transducers. The objective is to obtain transducers that present a similar performance compared with conventional flat transducers, but more robust for applications involving curved surfaces and/or generation/detection of Lamb waves and a better spatial resolution. Moreover, a linear array configuration is proposed and tested as a means to improve spatial resolution in the non-focused direction. Results show that, compared with conventional flat transducers, it is possible to obtain similar peak sensitivity figures (-22 dB) and bandwidth (75% at -20 dB), though frequency band is slightly displaced towards lower frequencies, with cylindrically focused transducers so there are no apparent reason for quasi-cylindrical configurations. The linear array realization is an effective way to increase spatial resolution along the non-focused direction.**

Keywords—air-coupled transducers; focused transducers; acoustic field, cylindrical acoustic field.

I. INTRODUCTION.

The availability of better air-coupled ultrasonic transducers has made possible many different applications in different fields. In particular, air-coupled ultrasound is a good solution for the inspection/study of flat or plate components than cannot be wetted, but experience some problems with curved surfaces because of the strong refraction at non-normal incidence at any air/solid interface. Another successful application is the generation/reception of Lamb waves using the coincidence principle [1]. However, as this technique tunes the energy to one particular mode, it can find some problems as it is very sensitive to thickness variations, roughness of the plate, local anisotropy or when the system is subjected to vibrations. Some other times, when several modes are to be observed simultaneously (e.g. laser generation) this can also become a problem. In these cases, use of cylindrically focused transducers can provide a more robust solution as far as the focusing system can be implemented without compromising the sensitivity and bandwidth of conventional flat transducers. In addition, cylindrically focused transducers present the advantage of a better spatial resolution in one direction. Moreover, to optimize the spatial resolution along the lens axis, it is proposed the use of a linear array.

Cylindrically focused 250 kHz air coupled transducers have been designed, fabricated, characterized and tested. The proposed design contains a combination of flat and cylindrical matching layers plus a transition flat/cylindrical lens between them. Four realizations have been carried out: two monolithic transducers with a cylindrical lens (75 mm radius), one monolithic transducer with a lens flat in the centre and them cylindrical and one linear array with four elements and a cylindrical lens (75 mm radius). In particular, sensitivity, bandwidth and acoustic field have been measured and they have then been tested for generation and reception of Lamb waves and for through trasnmission in cylindrical glass fiber reinforce polymer pipes. Results are compared with those obtained using similar but flat air-coupled transducers.

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II. TRANSDUCERS DESIGN AND CONSTRUCTION

All transducers presented in this work have been fabricated using 1-3 connectivity piezocomposite disks or slabs working in thickness mode with centre frequency at 250 kHz. Piezocomposites are made of PZT5A fibers (250 um diameter) embedded in an epoxy matrix (random distribution) oriented along the normal direction to the disk or slab plane; ceramic volume fraction is 65%. Surfaces are plated and the composite is poled in the thickness direction. In all cases, transducer housing is made of aluminum.

A. Monolithic flat transducer.

A pair of flat wideband and high sensitivity, piston-like air-coupled transducer [2] have been used for comparison purposes. In this case, active area is circular with diameter 25 mm. Matching to the air is performed by using a stack of five low loss matching layers where the outer matching layer is a quarter wavelength layer [3], [4]. Materials and dimensions for the inner layers were determined by the optimization method based on the concept of frequency and impedance detuning [5].

Fig. 1. Picture of the 250 kHz cylindrically focused air-coupled transducers. Left: Monolithic transducers. Right: 4-elements linear array.

B. *Monolithic cylindrically and quasicylindrically focused transducers*

Four cylindrically focused transducers have been made using 25 x 25 mm 1-3 connectivity piezocomposites slabs. Impedance matching to the air is performed in a similar way as in flat transducers (see section II.A) with the exception that the third intermediate matching layer is not flat but take the shape of a cylindrical lens. Radius of curvature of the lens is 75 mm. Fig. 1 shows a picture of the fabricated transducers.

C. *Linear array transducer cylindrically focused*

As a proof of the concept of using a linear array to improve resolution in the non-focused direction, one kerfless linear array transducer has also been made. The transducer design is the same as in the previous case, but in this case four elements are produced by cutting the metallization on the back electrode as shown in Fig. 2 (200 µm wide and 200 µm depth). Dimensions of the four elements are the same: 25 x 6.175 mm with the longer side oriented normal to the axis of the cylindrical lens (see Fig. 2). As in the previous cases, radius of curvature of the lens is 75 mm. Fig. 1 (right) shows a picture of the fabricated linear array transducer.

