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Modified PZT ferroelectric ceramics for fetal heart sensors

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Sumario. En este trabajo se valida el uso de cerámicas PZTN 54/46/1 en sensores ultrasónicos para detectores de latido fetal. Se obtienen las características de emisión-recepción y se comparan con las de transductores similares hechos con cerámicas PZT-5A que son las más usadas para estas aplicaciones. Se describen los procesos de manufactura de la cerámica, de puesta a punto del sensor y la caracterización de ambos. Los resultados obtenidos muestran que las cerámicas PZTN funcionan satisfactoriamente en estos dispositivos.

Abstract. In this work, the validation of utilizing PZTN 54/46/1 (niobium-doped lead zirconate titanate) ceramics in the construction of ultrasonic sensors for fetal heart rate detectors is accomplished. This is carried out by obtaining their emission-reception characteristics, and comparing them to those of similarly-built transducers using PZT-5A ceramics, which are commonly employed in these applications. The processes of ceramic manufacturing, sensor setup and characterization are described. Characterization results show satisfactory performance of PZTN ceramics.

Keywords: Acoustical instruments and techniques 07.64.+z, Acoustic transduction *43.38.-p, PZT ceramics 77.84.Dy.

1 Introduction

Human pregnancy is commonly detected and evaluated via ultrasonic methods, being fetal heart rate detectors the most used devices in precise diagnosis from early gestation to full term. Also, the behavior of fetal heart and the state of placenta are studied using such tools. Techniques change constantly and today they have become effective applications in related medical endeavors.[1,2] Comparative investigations concerning different diagnostic methods (ultrasonic Doppler,[3] fetal phonocardiogram (PCG)[4] and fetal electrocardiogram (ECG)[5,6] , have shown the advantage of using ultrasonic techniques over other pregnancy detection methods.

Doppler-based ultrasonic fetal heart rate detectors usually work at 2 MHz, and include an ultrasonic transducer which is acoustically coupled to the mother's abdomen, and other electronic equipments. An ultrasonic beam is directed towards the fetus' heart and a small fraction is reflected by the heart's moving surface. The reflected ultrasounds, which are shifted in frequency, are detected by the transducer. Finally, the low-frequency signals associated to heartbeats are filtered from the high-frequency signals, and amplified to achieve audio detection.

The main constitutive part of fetal heart rate detectors is the high-sensitivity transducer, which produces low-power (below 20 mW) ultrasonic waves. Emission and reception processes are usually carried out by a single transducer constructed with two identical semi-circular piezoceramic elements embedded in a layer in such a way that the required acoustic impedance and electric contact are accomplished. PZT-5A ceramics are among the most used piezoceramics for low power applications due to their high sensitivity related to high dielectric permittivity.

For any ultrasonic instrument with medical purposes, it is required to provide its emission-reception characteristics. So, the shape of the radiation field, the emission power, and the reception features of the sensor are needed. In order to achieve such requirement, it is relevant to evaluate the following characteristics: the maximum emission power PM, the spatial-average temporal-average intensity I_{sata}, the effective radiation area ERA (Food and Drug Administration), and the negative-peak pressure[7] p_{-}. The maximum emission power PM informs about the amount of energy transmitted to the evaluation medium (water), and should not exceed 20 mW. The spatial-average temporal-average intensity I_{sata} is associated to the rate of heat per unit volume per unit time generated by ultrasound in the medium[8]. The effective radiation area ERA is the portion of the face of the transducer that actually emits. The negative-peak pressure p_{-} concerns with the existence of cavitation within the medium. Cavitation is an undesirable effect provoking damage to the biological tissue[9-11]. The aim of this work consists in validating PZTN 54/46/1 (niobium-doped lead zirconate titanate) ceramics for the construction of transducers for a fetal heart rate detector, by comparing the results obtained for different transducers produced with PZT-5A (Morgan Electro Ceramics)[12] and PZTN ceramics. The piezoelectric characteristics of both ceramic types and the capabilities of the designed transducers are presented.

2 Experimental setup

PZTN ceramics were obtained by the traditional process, that is, solid-state reaction of several oxides and carbonates. Raw materials were weighted to obtain the relation $Pb(Zr_{0.54}\ Ti_{0.46})O_3$ + 1 wt% Nb_2O_5, followed by calcination at 960 °C, sintering at 1250 °C, and electric poling at 2 kV/mm[13,14]. Once the ceramics were obtained, a full characterization process was performed via the resonance-antiresonance method[15].

