Air-coupled and Water Immersion Sectorized Array Transducers for Industrial and Medical Endoscopy

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***Abstract*—This paper describes the design, fabrication, characterization and test of three sectorized array transducers: one for air-coupled operation (400 kHz, 25 mm diameter) and two for water-coupled operation (4 MHz, 10 mm diameter and 2 MHz, 5 mm diameter). The objective is to use these transducers in pulse-echo mode along with a conical reflector to generate a 2D cylindrical acoustic field with angular resolution that can be used for industrial and/or medical ultrasonic endoscopy. Some examples of use of these prototypes to inspect different pipes (size and materials) and to determine both inner diameter and wall thickness are also shown.**

Keywords—Sectorized transducer array; ultrasonic endoscopy; water-coupled transducers, air-coupled transducers. resonant spectroscopy.

I. Introduction

Inspection of large or small pipes and/or tubes is commonly found in many different ultrasonic industrial and medical applications. Industrial use of endoscopes is mainly focused on the determination of the pipe wall thickness (corrosion) and the inner diameter (fouling). These application are mainly limited by the pipe diameter, geometry and pipe cross-section variations. In medical applications, ultrasonic endoscopy is used as diagnosis tool for arteries (IVUS) and the digestive tract.

Flat monolithic transducers with conical reflectors have already been proposed as an easy and cheap solution for industrial and robotics applications [1] but the main drawback of this design for endoscopic applications is the need to keep the transducer aligned with the pipe axis. Moreover, any separation of the pipe/vessel shape from cylindrical can compromise the viability of this approach. Conventional solutions avoid this problem by focusing the acoustic field at one point of the cylindrical wall by either a lens or a mirror, but in this case the inspection of the whole section requires to include some type of mechanical rotation of either the whole transducer or just the mirror ([2]).

To alleviate this problem of the monolithic transducer + conical reflector design, we propose a sectorized flat array transducer with 8 elements and a conical reflector to generate a 2D acoustic field with cylindrical geometry and angular resolution (Fig. 1). A similar design was tested for echo-location and contactless human-machine interface in Ref. [1].

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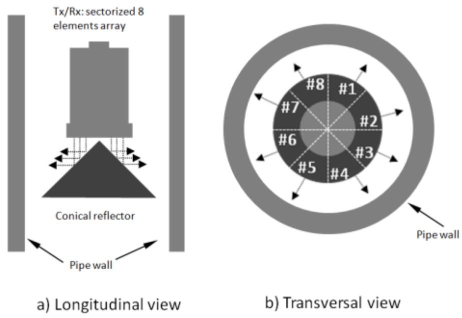

Fig. 1. Schematic representation of the transducer, the conical reflector and the pipe/vessel..

This solution makes possible to inspect non symmetric pipes or the inspection even when the transducer centre is not precisely located along the axis of the pipe. To proof this concept, three different 8-elements sectorized arrays have been produced, characterized and tested. One air-coupled array: 400 kHz and 25 mm diam., and two water coupled arrays: 4 MHz with 10 mm diam. and 2 MHz with 5 mm diam. The capability of this design to determine both pipe inner diameter and pipe thickness is tested in a few cases.

The conical reflector design presented in this paper is an independent part of the transducer, but future work will incorporate the cylindrical reflector in the transducer housing in one single piece.

II. Transducer Fabrication

A. Piezoelectric elements.

In all cases, 1-3 connectivity piezocomposite disks have been employed. They are made of PZT5A fibers (250 μm diameter) randomly embedded in an epoxy resin matrix. Ceramic volume fraction is 65% and acoustic impedance about 15 MRayl in all cases. They are poled in the thickness direction and all of them are operated in thickness mode. All arrays are kerfless arrays with 8 elements (see Fig. 2). The different elements are obtained by cutting the metallization of the back electrode (100 μm wide and 100 μm depth). Composite disks diameters are: 25 mm for the 400 kHz air-coupled array, 15 mm for the 5 MHz water coupled array and 5 mm for the 2 MHz water-coupled array.