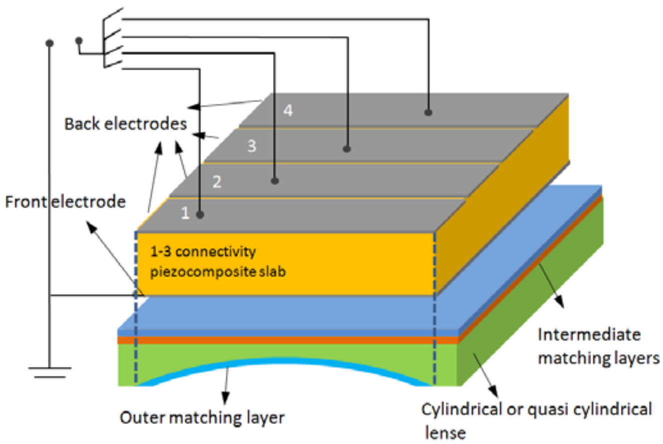

Fig. 2. Scheme of the linear array transducer: elements distribution and lens orientation

Fig. 3. Transducers in through transmission and confocal configuration for peak sensitivity and bandwidth measurement.

III. TRANSDUCERS CHARACTERIZATION

A. *Sensitivity and bandwidth.*

Sensitivity vs frequency is obtained as the ratio of the modulus of the FFT of the electrical signal received at the receiver transducer (Rx) terminals to the modulus of the FFT of the electrical signal applied to the transmitter transducer (Tx). For sensitivity and bandwidth measurements two identical transducers were positioned in confocal configuration (see Fig. 3), distance about 150 mm. In order to evaluate the influence of including a cylindrical lens in the stack of matching layers, similar measurements were performed for a couple of flat transducers having a similar impedance matching solution but no lens. In this case, separation between Tx and Rx was smaller: 26 mm.

Tx was driven by an Olympus 5077 pulser/receiver using a 100 V semicycle of square wave. Received signal was transferred directly, no gain and no filtering, to a digital oscilloscope (Tektronix 5074). Results are shown in Fig. 4. Received signal in the time domain is similar in both cases. This is a somewhat unexpected result, as it was expected that the distortion of the impedance matching due to the presence of the lens would have a larger effect. Moreover, the slightly smaller amplitude obtained with the pair of cylindrically focused transducers can be due to the larger air-path in this case. Both bandwidth and peak sensitivity (with a value of -24 and -27 dB, respectively) are similar, the only difference is that the frequency band of the cylindrically focused transducer is slightly displaced towards lower frequencies. This can be due to the extra thickness of the lens at the lens edge.

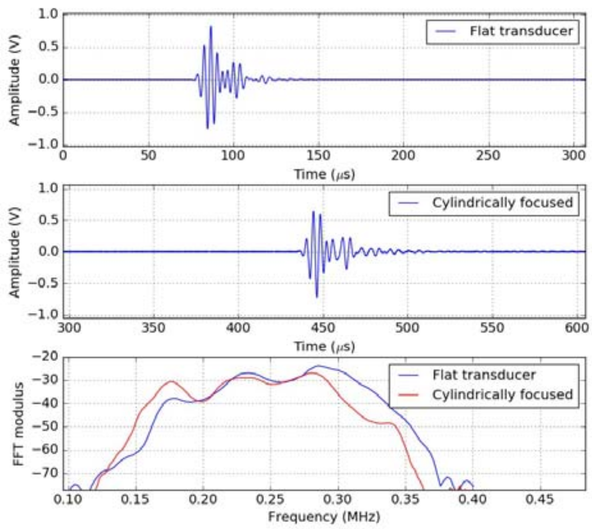

Fig. 4. Magnitude of the FFT of the received signal in through transmission of flat (blue), cilindrically focused (red) transducers.

B. Acoustic field.

The acoustic fields of the monolithic transducer and of each element of the array were also measured. A flat transducer (like that used in the previous section) with a "pinhole" mask (a small central aperture of 0.3 mm) was used as receptor, while the emitter was moved over a rectangular grid. The maximum value of the received signal was used to construct a C-Scan that represents the amplitude of the emitted acoustic field. A Difrascope air-coupled ultrasound equipment along with a DIS-500 positioning system, both from DASEL SL (Madrid, Spain), were used for the experiments.

Figure 5 shows the acoustic field measured in the three principal planes: YZ, XZ and XY, the last at the focus position. As expected, the curvature in the *y* direction generates a focused beam with maximum at *z = 49 mm*, and width *Δy = 3.9 mm,* measured at *-6 dB*. The large size of the transducer in the *x* direction and the lack of curvature generate a much wider beam, with *Δx = 26.2 mm*. The elongated aspect of the focal spot can be appreciated in Figure 5.c.

