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ScienceDirect

Procedia Engineering 5 (2010) 99–102

Procedia Engineering

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Proc. Eurosensors XXIV, September 5-8, 2010, Linz, Austria

Comparative finite element analyses of piezoelectric ceramics and polymers at high frequency for underwater wireless communications

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Abstract

Despite huge advances in wireless communications in the last few years, underwater wireless communications is still a not fully developed technology, due to the lack of efficiency of radio waves for underwater communication. This problem can be overcome by using acoustic waves instead. In order to implement high-speed acoustic communications, it is imperative to develop transducers with high performance at high frequency. In this paper, a study of both piezoelectric ceramics and polymers used as water-coupled ultrasonic transducers is presented. As the main goal is to analyze their performance for high-speed communications, the behaviour of the piezoelectric ceramic (lead zirconate titanate, PZT) and the piezoelectric polymer (poly(vynilidene fluoride),PVDF) at high frequencies in underwater environment are compared. Results show that PVDF has a better response under the same ideal conditions, mainly with increasing frequency.

Keywords: Piezoelectric materials, PVDF, PZT, ultra-sound transductors, underwater communications, acoustic communications, finite element analysis

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1. Introduction

The sea covers 71% of the surface of the earth and, despite the geographical proximity, solar system is better know than the deep of the oceans. One of the main reasons for this fact is the difficulty of communications in subaquatic environments. Thus, it is important to develop wireless communication technologies between the agents of exploration and monitorization of the oceans, lakes and dams, among others, once the existing technologies, based on radio waves, are not efficient in underwater environments. On the pursuit of new broadband ultrasonic underwater communications systems capable to reach high rates, it is necessary to develop wideband ultrasonic transducers for underwater environments. The technologies based on lead zirconate titanate (PZT) ceramics lose performance when working at frequencies in the MHZ range. In order to achieve higher frequencies on water-coupled ultrasonic transducers, it is necessary to use materials with better response to high frequencies, such as the piezopolymer poly(vinylidene fluoride) in its beta phase (β-PVDF) [1].

In the last decades it has been increasing interest on electroactive polymer materials for technological applications, especially in the electronics engineering domain. Among all piezoceramics currently in the market, the

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doi:10.1016/j.proeng.2010.09.057

PZT-5H has the highest piezoelectric coupling coefficients [2, 3]. Among polymers, poly(vinylidene fluoride) has remarkable properties leading to electro-optics, electro-mechanical and biomedical applications. In particular its piezo and pyroelectric properties provide possibilities for many technological applications. The semicrystalline nature of PVDF, combined with the occurrence of at least four crystalline phases (α, β, δ and γ) implies a challenging physical microstructure. The most frequently described and important phase is the β phase due to its high piezo and pyro-electric properties, when compared to the other crystalline phases and even compared to other polymer materials [4].

To design the ultrasonic transducer it is necessary to define several characteristics, such as environment of operation, beam directionality and bandwidth frequencies.

The definition of operating frequency, either for a transmitter or a receiver, has different meanings. The transmitters usually operate at frequencies near the resonance, which allow higher performance output. The receivers, on the other hand, are usually used below their resonance frequencies allowing them to work at much higher bandwidths.

2. Description of the transducer model

In the present simulation study, a finite element 2D axis-symmetric model was used, as it is shown in Figure 1 (green plane). The disks dimensions were calculated from equations (1), (2) and (3):

$$r = \lambda; \tag{1}$$

$$\lambda = c_w / f; \tag{2}$$

$$t = c_{piezo}/(2f); \tag{3}$$

where c_w is the speed of sound in water (1500 m/s), c_{piezo} is the speed of sound in the piezoelectric material $\left(\sqrt{k/\rho}\right)$, r is the radius of the transducer disk, t is the thickness, λ is the wavelength of sound waves in water, k is the stiffness of the piezoelectric material and ρ is the density of the piezoelectric material.

To proceed with computing simulations, the following boundary conditions were defined: z-axis is a symmetric-axis; x-axis is a hard boundary (wall); and the edges of the simulation world are formed by a perfect match layer that absorbs all sound pressure waves. The size of mesh is about one tenth of the wavelength of the sound wave in water, in order to maintain the simulation accuracy without increasing excessively the simulation time.

