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Design, analysis and fabrication of high frequency piezoelectric transducers

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Abstract Applicability of the finite element method to optimize high frequency transducers is reported. Two recent studies on piezoelectric transducers or systems are presented, in which the FEM algorithm is used for the optimization of transducers performance. They provide resonance frequencies from greater than 1 MHz to below 10 kHz. First, miniature multimode monolithic flextensional transducers, with *active* shells, are described. They combine the advantages of small size and low-cost manufacturing with control of the shape of the acoustic radiation/receive pattern. Then, linear arrays are studied and a technique is developed to reduce cross-coupling in acoustical arrays. In each case, numerical results are compared to experiments and show how the finite element tool is used to improve the understanding of the physical behavior of the system.

Keywords Piezoelectric transducers · Finite element modelling · Linear arrays · Vector sensor · Directional transducer

1 Introduction

Ultrasonic transducers and arrays are widely used in imaging applications, such as medical diagnosis, nondestructive evaluation and underwater acoustics. Designing more accurate transducer arrays is an important issue for improving the quality of ultrasonic imaging. This paper presents recent research work on piezoelectric transducers for underwater and medical imaging applications. Using Finite Element Method to design transducers with piezoelectric materials allows heterogeneous transducers of any shape to be modelled and all possible components of the displacement field, without assumptions, to be considered. Moreover, it can be used for the design of a full transducer or an array.

This paper presents the general description of the finite element set of equations, and two recent studies on piezoelectric transducers or systems. First, miniature multimode monolithic flextensional transducers, with *active* shells, are presented. Then, linear arrays are studied and a technique to reduce cross-coupling in acoustical arrays is performed. In each case, numerical results are compared to experiments and show how the finite element tool is used to improve the understanding of the physical behavior of the system.

2 Brief description of the fem approach

The ATILA finite element code has been used for the described applications [1]. It can model piezoelectric, magnetostrictive, elastic and fluid materials. Static analysis provides information concerning prestresses and the behavior under hydrostatic pressure. Modal analysis provides information on vibration modes, resonance and antiresonance frequencies and associated coupling factors. For

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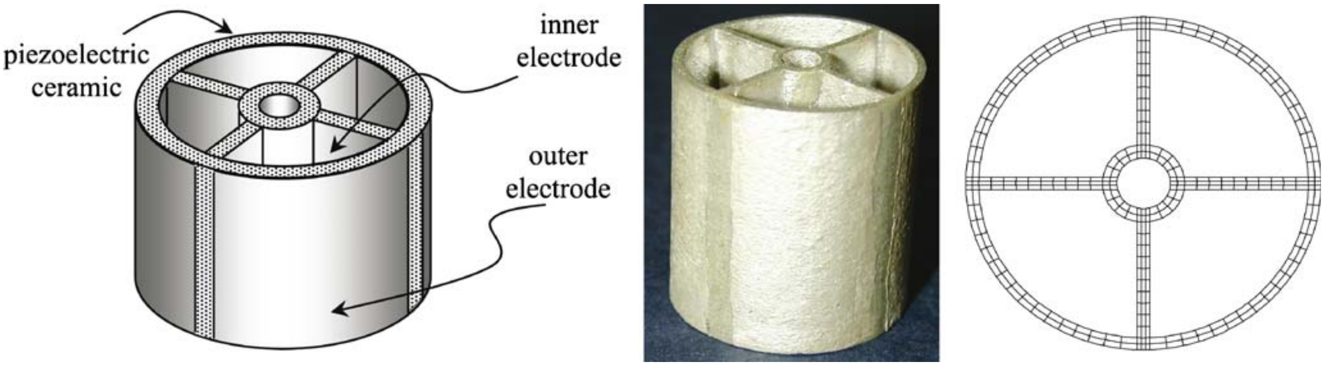