Transducers were built by using two types of coupling layers, one flat and other with a 2° angle (Fig. 1). Ceramic discs were divided in two equal parts. Cooper conductors of 0.1 mm diameter were soldered to each side of the ceramic elements in such a way that the plane contact between ceramics and coupling layer was fulfilled. Then, the ceramic elements were glued to the layer by using epoxy resin followed by a 24-hour drying period. A brass ring is attached to facilitate the assembly into the plastic body of the sensor.

Three types of transducer were constructed: C-1 (PZTN ceramic & flat layer, three specimens), C-2 (PZTN ceramic & 2° angled layer, three specimens), and C-3 (PZT-5A ceramic & flat layer, one specimen).

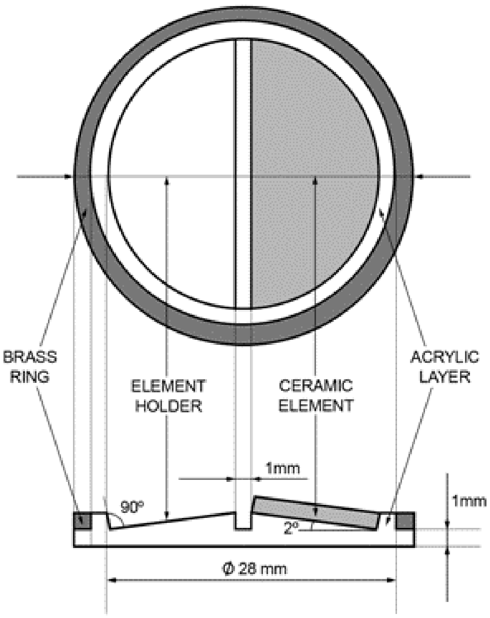

Figure 1. Transducer design with 2º degree layer.

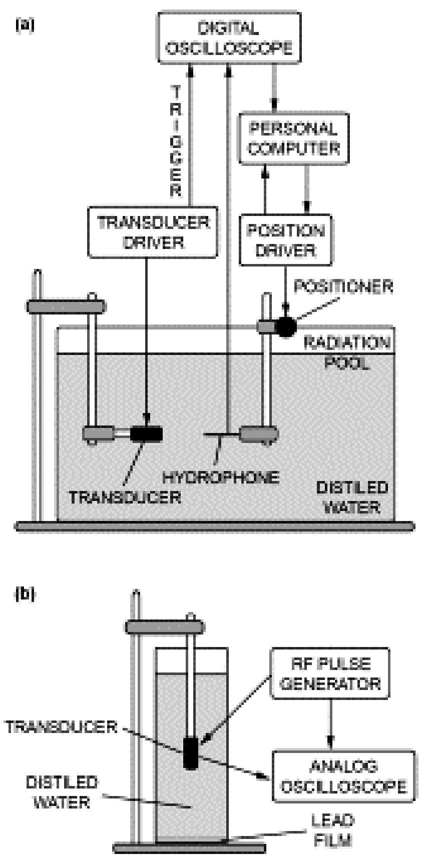

Figure 2. Transducer evaluation systems: (a) emission and (b) reception.

Transducers were characterized in emission and reception. Fig. 2a shows the Specialty Engineering Associates scanning installation used for emission characterizations[16]. This system permits to scan along the X, Y and Z axes and in XY, XZ and YZ planes. A PZT-Z44-0400 gauge hydrophone was used. Radiation measurements were performed in XY planes distant 0-50 mm from the face of the transducer. Each transducer was excited by means of a Matec TB 1000 card working in a continuous regime with central frequency of 2 MHz and 2 peak-to-peak volts (V_{pp}). Field measurements (V_{pp} and dBm) were carried out for 1 and 8 pulses of excitation covering areas of 32 x 32 mm^2 with a 1 mm step size and 6.32 µm precision. In order to calculate the intensity and power, the assumption of a progressive plane wave is considered, that is, intensity is proportional to the square of the acoustic pressure. According to the safety standards[9], we must state PM as the temporal mean output power at -26 dB, the spatial-peak temporal-average intensity as

$$I_{sata} = \frac{PRF}{A_6 \rho c} \iint_{S_6} \left[\int_{t_0}^{t_f} \left(\frac{V_p}{M} \right)^2 dt \right] dS$$

(where PRF is the pulse repetition frequency, S_6 is the surface where the intensity is greater than -6 dB, ρ is the density of water, c is the ultrasound velocity in water, V_p is the positive-peak voltage, and M is the sensitivity of the hydrophone, t_0 and t_f are initial and final time of pulse, A_6 is the area of S_6), the ERA at -6 dB is the beam cross section area in a plane parallel to the face of transducer 5 mm apart, and $p\_$ is measured during the experiments. In characterizing reception, a system configured for ultrasonic velocimetry (Fig. 2b) was used[17]. Each transducer was excited by a RF pulses regime with 2 MHz frequency and 60 V_{pp} during 2 µs. Measurements were prepared in a beaker, with a lead film covering the bottom so reflections could be guaranteed, filled with distilled water at 300 K.