The beam pattern can be defined as the relative sound pressure amplitude as a function of the angle. Different patterns can be achieved using particular forms and/or arrays of transducers. Usually, the pattern is composed by a main lobe and some side lobes. The width of the beam is defined as the width of the main lobe (in degrees). The directivity index indicates the signal to noise ratio using a directional transducer. This is achieved through the overall concentration of energy along the axis of maximum response, where the main lobe is located.

At high frequencies, ultrasonic transducers normally operate in thickness mode, that is, the deformation occurs in the z-axis (Figure 1(b)). So, in order to compare the performance of materials and working conditions, a model of a hard solid disk was used. In this model, only the up side of the piezoelectric transducer transfers energy to the medium, along the z-axis. Once the maximum energy transfer is achieved at thickness resonance, it is necessary to recalculate the ideal disk thickness for each material at different frequencies (equation (3)) [5]. Also, in order to maintain the consistency of the model, the radius (r) of the disk is recalculated for each working frequency, to be equal to the wavelength of transmission (equation (1)). The direction of the energy transfer is the same in all simulations, showing a sound wave beam with directivity near 180° with a high central lobe. Both transducers are excited with sine wave voltages of 10 V.

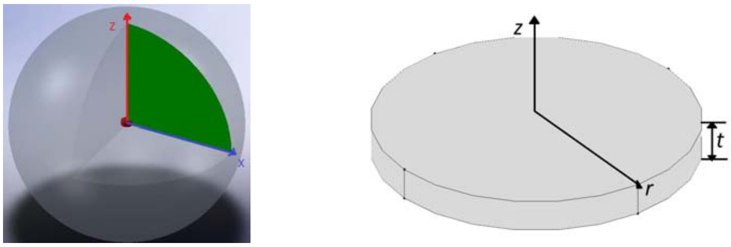

Fig. 1. (a) 2D symmetric model of the simulation world, (b) 2D symmetric model of the transducer.

3. Simulation results

The model was simulated for several operation frequencies for each material type. Only the results for 100 kHz and 40 MHz will be presented, once the results for the intermediate frequencies only reinforce the obtained conclusions. To compare the performance of materials, the sound pressure wave amplitude of the central and the side lobes were used. In this case, the side lobe is at 90º from the central lobe.

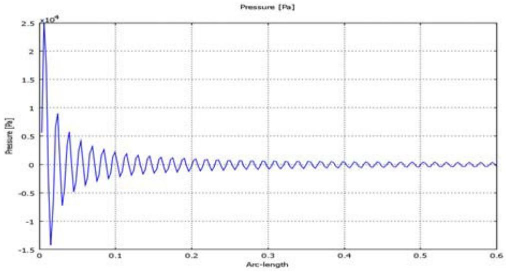

Fig. 2. Amplitude of the central lobe for PZT-5H at 100 kHz.

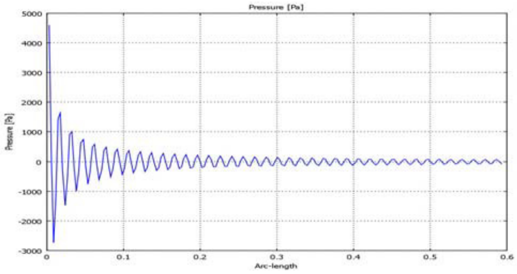

Fig. 3. Amplitude of the side lobe for PZT-5H at 100 kHz.

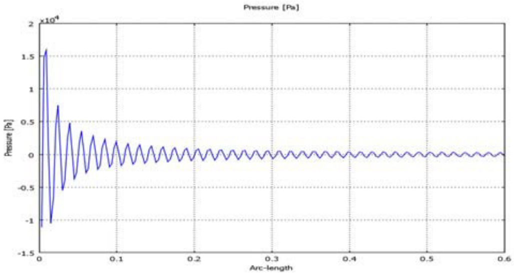

Fig. 4. Amplitude of the central lobe for PVDF at 100 kHz.