Fig. 1 Example of monolithic piezoceramic transducer design: the wagon wheel transducer. *Right*: finite element mesh of the wagon wheel transducer, showing the four quadrants

harmonic analysis of in-air or in-water structures, the following system of equations is considered [2]:

$$\begin{bmatrix} [K_{uu}] - \omega^2 \quad [M] & [K_{u\Phi}] & -[L] \\ [K_{u\Phi}]^T & [K_{\Phi\Phi}] & [O] \\ -\rho^2 c^2 \omega^2 [L]^T & [0] & [H] - \omega^2 [M_l] \end{bmatrix} \begin{bmatrix} \mathbf{U} \\ \mathbf{\Phi} \\ \mathbf{P} \end{bmatrix} = \begin{bmatrix} \mathbf{F} \\ -\mathbf{q} \\ \rho c^2 \psi \end{bmatrix}$$

where **U**, **Φ**, **P**, **q**, ψ and **F** are vectors containing the nodal values of, respectively, the mechanical displacement, the electrical potential, the pressure in the fluid, the electrical charges, the normal derivative of the pressure on the external fluid domain and the applied forces. $[K_{uu}]$, $[M]$, $[K_{u\Phi}]$ and $[K_{\Phi\Phi}]$ are, respectively, the structure stiffness, consistent mass, piezoelectric and dielectric matrices. $[L]$, $[H]$, and $[M_1]$ are, respectively, the connectivity matrix that represents the coupling between the structure and the fluid, the fluid compressibility and consistent mass matrices for the fluid. ω is the angular frequency. The resolution of this set of equations provides the nodal values of the pressure field, displacement field and electrical potential. The radiated near-field of the transducer can be obtained using the finite element method if dipolar damping elements are attached to the mesh external circular boundary. In-air and in-water impedance versus frequency can be computed, as well as the Transmitting Voltage response and the directivity patterns.

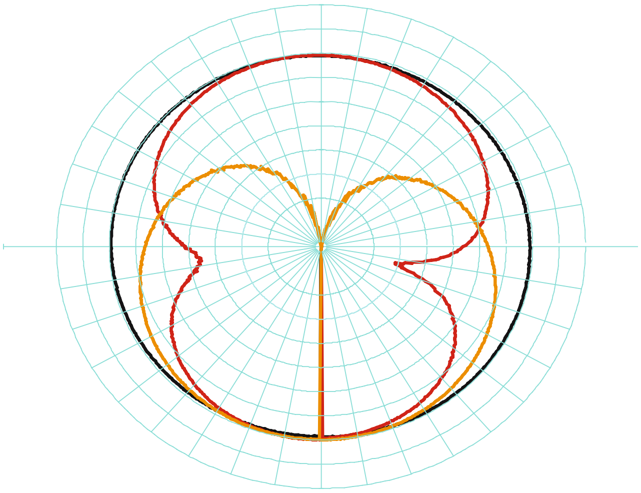
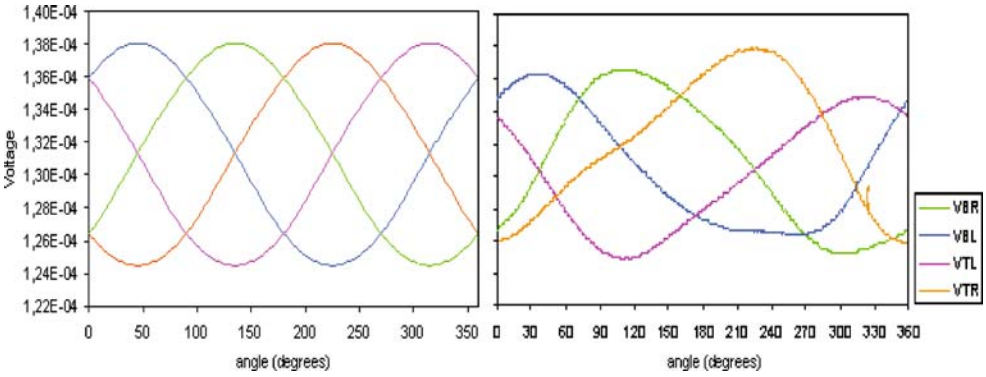


Fig. 2 Wagon-Wheel transducer: experimental beam pattern: monopolar (*black curve*), dipolar (*red curve*), cardioid (*orange*) beam pattern. Scale: 5 dB between two lines. The maximum is normalized

3 Miniature multimode monolithic flextensional transducers

During the past few years flextensional transducers have been used extensively for fish-finding, oil exploration, sonar systems, and low frequency biomedical applications in the 1–100 kHz range. Our present goal is to develop a family of small, low-cost, underwater and biomedical transducers based on extrusion technology. Miniature versions of high-power, low-frequency transducers are being tested to produce broadband transmit and receive response, engineered vibration modes, and optimized acoustic beam patterns. Transducer topologies with various shapes, cross-sections, and symmetries can be fabricated through high-volume, low-cost ceramic and metal extrusion processes [3]. Dimensions of the pieces can be as small as 1 mm and as large as 10 cm, which provide resonance frequencies from greater than 1 MHz to below 10 kHz. The acoustic vibration modes, resonance frequencies and radiation patterns of these transducers are controlled through the symmetry of the transducer material and its external shape, poling pattern, the driving and receiving electrode geometries and the driving conditions. This section is devoted to small, multimode flextensional transducers with *active* shells. In particular, a transducer shaped like a wagon-wheel, that combines the advantages of small size with control of the shape of the acoustic radiation pattern is presented. It consists of a cylindrical shell with a small concentric tube at the center. Four arms are attached between the outer and inner cylinders (Fig. 1). The small tube at the center of the transducer is inactive, and intended