Figure 6 shows the acoustic field measured when exciting the array element #3. While the beam shape is equivalent to that of the monolithic transducer in the *yz* plane (Figure 6.a), the discretization in the *x* direction produces a narrower beam, with *Δx =12.8 mm*. Thus, in the focal plane at *z = 47 mm*, a more symmetrical spot is obtained (Figure 6.c)

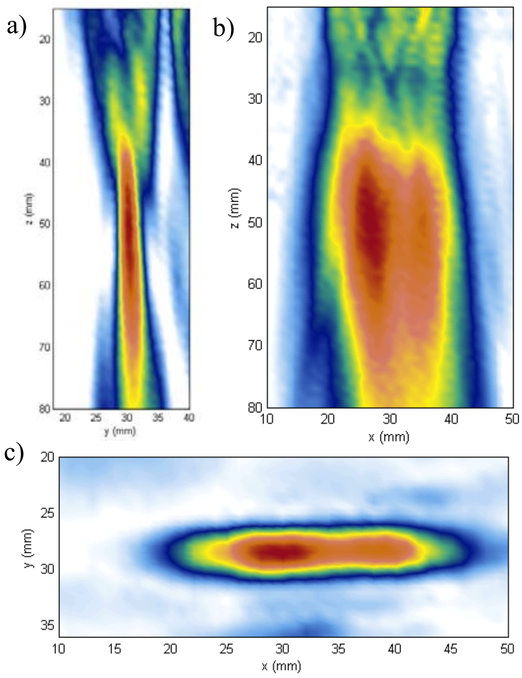

Fig. 5. Measured acoustic field of the monolithic transducer in planes (a) YZ (b) XZ and (c) XZ at Z = 49 mm.

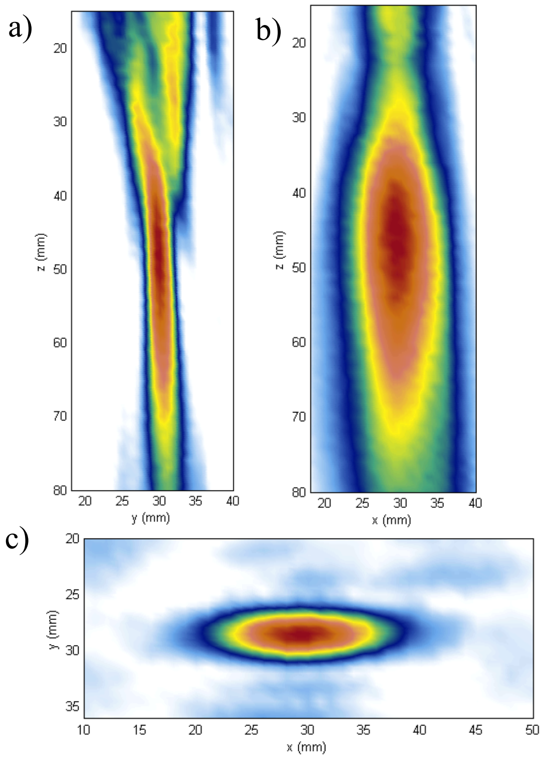

Fig. 6. Measured acoustic field of the elemnt 3 of the array transducer in planes (a) YZ (b) XZ and (c) XZ at Z = 47 mm.

IV. TRANSDUCERS TEST

A. Inspection of curved elements in through transmission configuration.

A glass fiber reinforced cylindrical pipe (200 mm outer diameter) and wall thickness of 3 mm has been inspected in through transmission configuration using both the flat transducers and the cylindrically focused transducers. In this later case, transducers are positioned so that the axis of the cylindrical lens is parallel to the axis of the pipe. Distance between transducers and pipe is set equal to the focal distance. Transmitter transducer is driven by an Olympus 5077 pulser/receiver using a 200 V semicycle of square wave. Received signal was amplified 30 dB in the receiver stage and then transferred to a digital oscilloscope (Tektronix 5074) to digitize and display the signal.

Fig. 7 shows the through transmitted signal through the pipe wall using the flat transducers (7.a) and the cylindrically focused transducers (7.b). As expected, use of cylindrically focused transducers provides a larger amplitude of the transmitted signal due to the better matching of the wave front to the geometry of the solid surface, that decreases the refraction effects, therefore, this is can be used as a means to improve signal to noise ratio in this type of inspections.

