Annular multifrequency piezoelectric array for enhanced wideband ultrasonic response.

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***Abstract*—This paper presents the main results of a research carried out to achieve ultrasonic piezoelectric transducers with a bandwidth larger than that of present devices. The design is based on a kerfless multifrequency annular array, which is machined out of a 1-3 connectivity piezocomposite disk. The elements of the array are designed so that they i) present a different resonant frequency and ii) the individual frequency bands of the elements overlap to furnish an overall response that approximate to the sum of the individual responses. A two elements array is presented: a central disk and a external ring with centre frequencies of 0.55 and 0.25 MHz, respectively. The transducer is designed for water immersion and is tested in pulse-echo. Bandwidth of the final design extends from 0.19 MHz up to 0.98 MHz, with a 6dB relative bandwidth close to 130%.**

Keywords—ultrasonic transducers; annular array; wide-band; multifrequency array.

I. Introduction

Piezoelectric ultrasonic transducers are normally based on geometrical resonances of a piezoelectric element; this makes them to present a reduced frequency bandwidth response when compared with other non-resonant ultrasonic transducers (e.g. electrostatic transducers [1], [2], hydrophones, etc.). However, wide frequency band response is a key element in many different applications like, for example, ultrasonic communications [2], [3] and spectral materials characterization. In addition, wider frequency band also mean shorter impulse response which is important to improve the axial resolution in fields like medical image and Non Destructive Testing applications [5], [6]. Moreover, in the case of air-coupled transducers, to achieve wideband response is even more difficult due to the huge acoustic impedance between the air and the piezoelectric material [7]-[11].

In this paper we present a transducer design, aimed to achieve larger frequency bandwidths, based on an annular array configuration which has been designed according to the following key ideas: i) each element presents a frequency band centered at a different frequency, ii) the frequency band of the different elements overlaps iii) the final bandwidth of the array is approximately the sum of the individual bandwidths of the different elements. Design, construction and characterization of an annular multifrequency array with two (a central disk and an external ring) are shown.

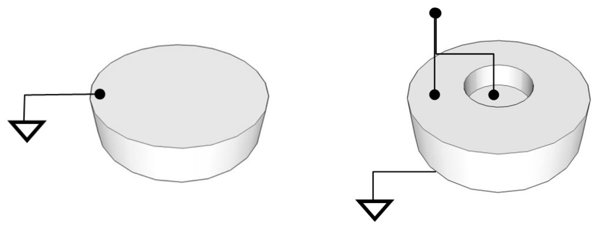

Fig. 1. Schematic representation of the original 0.25 MHz resonant frequency piezocomposite disk (left), and the mechanized two elements annular array: external ring with resonant frequency at 0.25 MHz and internal disk with resonant frequency at 0.55 MHz.

II. Array Design and Construction.

A. Piezoelectric elements: design and characterization.

Starting point is a 1-3 piezocomposite disk made of a random distribution of PZT5A piezoelectric fibers in an epoxy matrix (ceramic volume fraction 65%), poled in the thickness direction and with surfaces electroded (Fig. 1, left). Thickness is 6.2 mm and the diameter 25 mm.

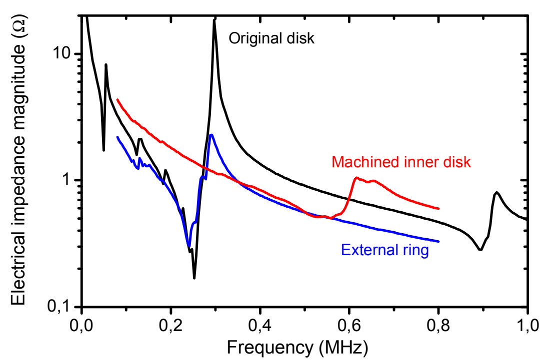

Fig. 2. Electrical impedance vs. frequency of the original 1-3 connectivity piezocomposite disk, and the machined external ring and inner disk.

Funding by MINECO, through project DPI 2011-22438 is acknowledged.