Fig. 3 Variations of the modulus of the four voltages as a function of θ angle of the incident plane wave of 1 Pa impinging the wagon-wheel transducer. *Left*: numerical results, *right*: experimental results (*TR*: top right, *TL*: top left, *BR*: bottom right, *BL*: bottom left)



mainly as a means of mounting a stress bolt or carrying a cable for power and driving circuits. Each portion of the outer shell, and the arms can be activated simultaneously, or independently. The outer shell can be poled and driven from inside to outside or vice versa. The number of arms can also be increased to give the transducer a more robust design with possibly higher pressure tolerance at the expense of sensitivity, or the number of arms can be decreased to provide a more compliant structure.

In addition to the geometrical and dimensional modifications, different sections of the transducer can be driven with a phase difference and with different voltages to control the acoustic beam pattern. A directional beam pattern can be achieved through cancellation of sound pressure in one direction and addition in the opposite direction. With four leads attached to the inner surfaces, each quadrant can be driven independently by adjusting the phase, frequency, and amplitude of the applied voltage. Combining these possibilities in the optimum manner provides a useful method of controlling the acoustic beam pattern (Fig. 2). The procedure is similar to that carried out earlier with the Double-Driver cymbal transducer [4]. An advantage of the wagon-wheel is that beam patterns can be controlled in two-dimensions, whereas beam patterns of the Double-Driver cymbal were mainly one-dimensional.

Moreover, in a number of undersea applications, it is desirable that the hydrophone possesses directivity characteristics that reveal the direction of the source of incoming acoustic energy. By monitoring the pressure-wave signals received on all four quadrants of the wagon-wheel transducer, both the direction and the gradient can be determined (Fig. 1). Summing the four measurements gives the average pressure.

Numerical and experimental tests have been performed to evaluate the wagon-wheel transducer as a vector sensor. In the initial vector sensor experiments only the shell is active, the arms are unpoled, and the transducer is immersed in water. A plane wave impinges on the transducer, at an angle θ with respect with the horizontal x-axis along one of the arms. The angle θ is varied from 0° to 360° with the amplitude of the incident plane wave set at 1 Pa. Four voltages are calculated using ATILA finite element code and are measured. The variations of the voltage on each