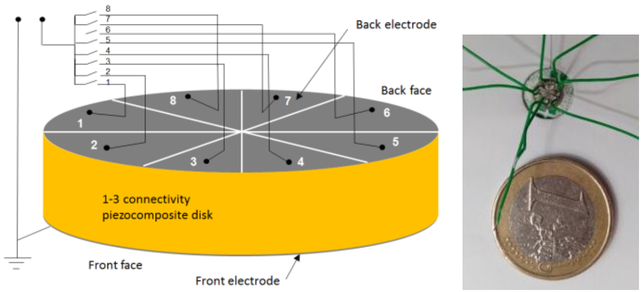

Fig. 2. Left: Schematic view of the 8-elements kerfless sectorized array. Right: Picture of the 5 mm diameter water-coupled array (2 MHz) before encapsulation.

B. *Air-coupled array*

Fig. 3 (left) shows a picture of the air-coupled array prototype. In the case of air-coupled transducers matching to the air is a critical point. In this case, this is achieved by a stack of five low-loss matching layers (see Ref. [3] and Ref. [4]) designed by the optimization method based on frequency and impedance detuning (see Ref. [5]). Housing is made of aluminum, and no connector is included at this stage

Fig. 3 right, shows the air-coupled array together with the conical reflector used to generate the acoustic field with the desired cylindrical field geometry for endoscopy. This conical reflector is an independent part, but future work will incorporate the cylindrical reflector in the transducer housing in one single piece. Array lift off respect to the tip of the conical reflector is 2 mm.

C. *Water-coupled arrays*

Fig. 3 shows a picture of the water-coupled array prototypes. The 4 MHz array (diameter of the active area is 15 mm) has a 20 mm long backing made of epoxy resin loaded with tungsten particles (50%, weight). The 2 MHz array (diameter of the active area 5 mm) has a 10 mm long backing made of of epoxy resin loaded with alumina particles, 5µm diameter (50% weight). No matching layers were included at this stage, but they can be added in further steps. Housings are made of aluminum, and no connectors are included.

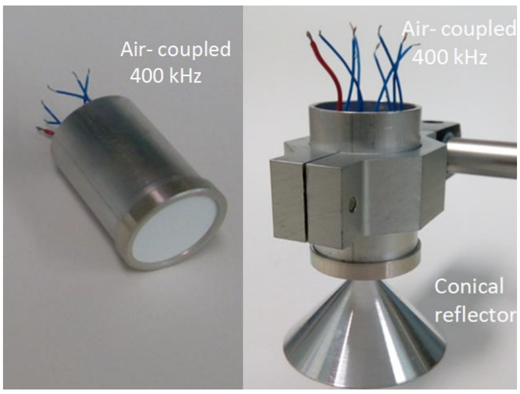

Fig. 3. Left: Picture of the prototype of the air-coupled 400 kHz sectorized array (housing outer diameter: 29 mm). Right: air-coupled array together with the conical reflector.

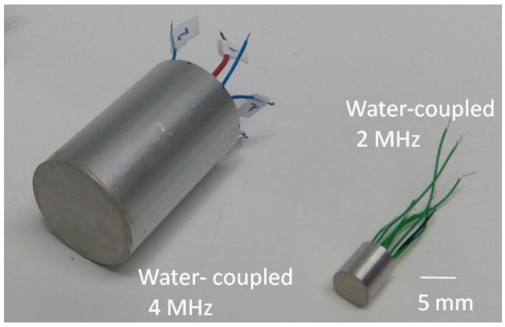

Fig. 4. Picture of the prototypes of the 4 MHz array (left) and the 2 MHz array (right).

III. ARRAYS CHARACTERIZATION

A. *Air-coupled array.*

To characterized frequency band, pulse shape and directivity of each element, the conical reflector was positioned on a flat surface and the transducer facing it (see Figs. 3 and 5). A cylindrical reflector (20 mm diameter) was positioned on the flat surface at a distance of 200 mm (see Fig. 5 and 6). Transducer was driven by a semicycle of square wave (Olympus 5077 pulser receiver 100 V, 0dB gain); signal was transferred, digitized and displayed by a Tektronix DPO 7054 scope. Fast Fourier Transform (FFT) of the signal is extracted by MATLAB.

