CHARACTERIZATION AND NUMERICAL MODELLING OF HIGH FREQUENCY TRANSDUCERS

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Abstract
Applicability of the finite element method to optimize high frequency transducers is reported. The FEM algorithm is used for the optimization of transducers performance and two studies are presented. The first one concerns the influence of the matching layer and shows the existence of coupled modes in the bandwidth of the transducer, due to shear wave propagation in the matching layer. This study is concluded by the definition of a choice criterion guaranteeing no lateral mode in the bandwidth of the transducer. Secondly, an original technique is proposed to reduce cross-coupling in acoustical arrays and is applied to a subset of the arrays. The feasibility of the method is successfully tested on a simple five elements array.

Introduction

Ultrasonic transducer arrays are widely used in imaging applications, such as medical diagnosis, non-destructive evaluation and underwater acoustics. Designing better transducer arrays is an important issue for improving the quality of ultrasonic imaging. The classical linear array consists of parallel, identical and equidistant long piezoelectric transducers bars separated by a finite distance (inter-element spacing). Epoxy is generally used to fill the array. Usually, a backing with a high acoustic absorption coefficient is used in order to reduce waves reflected in the back. One or more matching layers are bonded to the top of the array, between the piezoelectric material and water load, in order to improve the transmission and bandwidth properties of the transducer. Even if analytical and semi-analytical models have been developed to study transducer arrays, they are often reduced to particular cases. Therefore, numerical models seem to be a well-suited approach to describe the behavior of the arrays, in particular because it allows the description of phenomenon such as, parasitic modes, inter-element cross coupling, subdicing effects, baffle effects.

This paper presents two studies that have been performed on linear arrays, using the ATILA finite element code [1]. First the influence of the matching layer is studied and shows the existence of coupled modes in the bandwidth of the transducer, due to shear wave propagation in the matching layer. A choice criterion of the matching material is found to avoid these coupled modes, that has been experimentally tested. Secondly, element cross-coupling, which is generally accepted to be a main problem in phased array systems, is presented. An original technique to reduce cross-coupling in acoustical arrays is proposed and applied to a subset of the arrays. It shows that the far-field directivity pattern is improved, with a main lobe in the axial direction

Brief description of the FEM approach

The ATILA finite element code was developed in the Acoustics Department of ISEN-France, for the modeling of sonar transducers [1]. Static analysis gives information on the stresses and the behavior under hydrostatic pressure. The modal analysis yields the vibration modes, the resonance and antiresonance frequencies, and the electroacoustic coupling factors. Finally, the admittance and the displacement field, in air or in water, as well as the Free Field Voltage Sensitivity, the Transmitting Voltage Response, and the directivity pattern, are obtained using harmonic analysis.

In this study, the plane strain approximation is considered because the transducer length is assumed much larger than the two other dimensions. The harmonic state is assumed and the $e^{j\omega t}$ term is implicit, where ω is the angular frequency. Application of the finite element method to harmonic analysis of piezoelectric transducer radiating in water is described in many papers [2,3].

The resolution of the classical system of the finite element method [1] gives the nodal values of pressure field, displacement field and electrical potential. The radiated near field of the transducer can be easily obtained using the finite element method if dipolar damping elements are attached to the mesh external circular boundary. These elements are specifically designed to absorb completely the first two components of the asymptotic expansion of the radiated field. The far-field pressure is then computed with the help of an extrapolation method [2,3].

The mesh of a piezoelectric bar, with a quarter wave matching layer, radiating into water is described in fig. 1. Only one half of the domain is meshed due to symmetry. The thickness and width of the piezoelectric bars are respectively W (variable) and T (=cst=1mm) ; the matching layer thickness is noted l. During all the numerical study, the transducer length is kept equal to 2 cm.

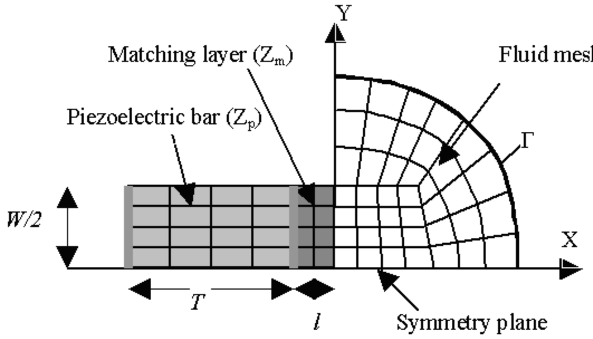

Figure 1 : Finite element mesh used to analyse the transducer

Behavior of piezoelectric bars with a quarter wave matching layer

Classical characteristics for the matching layer

The characteristics used for an elastic material are the Young Modulus (Y), the Poisson's ratio (ν) and the mass density (ρ).

A matching material (Y=1.283 Kg/ms^2, ν=0.33, ρ=2770 Kg/m^3 and Z_m=7.25 MRayls) has been chosen as reference using classical impedance relation (intermediate acoustical impedance $Z_m = \sqrt{Z_p Z_f}$ [4]).