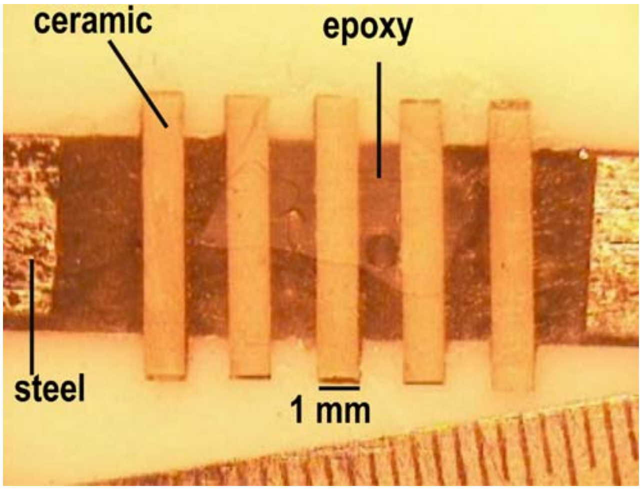


Fig. 4 Picture of the array of five piezoelectric bars

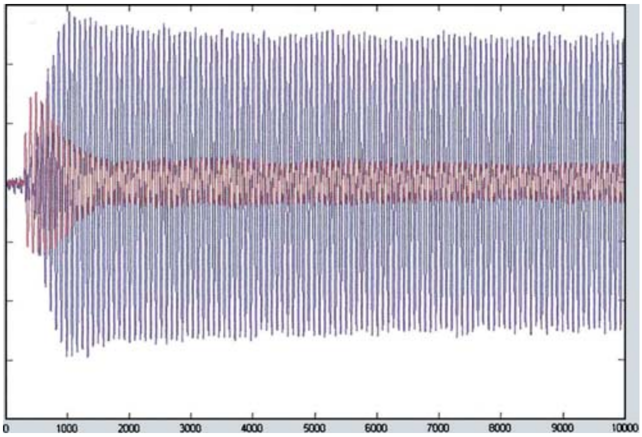


Fig. 5 Experimental displacement field of the first neighbour as a function of time. The middle element is active (harmonic excitation at 235 kHz, amplitude 10 V) and the first neighbour is grounded (*blue curve*, displacement=±21,1 nm) or it has a specific electric potential (*red curve*, displacement=±2,7 nm). 10000 points have been obtained, corresponding to a maximum time of 500 µs

quadrant have clearly shown the ability of the wagon-wheel transducers to be used as a vector sensor [5] (Fig. 3). The small discrepancies observed on the experimental curve are due to the slight asymmetry of the transducer.

4 Numerical method to reduce the cross-coupling in acoustical arrays

Element cross-coupling is generally accepted to be a major problem in phased array systems, because it increases the element aperture [6]. It can be due to mechanical coupling between elements of the array or to acoustic coupling when the array is immersed in water. Thereby, it reduces the directivity of the element and causes an unacceptable loss in signal amplitude as the beam is steered off the axis of the transducer. When the active element is driven, it generates parasitic displacement fields at the radiating surfaces of the neighboring transducers. These parasitic vibrations are particularly high at the resonance frequency and can be reduced by applying specific electrical potential on each neighboring element of the active transducer. These electrical potentials are computed using the FEM, by applying the properties of linear superposition [7]. The applied electrical potentials of neighboring elements are computed with a view to cancel the parasitic displacement field. The numerical technique has been tested with a linear array composed of five piezoelectric bars (PZ27 standard “Ferroperm” piezoelectric ceramic). Each element is 1×3×4.5 mm and is poled in its thickness. Although this sample is not representative of the typical ultrasound medical arrays, its geometry allows to obtain a strong acoustical cross-coupling at the resonance frequency (235 kHz) and thus validate the cross coupling cancellation method previously exposed. The polymer used to fill the kerfs between elements is a non-conductive epoxy resin (1 mm width). Moreover two parts of steel were bonded on each side of the array in order to facilitate its handling (Fig. 4). The technique proposed here has been previously numerically tested [7]. In this part, we propose an experimental verification.

Transducer displacements in the array have been measured with a laser vibrometer. The transducer at the center of the array is excited (harmonic excitation at 235 kHz, amplitude: 10 V, displacement: ±51.4 nm). Each neighbour is excited with a specific voltage (amplitude and phase). Figure 5 presents the measured displacement field of the first neighbour without (blue curve) and with (red curve) the specific electrical potential. The left part corresponds to the transient part of the signal. Ten thousand points have been obtained, corresponding to a maximum time of 500 μs. It clearly shows that cross-coupling is reduced with a specific electrical potential applied on the neighbour (without specific voltage: displacement=±21,1 nm, with specific voltage: displacement=±2,7 nm). Experiments are in progress for in-water radiation.

5 Conclusion

In this paper, two examples for the optimisation of transducers performance with the help of the FEM were proposed. The first example concerned the development of a miniature multimode monolithic flextensional transducer and the potential of this transducer to control beam pattern in two dimensions was demonstrated. This is a significant result particularly for undersea applications. The second example investigated the development of a synthetic method in order to reduce cross-coupling in ultrasound phased array system used for medical applications. The tests were performed on a linear array composed of five piezoelectric bars (PZ27) and the validity of the developed method was verified. These preliminary results therefore show that numerical modelling of transducers is a well suited approach to understand the behavior of structures, such as miniature piezoelectric transducers or arrays. Current studies include micro-machined ultrasonic transducers (MUT) for phased arrays in high frequency acoustic imaging to overcome resolution and frequency limits of bulk PZT transducers. The advantage of structures on silicon substrate is that transducers could be integrated with the electronics of the system. The basic element consists of a micro-machined membrane that is driven by either capacitive (CMUT) or piezoelectric (PMUT) or magnetostrictive (MMUT) actuation. Our aim is to design and realize a new concept of acoustic PMUT or MMUT microsystem, where active layers (piezoelectric or magnetostrictive) vibrate in another mode than the classical bending mode, for applications between 10 and 50 MHz.

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