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2D airborne ultrasound piezotransducer arrays for corneal imaging

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Abstract — **Non-contact ultrasound applications are raising more and more interests. However, very few applications have been reported, for now in medical applications. In this work, compact airborne piezotransducers have been designed, built and characterized for a novel medical application: contactless corneal imaging. The emission transducer is cylindrical with a 5.5 mm diameter and the reception transducer is a 2D array of 4x16 elements. A specific emission-reception electronic is also designed for these transducers to drive their high electric impedances that are larger than kiloOhms. The measured parameters - directivity, sensitivity and frequency bandwidth – of both transducers respond well to the needs of corneal imaging application.**

Keywords— Non-contact ultrasonic imaging, airborne ultrasound transducer, 2D airborne transducer array

I. Introduction

The eye has a multilayer anatomy. From the deepest with the retina to the surface with the cornea, each tissue has a particular function. The cornea is responsible for the majority of the light focusing and for protecting the eye from the outside. Therefore, it is important to study the cornea and to monitor it. Diseases like keratoconus, who affect more than 20 millions of people worldwide, modify the cornea thickness [1] and could be detected and monitored by elastography.

Corneal imaging has already been shown using ultrasound (US) with a contact probe [2] and with optics technology [3]. Such technologies have strong drawbacks for the corneal imaging. Indeed, the classical US probe needs a contact between the cornea and the probe, usually it is medical gel. Therefore, the contact modify the properties of the cornea. Also, such contact on the eye can be stressful and painful for the patient. Optical imaging needs a complex, heavy and costly setup.

In order to image the cornea without interfering with it, the system should work without contact and should not be perturbed by the eye's deeper layers. Airborne ultrasound are a good solution because there is a high reflecting coefficient between the air and the eye. There is different airborne ultrasound transducers technologies. cMUT [4], electrostactic transducer [5] and PVDF transducers [5] are able to generate ultrasound in the air from few kHz to the MHz frequency range. Another technology is under study for its capability of matching the air's acoustic impedance: the airborne piezoelectric transducer [5-6]. The piezoelectric material is covered with 1 or more matching layers in order to create an acoustic impedance gradient from the piezoelectric material to the air, and vice-versa. Therefore, the acoustic transmission can be improved. Up to now, only large single piezo-transducer have been under studied or manufactured. Also, on the shelf products are not compatible in dimensions, nor in performances with our application. We present here a compact airborne emission transducer, and an airborne reception 2D array transducer of 4x16 (64) elements aimed at the development of a high frequency Surface Motion Camera (SMC) [7].

II. Specifications & Design

A. Specifications

The main challenge with airborne ultrasound concerns the transmission of acoustic energy from the transducer to the air. The transmission level is very low compared to the usual applications of contact ultrasound in medical imaging or in Non Destructive Testing (NDT). According to the preliminary investigations dedicated to the cornea imaging application, it is decided to separate the transmitting transducer from the receiving transducers. The single airborne cylindrical transducer presented in this article has the role of transmitter, and the elements of the 2D array act as receivers.

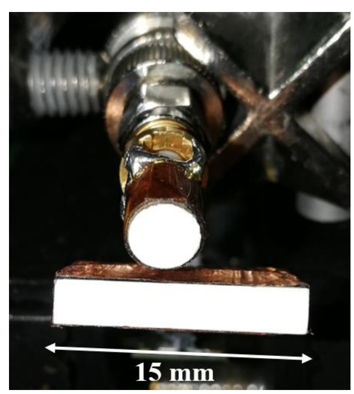

Fig. 1. Picture of the 5.5mm diameter cylindrical transmitting transducer and the 3.6mm x 15mm receiving 2D array transducer.

TABLE I. *THEORETICAL ACOUSTIC IMPEDANCE OF MATCHING LAYERS [2]* ($Z_{PZT\,Composite}$=20 MRAYL., Z_{AIR}=340 RAYL.)

i/n	Z_i (MRayls)
1/1	0.088
1/2	0.523
2/2	0.018
1/3	1.277
2/3	0.088
3/3	0.006
1/4	2.180
2/4	0.257
3/4	0.03
4/4	0.004

TABLE II. *PROPOSED DESIGN FOR HIGH PERFORMANCES*

	Z [Mrayl]	c [m/s]
Air	0.000420	345
ML3[9]	0.10	260
ML2	0.5	1250
ML1	3.0	2700
PZT	18.6	3750
Backing	5.2	1230

The transmitting transducer illuminates the surface of the cornea and the receiving 2D array transducer record the ultrasonic echoes. The transmitting and receiving transducers are close to each other and the working distance to the cornea is between 10 and 25 mm. The central frequency of the ultrasound system is centered at 500 kHz and its relative bandwidth value is equal to 50% at -20dB. The cylindrical transducer has a 5.5 mm diameter and the 2D array transducer is composed of 4 lines of 16 elements. The pitch is 0.95mm with an element of 0.75mm x 0.75mm dimension. The total dimension of the 2D array transducer is 3.6mm x 15mm. The transmitting transducer is decoupled from the receiving 2D array transducer - see Fig. 1.