3 Results and discussion

One of the most important characteristics of ceramics employed in the construction of reception transducers is the dielectric permittivity (ε), as large values of ε correspond to small values of the capacitive reactance, resulting in good transducer-equipment coupling. Also, the resonance-antiresonance method was followed in order to obtain the electromechanical coupling factor of the thickness vibration mode (k_t), the mechanical factor (Q_m), and the frequency constant of the thickness vibration mode (N_t), respectively, which describe the reception response of transducers. The parameters presented in Table 1 are in fact average magnitudes calculated from the measurements corresponding to 100 PZTN ceramics manufactured following the method described above. These ceramics present characteristics similar to those of PZT-5A, with the particularity that PZT-5A has higher permittivity values.

In Table 1, the average of reception responses of the experimental transducer types are compared to the average of reception responses of three commercial SONICAID transducers of the same model, as well as their averaged emission characteristics. In all cases, the area of transducers is 2.454 cm^2, while the effective radiation area differs for each transducer, as the layer-ceramic pasting process is not perfect. Transducer type C-1 presents the largest effective radiation area (0.846 cm^2), while C-3 shows the smallest one (0.460 cm^2). This feature does not affect the reception sensitivity, that is, transducers with different radiation areas have similar sensitivity in reception due to the higher value of PZT-5A permittivity compared to that of PZTN (Table 1). Nevertheless, C-1 presents larger values of PM and I_{sata}, so energy transmission and medium warming are also larger. In every case, the values of PM and I_{sata} are sufficiently small so fetus health is not compromised. The values of $p\_$ appear between 4.4-8.2 kPa, indicating that these transducers would not cause any injury to biological tissue[16], that is, cavitation within the human tissue would not be produced. Transducer types with flat layers (C-1 and C-3) show better reception characteristics than those of the transducer type C-2 which has an angled layer, as gluing defects cause that emission and reception foci do not coincide. The results obtained from the transducer with a flat layer show that it is possible to use PZTN ceramics for this type of applications. The results show a good agreement, in reception, between our transducers and SONICAID transducers.

Final evaluation of PZTN ceramics is carried out through the detection performance of the transducers presented here by using two (one hand-held, one table-supported) prototypes of fetal heart rate detector. Both prototypes fulfill the general description given above, that is, Doppler-based devices with 2 MHz continuous transmission mode. It was found that the three transducer types C-1, C-2 and C-3 presented here are high-sensitivity transducers. Successful performance of the two prototypes was observed after a one-year evaluation period in four obstetric hospitals located in Havana City, Cuba.

Table I
Characteristic parameters of ceramics and transducers

Ceramic	Material Properties								Transducer	Emission-Reception Characteristics				
	kp	kt	Qm	ε	Nt	s_{11}^{E} x10^{-12} (m^2/N)	d_{31} x10^{-12} (C/N)	g_{31} x10^{-3} (Vm/N)		V_{pp} (V)	PM (mW)	p_{-} (kPa)	I_{sata} (mW/cm^2)	ERA (cm^2)
PZTN	0.55	0.56	74	1488	2079	14.78	-168	-10.44	C-1	3.1	3.01	8.2	18.3	0.846
									C-2	2.9	0.88	4.4	6.95	0.664
PZT-5A	0.52	-	102	1741	1931	16.7	-176	-11.0	C-3	3.2	0.93	5.1	9.2	0.460
									SONICAID	3.4	-	-	-	-

4 Conclusions

Three different transducer types were manufactured and compared together to three commercial SONICAID transducers of the same model. Such transducers were produced using PZT-5A and PZTN ceramics. The piezoelectric characteristics of both ceramics and the capabilities of the designed transducers in emission and reception showed that the appliance of PZTN ceramics to emission-reception transducers is possible. The experimental transducers presented here would not cause cavitation within the biological tissue.

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