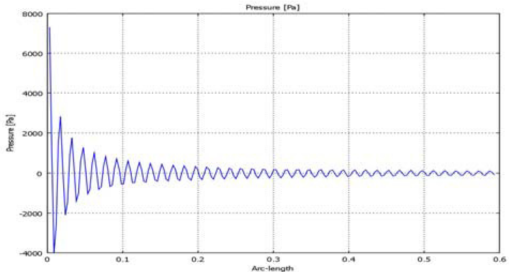

Fig. 5. Amplitude of the side lobe for PVDF at 100 kHz.

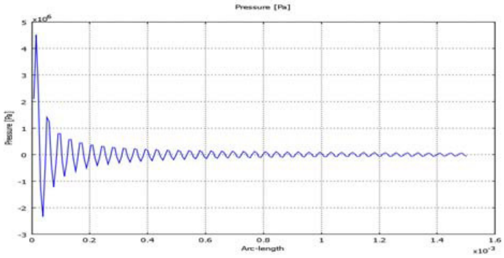

Fig. 6. Amplitude of the central lobe for PZT-5H at 40 MHz.

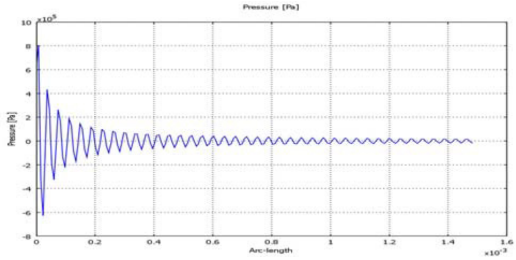

Fig. 7. Amplitude of the side lobe for PZT-5H at 40 MHz.

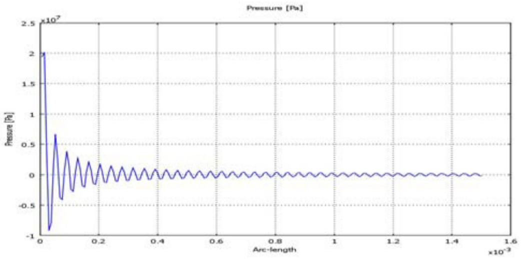

Fig. 8. Amplitude of the central lobe for PVDF at 40 MHz.

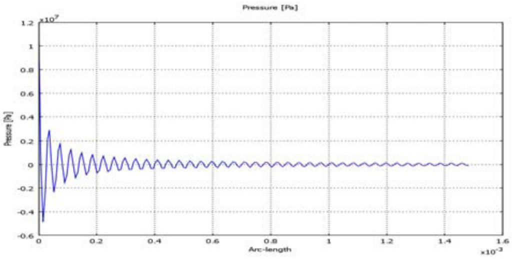

Fig. 9. Amplitude of the side lobe for PVDF at 40 MHz.

Figures 2, 3, 4 and 5 show that at 100 kHz the PZT-5H disc produces higher sound wave amplitudes both in central and side lobes, relatively to PVDF. When the frequency increases, the sound wave amplitude of PVDF also increases relatively to PZT-5H. At 40 MHz the amplitude of the sound wave produced by PVDF is about four times the one produced by PZT-5H, as it is shown in figures 6, 7, 8 and 9.

4. Conclusion

In this article, the performance of two types of piezoelectric materials: ceramic PZT-5H and polymer PVDF was evaluated for water-coupled ultrasonic transducers applications. It was used a finite element 2D axis-symmetric model, using low (100 kHz) and high (40 MHz) frequencies. The obtained results show that at low frequencies, the PZT-5H has a slightly better performance, but at high frequencies, PVDF shows an improvement of at least four times in performance. The main reason for this behaviour is that PVDF has acoustic impedance well below PZT, which better matches the one of the water. At higher frequencies, the effect of impedance mismatch overcomes the higher piezoelectric coefficient of PZT, thus decreasing its performance.

Acknowledgements

The authors thank the FCT for financial support under grants PTDC/CTM/69362/2006 and PTDC/CTM/69316/2006. M. S. Martins and V. Correia thank the FCT for the PhD Grants SFRH/BD/60713/2009 and SFRH/BD/48708/2008, respectively.

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