B. Transducers design & fabrication

The transmitting transducer is built with piezocomposite material. The objectives are to reduce transducer's acoustic impedance and to decrease the influence of the radial mode on the thickness mode. On the another side, the receiving array transducer is built with bulk piezoceramic in order to maximize its sensitivity and because of the small size of the array's elements. A lot of research has been achieved on the needed value of acoustic impedance for matching layers [8-9], as shown in equation 1.

$$Z_i = \left(Z_{PZT}{}^{n+1-i} * Z_{air}^{i}\right)^{i/(n+1)} \quad (1)$$

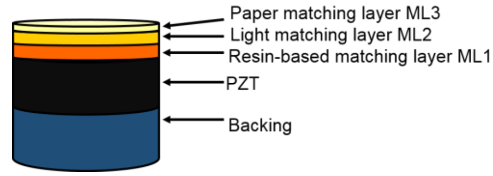

Fig. 2. Design of the airborne transducer's stack

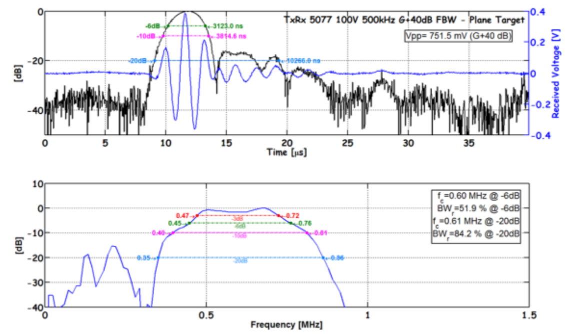

Fig. 3. Single transducer pulse-echo

Where Z_i is the impedance of the layer i, n the total number of layers, Z_{PZT} the impedance of the piezoelectric material and Z_{air} the impedance of the air. Theoretical acoustic impedances are calculated in the table 1. Such formula does not take into account the layer's attenuation, low acoustic impedance materials which are required are inevitably porous and highly attenuating. Therefore, adding more layers decrease the sensitivity while fewer layers decrease the bandwidth (only the central frequency is enhanced by the layers). Moreover, outer matching layer is not always reachable in practice, or poorly implementable within a transducer architecture. The design we proposed is resumed in the Table II and Fig. 2. Such design is a good trade-off between attenuation, bandwidth and sensitivity.

III. CHARACTERIZATION

Transmitting and receiving transducers are characterized by their electrical impedances and acoustical performances. A dedicated electronics is realized by *Lecoeur Electronique* - France - to especially drive these transducers.

A. Transmitting transducers

The measurement of the electrical impedance of the transmitting transducer – over 60 transducer samples – leads to the following averaged value:

Z_{avg} = 1.7 kΩ –j 1.3 kΩ at 500 kHz.

Pulse-echo measurement at 20 mm distance from a reflecting planar surface is realized. Figure 3 shows the response and the frequency spectrum of a representative transducer. The transducer bandwidth is 50% at -6dB and its central frequency value is roughly equal to 600 kHz. The transducer directivity obtained from the acoustic field measurement series is 10° at -3dB. (see one scan example on Fig.4).

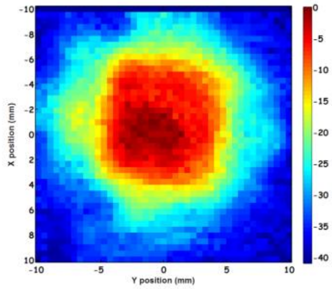

Fig. 4. 5.5 mm diameter cylindrical transducer acoustic field at 20 mm. The color scale is graduated in decibel.

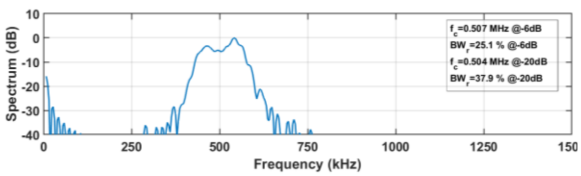

Fig. 5. Pitch-catch configuration spectrum (no averaging)

B. Receiving 2D array transducer

The averaged electric impedance of the elements of the 2D transducer array is: Z_{avg} = 11.0 kΩ –j 44 kΩ at 500 kHz. The cross-coupling level effect is measured. The measurement procedure is as follows: one element is excited without any reflecting surface in front of it and the responses of neighboring elements are measured. The maximum voltage amplitude of measured signals is 60dB less than that of the excitation signal. The cross-coupling level is therefore assumed to be negligible and will have few effect on the final image's quality.

C. Pitch-catch measurement

Pitch-catch measurement between a transmitting transducer and elements of the 2D array transducer is realized. The bandwidth of the ultrasound system is large as shown in Figure 5. Its value is equal to 38% at -20dB with a dynamic over 30dB without averaging.

IV. Conclusion

The results presented in this article show the feasibility of an airborne ultrasound system working at high frequency. A transmitting airborne transducer and a receiving airborne 2D array transducer– both working in pitch-catch mode - are successfully designed. Based on the developed technology, the future work will focus on the implementation of an array of transmitting transducers (64 elements) working with a larger receiving 2D array transducer (256 elements) into a more complex but single probe. Its main application will be high framerate surface motion corneal imaging.

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