Fig. 5 shows the received echo (using just one element) and the modulus of the FFT of this same echo. Center frequency of this element is 0.45 MHz and peak to peak amplitude of the received echo was 45 mV. Similar figures were obtained with the rest of the elements of this array. Frequency band is similar to that obtained without the conical reflector, so it does not represent a significant disruption.

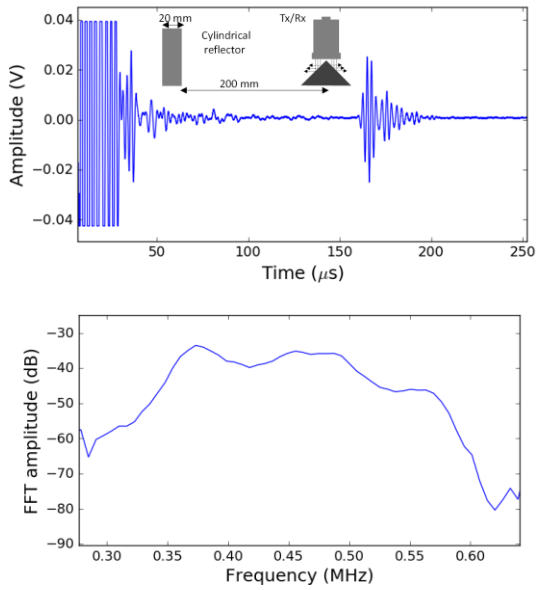

Fig. 5. Top: Received echo from a 20 mm cylindrical reflector located at 200 mm. Bottom: Magnitude of the FFT of the received echo.

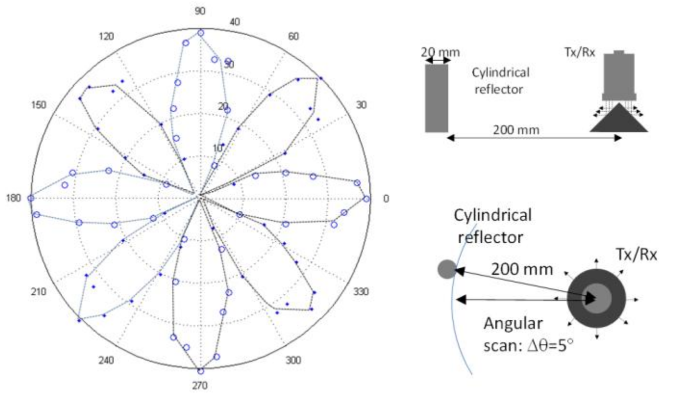

Fig. 6. Top: Received echo from a 20 mm cylindrical reflector located at 200 mm. Bottom: Magnitude of the FFT of the received echo.

To characterize the directivity of each element, the cylindrical reflector was rotated around the transducer (Fig. 6) in steps of 5 degrees, separation between the axis of the cylindrical reflector and the conical reflector was 200 mm. Received echo was recorded (just using the element of the array in front of the cylindrical reflector). Fig. 6 shows the angular plot of the echo peak to peak amplitude versus angle.

B. Water-coupled array.

Both water-coupled arrays were first tested in pulse-echo mode but without the conical reflector, and using just a flat reflector. The objective is to have a direct estimation of the sensitivity and bandwidth of each element and the variations between elements. Sensitivity is obtained as the ratio of the magnitude of the FFT of the voltage signal generated at the transducer terminals by the received echo to the magnitude of the FFT of the electrical signal applied to the transducer terminals.

Both sensitivity band and received echo in the time domain are shown in Fig 7 for one element of the 2 MHz 5 mm diameter array. 6-dB bandwidth varied between 26 and 33%, while peak sensitivity varied from -54 to -48 dB. With the 4 MHz array we obtained: 6-dB bandwidth about 40% and a peak sensitivity between -32 and -28 dB.