PZT5H piezoelectric materials is considered (Z=34.5 MRayls). The thickness of the bars are T=1mm and the width to thickness ratio (W/T) is equal to 0.5 to have a dominate thickness mode [3,5]. The thickness (l) of the matching layer is equal to the quarter of the longitudinal wavelength in the matching layer calculated at the resonance frequency ($l = \lambda_l/4 = c_l/4f_r$)

Application to a PZT5H bar

Fig. 2 and fig. 3 show respectively the acoustical power and the electrical impedance, versus frequency, computed for a PZT5H bar matched with the reference material. It appears on these two graphs that three coupled mode exist : the first one is at 1.2MHz, the second one is at 1.8MHz and the third one is at 2.5MHz.

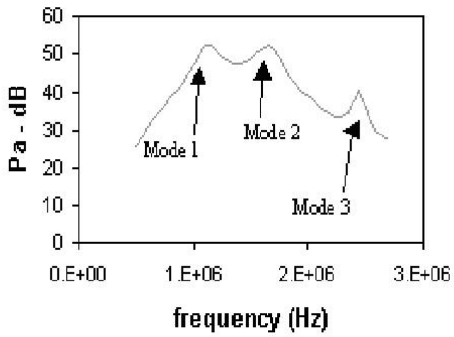

Figure 2 : Variations of acoustical power versus frequency for the PZT5H transducer matched with the reference quarter wave matching layer.

Between 1 and 2 MHz, the transducer vibrates like a piston mode. But after 2 MHz the matching layer has more lateral motion. Figure 4 shows the displacement field computed at 2.5 MHz.

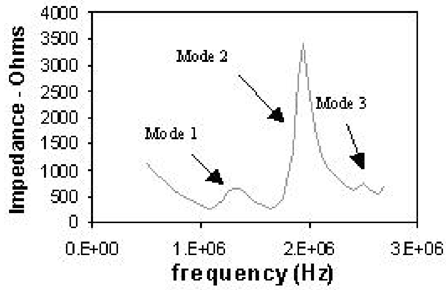

Figure 3 : Variations of electrical impedance versus frequency, for the PZT5H transducer matched with the reference quarter wave matching layer.

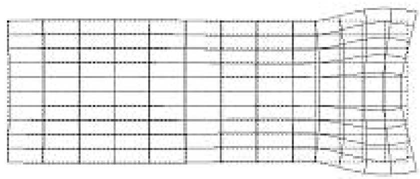

Figure 4 : Displacement field of the PZT5H transducer at 2.5MHz.

Parametric study and criterion optimizing transducer performances.

Last section shows that criteria proposed by the 1D model are not enough to guarantee a good matching of piezoelectric bars (with no lateral modes in the bandwidth of the transducer). Simulations have been made to see the influence of Y, ν and ρ parameters on the transducer behaviour and on lateral modes appearance [6].

The analysis of this numerical study permits us to find a choice criterion for the matching material which is function of the width of the transducer (W), the shear speed in the matching layer (c_s) and the resonance frequency of the piezoelectric bar (f_r). So, the behaviour of a piezoelectric bar (thickness mode, $T=\lambda_p/2$, $W/T \leq 0.5$) with a quarter wave matching layer ($l=\lambda_l/4$ and intermediate acoustical impedance $Z_m = \sqrt{Z_p Z_f}$) is identical to that predicted by the one-dimensional model (no lateral propagation) if W, c_s and f_r satisfy the relation :

$$W < c_s/2f_r \qquad (1)$$

This criterion means that, if the width of the transducer is smaller than half the shear wave length in the matching layer, then the behaviour of the transducer is not disturbed by shear wave.

Experimental test

A piezoelectric bar with a matching layer has been built. The matching layer verifies the classical criterions (a quarter of wave length, intermediate acoustic impedance) and the new criterion (half shear wavelength). Figure 5 presents the variations of the impedance versus frequency. There is a nice agreement between experiments and numerical results. It clearly shows that only two modes and no lateral mode appear in the bandwidth of the transducer.

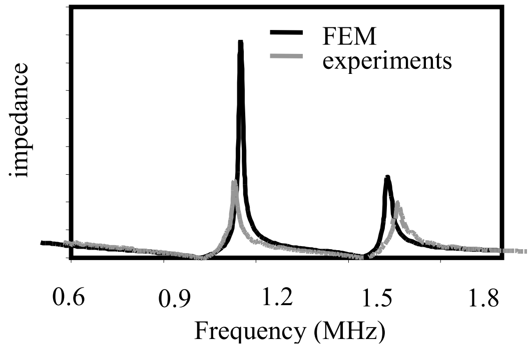

Figure 5: Experimental and numerical variations of the impedance of the transducer versus frequency, when the matching layer verifies the new criterion.