As a first characterization, the electrical impedance is measured using a Bode 100 (Omicron Lab) network analyzer, see Fig. 2. The thickness resonant frequency is located at 250 kHz. 1-3 connectivity composites are chosen to minimize the presence of radial modes (that are still to be seen at frequencies below 150 kHz, see Fig. 2.a) and to minimize the mechanical coupling between the two elements of the array.

Then, the disk was mechanized to reduce the thickness in a central circular area down to 3 mm. The resulting geometry is an external ring and a thinner internal disk, see Fig. 1 (right). Central disk and external ring will be the two elements of the array without any further mechanical isolation between them; this feature largely simplifies the fabrication. The electrical impedance vs. frequency for each of these elements is shown in Fig. 2.

Thickness reduction of the central disk is calculated so that the first thickness resonance of this element appears between the first and the second order thickness resonances of the external ring (see Fig. 2), which is effectively achieved as the first two resonances of the ring appear at 0.25 and 0.9 MHz, and the resonance of the disk appears at 0.55 MHz. The areas of the two elements are calculated to equate the electrical impedances at resonance of both elements. Main effects of the mutual influence between elements are that the radial modes disappear and that the central disk is largely damped, which is due to the influence of the external ring.

Once machined, the surface of the inner disk were electroded and cables were connected to the stepped face. The disk were mounted on an aluminum housing, leaving the flat surface of the array as the radiating face.

B. Passive components: Impedance matching layers and backing.

A high impedance backing (6 MRayl) made of epoxy resin loaded with heavy particles was added. This backing produces a large damping of the thickness resonances of both elements (see Fig. 3.b) and a slight shift of the resonant frequency towards lower values.

Then, quarter wavelength impedance matching layers were added to each element. As the transducer is intended for water immersion use, the acoustic impedance of matching layer (Z_{ML}) is given by Eq. (1)

$$Z_{ML} = \sqrt{Z_C Z_W} \quad (1)$$

Where Z_C and Z_W are the acoustic impedances of the composite (15 MRayl) and the water (1.45 MRayl), respectively. Therefore, the acoustic impedance of the matching layer must be 4.7 MRayl.

Main problem in the design of the matching layers for the two elements of the array is that they have to operate at two different frequencies (236 and 560 kHz for the external ring and the inner disk, respectively), both must have the same acoustic impedance, but we want them to have the same thickness to preserve the flatness of the radiation surface and to ensure that all radiation is transmitted in phase. Restrictions are summarized in Eq. 2, where subscript 1 and 2 stand for the external ring and the inner disk, respectively, t is the thickness, Z the impedance and ρ the density.

$$\begin{aligned} t_1 &= t_2 \\ Z_1 = v_1\rho_1 &= Z_2 = v_2\rho_2 \\ f_1 &= \frac{v_1}{4t_1} = 236\ kHz \\ f_2 &= \frac{v_2}{4t_2} = 560\ kHz \end{aligned} \quad (2)$$

Under these constrains, velocities and densities of the two matching layers must fulfill the following relations: $v_2 = 2.37\ v_1$ and $\rho_1 = 2.37\ \rho_2$.

We have used different polymers loaded with different particles to achieve materials this large difference in velocity and density values. In particular, for the external ring we have used a urethane rubber loaded with tungsten particles, and for the inner disk an epoxy resin loaded with alumina particles. Properties are summarized in table I.

TABLE I. MAIN PROPERTIES OF THE MATERIALS EMPLOYED AS QUARTER WAVELENGTH IMPEDANCE MATCHING LAYERS.

Element of the array (frequency)	**Material**	**Density (kg/m3)**	**Ultrasound velocity (m/s)**	**Ultrasound attenuation at resonant frequency (Np/m)**
Inner disk (560 kHz)	Epoxy resin loaded with alumina particles	1980	2280	28
External ring (236 kHz)	Urethane rubber loaded with tungsten particles	3870	1100	34

Consequently, acoustic impedance of the external ring and the central disk are 4.25 and 4.51 MRayl, respectively, close to the theoretically calculated value for the quarter wavelength impedance matching layer for water.