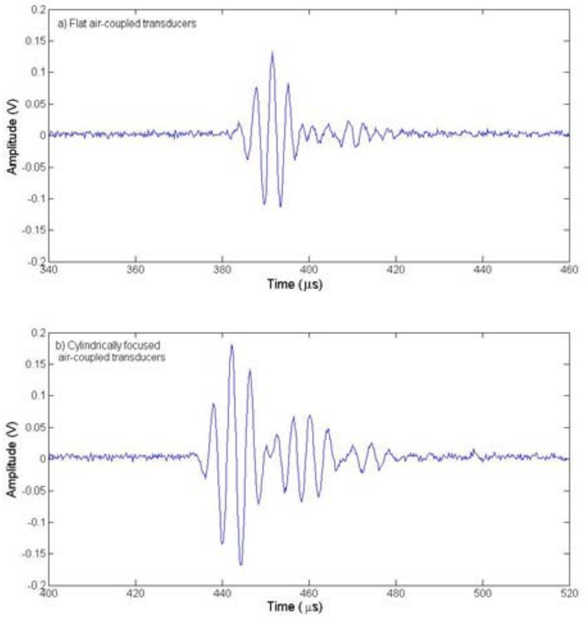

Fig. 7. Through transmission through a cylindrical pipe wall. 7.a. Flat air-coupled transducers. 7.b. Cylindrically focused air-coupled transducers.

B. Generation and detection of Lamb waves..

A 2 mm thick aluminum plate was used to generate and receive Lamb waves using the coincidence principle: angle of incidence is set so that the projection of the incident wave vector over the plate plane coincides with the wave vector of the Lamb wave to be generated (A_0 mode in this case). Experimental set-up is shown in Fig. 8. Same pulser/receiver and oscilloscope as in the previous case were used.

Fig. 9 shows the received signal using flat and cylindrically focused transducers. In this case, the latter case gives rise to a lower amplitude in the received signal but the main advantage is that the angle of incidence can be varied ±5 degrees and the amplitude of the received signal remains constant, while this variation is enough to completely detune the generation/reception of the Lamb wave using the flat transducers.

V. CONCLUSIONS

Design, fabrication and test of air-coupled 250 kHz cylindrically focused monolithic and linear array transducers (4 elements) have been shown. The comparison of the cylindrically focused transducer with a similar flat transducer reveals that the inclusion of a cylindrical lens have a very small effect on the transducer performance: peak sensitivity is reduced by 4 dB, bandwidth is similar and frequency band is slightly displaced towards lower values. The study of the acoustic field of the linear array prototype with four elements reveals that this is an effective means to reduce focal spot in the non-focused direction, while keeping the other properties of the cylindrically focused geometry. Finally, the cylindrically focused transducers were tested to perform through transmission through a cylindrical pipe and to generate and receive the A_0 Lamb mode in an aluminum plate.

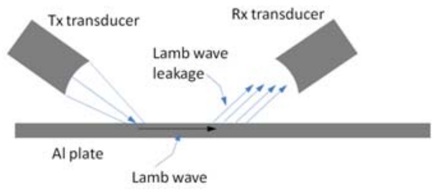

Fig. 8. Shematic representation of the use of cylindrically focused air-coupled transducer to generat and receive Lamb waves in plates.

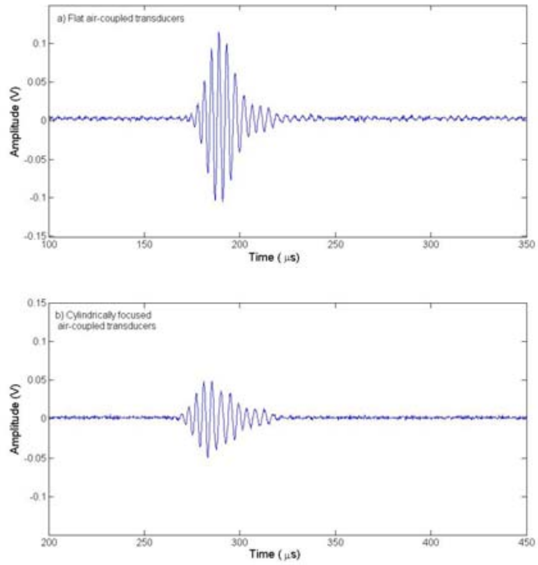

Fig. 9. Generation and detection of A0 mode in Al plate.

For the cylindrical pipe inspection, results show that the amplitude of the transmitted signal is larger for the focused transducer, probably due to the better matching between acoustic field geometry and solid geometry. This can be used to improve signal to noise ratio in the inspection of some curved surfaces. On the contrary, amplitude of the received A_0 Lamb mode is smaller for the focused transducers. Nonetheless, the amplitude of the received signal remains constant if orientation of the transducers is changed ±5 degrees. This means that this configuration is more robust and able to keep tuned to one particular mode even when changes of thickness, surface roughness, etc. are present.

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