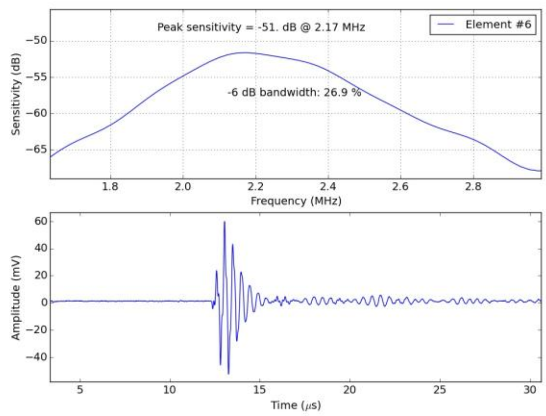

Fig. 7. Sensitivity frequency band and received echo in time domain from a flat reflector by element #6 of the 2 MHz array.

IV. PULSE-ECHO WITHIN A PIPE USING WATER-COUPLED ARRAYS WITH THE CONICAL REFLECTOR.

The described water-coupled arrays along with the conical reflector were introduced within different water-filled pipes and operated in pulse-echo to receive the echo coming from the pipe wall. Three different pipes have been employed for these tests, main properties appear in Table I.

TABLE I. PIPES USED TO TEST THE WATER-COUPLED ARRAYS

Pipe material	Wall thickness (mm)	Inner diameter (mm)	Wall first thickness resonance (MHz)
Al	1.5	15	2.1
Al	3.5	38	0.9
Steel	2.1	25	1.4

Inner pipe diameter can be estimated from the time of flight of the first received echo if the lift off of the transducer respect to the tip of the conical reflector is known. Pipe wall thickness can be estimated from the time of flight between the echo coming from the pipe inner surface and the echo coming from the pipe outer surface (if the material the pipe is made of is known). When thickness is too small or frequency too low or frequency band too narrow, these echoes may appear overlapped making impossible the thickness estimation based on the time of flight measurement. In these cases, wall thickness can be obtained from the analysis of the spectral components of the received echo if thickness resonances of the pipe wall appear within the transducer frequency band. In this case, thickness resonances appear as a local minimum of the reflection coefficient magnitude spectra.

Fig. 8 shows the received echoes for the pipe wall using one element of the 4 MHz array and the FFT of these echoes for two different pipes: Al wall thickness 3.5 mm and steel wall thickness of 2.1 mm. These combination of pipes and transducers provide two extreme cases. In the first one, the echoes from the inner and the outer wall surfaces appear clearly separated (1.1 μs) and it is possible to obtain wall thickness from this measurement, assuming velocity in aluminum 6300 m/s, obtained wall thickness is 3.47 mm. On the contrary, in the second case, both echoes appear overlapped and the only way to get the pipe wall is to extract the FFT and measure the location of the thickness resonances: 2.8 and 4.2 MHz, therefore, frequency of the first thickness resonance is located at 1.4 MHz, then, assuming ultrasound velocity in the steel of 5900 m/s, obtained wall thickness is 2.1 mm. In both cases it is possible to determine the pipe inner diameter from the transducer lift off and the time of arrival of the first echo.

For the Al 3.5 mm thick wall pipe, were echoes appear separated in the time domain, the resonant and frequency domain technique can also be used. In this case, resonances appear about 2.8, 3.6 and 4.4 MHz, so first order resonance must be about 0.9 MHz, hence, estimated wall thickness is 3.5 mm if 6300 m/s is the velocity in the aluminum pipe.

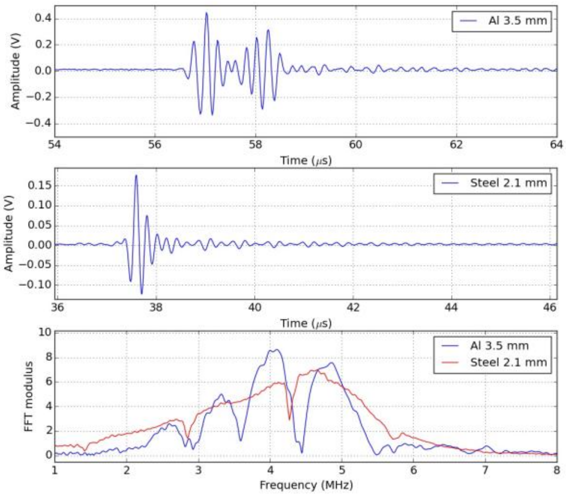

Fig. 8. Echoes (and theri) FFT received from two different pipes using the 4 MHz water coupled array and the conical reflector

Fig. 9 shows the received echoes (time domain and magnitude spectrum) from the Al pipe (1.5 mm thick wall), using two elements of the 4 MHz array. Echoes from the two pipe wall surfaces appear overlapped but the magnitude spectra shows two orders of the wall resonances (around 2.2 and 4.5 MHz) that make possible to determine pipe wall thickness that reveal a variation of the pipe wall thickness in front of the array elements #5 (1.5 mm) and #7 (1.37 mm).