Fig. 3c shows the electrical impedance of the inner disk, the external ring and both (parallel connected) with the matching layer attached to the radiating surface. The right frequency tuning of the matching layer can be verified by the split of the element resonance into two resonances. In particular, the resonant frequency of the external ring is split into two frequencies at 190 and 295 kHz, respectively, and the central disk resonance at 560 kHz, is split into two resonances at 440 and 680 kHz, respectively.

This effect of the matching layers also contributes to make the overlap of the frequency band of each of these resonances smother and, consequently, makes easier to achieve a flatter frequency band response for the whole array.

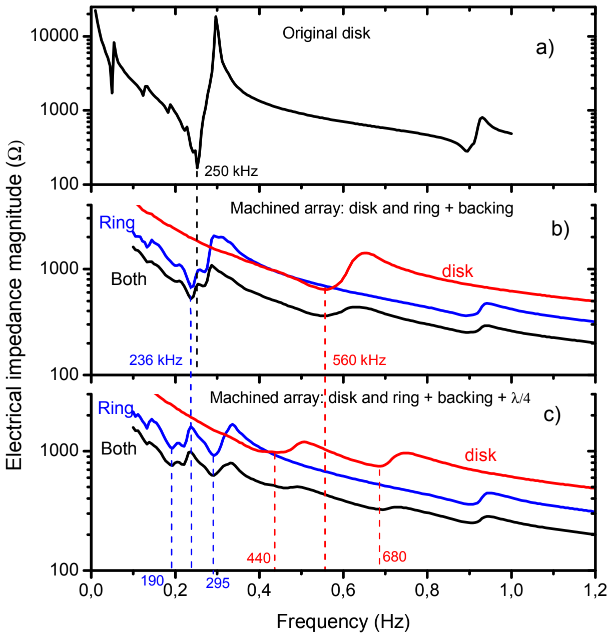

Fig. 3. Magnitude of the electrical impedance (magnitude) vs. frequency for the original disk (a), the annular array with the backing (b) and the annular array with the backing and the matchning layers.

III. ARRAY CHARACTERIZATION.

Figure 4 shows a schematic cross section view of the final design of the array (with the central disk, the external ring, the matching layers and the aluminum hosing).

Figure 5 shows two pictures of the final prototype. The two matching layers can be clearly seen at the radiating surface. The black color of the matching layer at the external ring is due to the tungsten particles used to load the urethane rubber, while the gray color of the matching layer at the inner disk is used to the alumina particles used to load the epoxy resin. At the back of the transducer, the two SMB connectors can be seen, that can be connected to use only one of the elements of both (parallel connected).

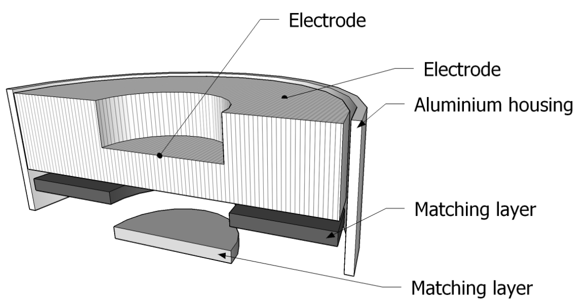

Fig. 4. Schematic view of the array cross-section structure: mechanized disk (central disk and external ring), matching layers and aluminum housing.

Fig. 5. Picture of front (right) and back face of the transducer prototype with the BNC terminated cable.

The electrical characterization of the array with an air load appears in Fig.3c. In addition, the array response where measured in pulse-echo operation mode in water immersion. As reflector we used an aluminum block located and 50 mm from the array. To drive the transducer we used a Panametrics 5058 pulser/receiver in pulse-echo mode. In this case the electrical signal used to drive the array is a spike. The received signal was filtered by the Panametrics 5058 and then sent to a Tektronix oscilloscope (DPO5074), where it was digitized and Fast Fourier Transform (FFT) extracted using a Hamming temporal window.

Magnitude spectrum of the echo so measured is shown in Fig. 6. Response of the two elements operated individually and of the whole array (both elements connected in parallel) is shown. Though frequency band of the array is close to the sum of the frequency bands of the two elements, frequency response is still far from being flat.

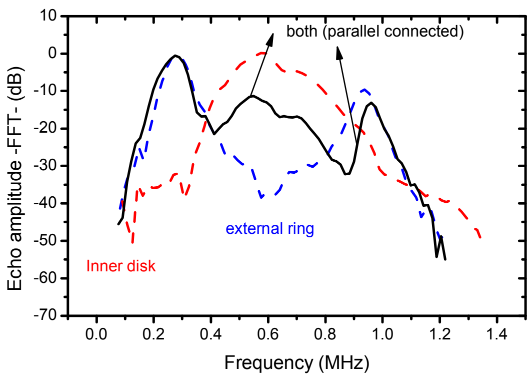

Fig. 6. Normalized response in pulse-echo, water immersion of the individual elements and the whole array: magnitude of the FFT of the echo reflected by an aluminium block.

This can be solved by changing the electrical matching of the elements, or by changing the relative areas, or by using two different pulsers, so that excitation conditions can be changed in order to equalize the overall response.

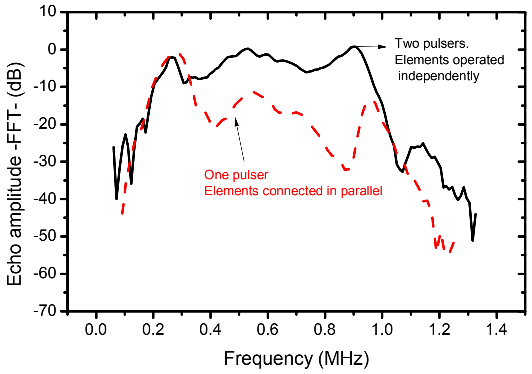

Fig. 7. Normalized response in pulse-echo, water immersion of the whole array under two different excitation conditions: magnitude of the FFT of the echo reflected by an aluminium block.

Figure 7 shows the response of the array in pulse-echo operation mode using two different pulsers to drive the two elements. External ring is driven with the Panametrics 5058 and the central disk is driven with a Panametrics 5077, which uses a semicycle of a square wave centered at 600 kHz. In this case, the relative excitation amplitudes used to drive each element is controlled so that a flater frequency band is achieved, that covers the frequency range from 0.15 to 0.95 MHz. Under these conditions it is posible to achieve a -6dB relative bandwidth close to 130%.

For comparison purposes, Fig. 8 shows the frequency band of the annular multifrequency array and the frequency band of a conventional wideband 0.25 MHz immersion transducer. In this later case the 6dB relative bandwidth is 45%.

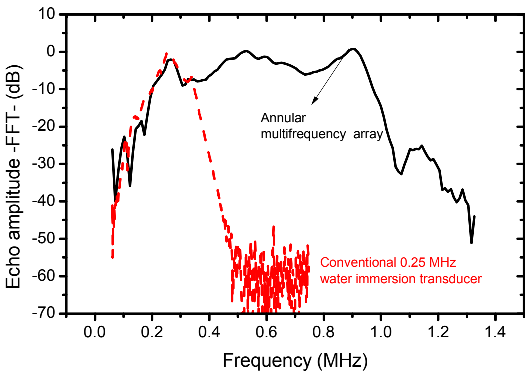

Fig. 8. Normalized response in pulse-echo, water immersion of the whole array and of a conventional 0.25 MHz centre frequency water immersion transducer.

IV. Conclusions.

The design, construction and characterization of a two elements kerfless annular multifrequency ultrasonic array has been shown.

The array consists of two elements: an external ring (centre frequency 0.25 MHz) and an internal disk (centre frequency 0.55 MHz). Both elements are mechanized out of a monolithic 0.25 MHz 1-3 connectivity piezocomposite disk. Quarter wavelength matching layers have been designed and built. They present similar acoustic impedance, but different ultrasonic velocity so that thickness is the same for both layers in spite of the different resonant frequency of each element. First, the electrical response of the array was characterized by measuring the electrical impedance and then the ultrasonic response was characterized by measuring the pulse-echo response. The array frequency band covers the frequency range from 0.15 to 0.95 MHz and it is possible to achieve a -6dB relative bandwidth close to 130% if the response of the two elements is equalized. This band can be compared with that obtained by conventional water immersion wideband transducers with centre frequency at 0.25 MHz that is about 45%.

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