Fig. 10 shows the received echoes (time domain and magnitude spectrum) using two different elements of the 2 MHz array for the Al pipe with 1.5 mm thick wall. Echoes from the two pipe wall surfaces appear overlapped making impossible the time of flight estimation but the signal spectra shows one thickness resonance around 2.1, as before, this make possible to determine the pipe wall thickness. Alternatively, it is possible to analyze the frequency content of the resonant tail of the echo to get a direct measurement of the wall resonant frequency. For data shown in Fig. 9 we obtained: 2.2 MHz (element #1) and 2.0 MHz (element #6).

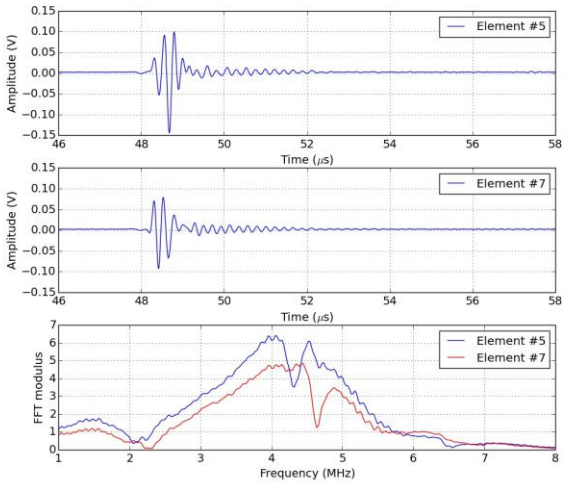

Fig. 9. Echoes and FFT received from one pipe with two different elements of the 4 MHz water coupled array and the conical reflector.

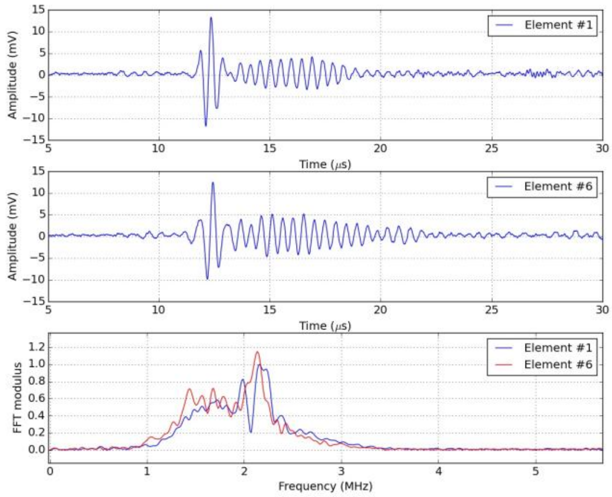

Fig. 10. Echoes received from one pipe (and their FFT) with two different elements of the 4 MHz water coupled array and the conical reflector.

V. Conclusions.

Results presented confirm the viability of the proposed technique to fabricate air-coupled (400 kHz) and water-coupled (2 and 4 MHz) sectorized arrays with 8 elements using 1-3 connectivity composites. The arrays are used along with a conical reflector to generate a 2D cylindrical acoustic field with improved angular resolution that can be used for endoscopy. Angular directivity pattern was measured. Results were shown for the 400 kHz air-coupled array, and this reveal the angular resolution of this configuration. It is shown that the presence of this conical reflector does not alter frequency band or pulse shape. This solution has been tested for different pipes, showing that it is possible to obtain pipe inner diameter and wall thickness from time of flight measurements (when echoes do not averlapp) or from the analysis of wall resonances (when the echoes appear overlapped).

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