Numerical method to reduce cross-coupling in acoustical arrays

Presentation of the problem

Element cross-coupling is generally accepted to be a major problem in phased array systems. It is widely recognized that cross-coupling increases the element aperture [7], thereby reducing the directivity of the element and causing an unacceptable loss in signal amplitude as the beam is steered off the axis of the transducer. Furthermore, anomalous radiation patterns have been observed in linear array elements with Lamb wave coupling, in which the element directivity may achieve maxima away from the axis of the element [7]. When the active element is driven, it generates parasitic displacement fields at the radiating surfaces of the neighbouring transducers. These parasitic vibrations can be reduced by applying specific electrical potential on each neighbouring element of the active transducer. It will be shown in this section that these electrical potentials can be computed with the help of the FEM and applying the properties of linear superposition of sound.

Computation of potentials applied on neighbouring elements

In this section, the method to compute electrical potentials applied on neighbouring elements is presented. This method uses results provided by the FEM and the properties of superposition principle. The aim of this method is to compute the applied electrical potentials of neighbouring elements which cancel the parasitic displacement field. In this way, it is possible to define an optimum configuration where the central element is excited by an electrical potential of 1V (a normalized value is used to simplify the calculations), generating a displacement field $\underline{u}_1$ on its active surface and where neighbouring elements are excited by electrical potentials A_i (i=2,3) to cancel the parasitic displacement field on their surface ($\underline{u}_i$=0, i=2,3). This optimum configuration can be decomposed in three configurations (fig. 6) which differ by the position of active elements. With a view to cancelling the displacement on the surface of neighbouring element, the A_2 and A_3 factors have to verify :

$$\begin{bmatrix} \underline{u}_{22} & \underline{u}_{23} \\ \underline{u}_{32} & \underline{u}_{33} \end{bmatrix} \begin{bmatrix} A_2 \\ A_3 \end{bmatrix} = \begin{bmatrix} -\underline{u}_{21} \\ -\underline{u}_{31} \end{bmatrix} \qquad (2)$$

Where $\underline{u}_{i,j}$ is the normal displacement field average value of the ith element and for the jth configuration. The resolution of this system gives the values of electrical potentials A_i (i=2,3) to be applied to neighbouring elements.

	(1)*	$\underline{u}_{31}$ 0V	$\underline{u}_{21}$ 0V	$\underline{u}_{11}$ 1V	$\underline{u}_{21}$ 0V	$\underline{u}_{31}$ 0V
+	(A_2)*	$\underline{u}_{32}$ 0V	$\underline{u}_{22}$ 1V	$\underline{u}_{12}$ 0V	$\underline{u}_{22}$ 1V	$\underline{u}_{32}$ 0V
+	(A_3)*	$\underline{u}_{33}$ 1V	$\underline{u}_{23}$ 0V	$\underline{u}_{13}$ 0V	$\underline{u}_{23}$ 0V	$\underline{u}_{33}$ 1V
=		$\underline{u}_3$=0 A_3	$\underline{u}_2$=0 A_2	$\underline{u}_1$ 1V	$\underline{u}_2$=0 A_2	$\underline{u}_3$=0 A_3

Figure 6: the linear superposition principle

Numerical results

The numerical technique presented in this last section has been tested with a linear array composed of five piezoelectric bars (PZT5H) and with the help of the FEM. Compliant material (epoxy) is used to fill the array. The thickness (*T*) of the element and the width to thickness ratio (*W/T*) are respectively 1 mm and 0.5. In fact, for *W/T*<0.5 a dominant thickness mode is obtained [5].

Two cases are considered. First, the central element is driven by an electrical potential of 1V and the four neighbouring elements are grounded. The far-field directivity pattern and the displacement field computed at the resonance frequency (maximum of radiated power) are displayed on fig 7. The central element vibration generates a strong displacement on neighbouring transducers. The far-field directivity pattern is strongly disturbed due to parasitical vibrations of neighbouring elements. We can notice main lobes in the directions of θ=±20°, which

represents a very strong elementary radiation pattern for a linear array.
Using the numerical technique explained previously, it is possible to correct the far-field directivity pattern of the central element by applying electrical potentials on the neighbouring elements, thereby reducing the displacement field on their active surface. These electrical potentials have been computed and are equal to A_2=(-0.16+0.51j) and A_3=(0.1-0.46j). The finite element modelling of the set of five piezoelectric bars where the four neighbours are excited by electrical potentials (A_2 and A_3) has been performed. Figure 8 displays the far-field directivity pattern and the displacement field computed. Interaction between neighbouring transducers are weaker than in the previous case (grounded neighbours) and the second neighbours are almost not disturbed. The far-field directivity pattern is clearly improved with a main lobe in the axial direction.

Conclusion
Applicability of Finite Element Method to optimize a piezoelectric transducer array was investigated. The FEM algorithm has been used to study the influence of the matching layer and yields to a choice criterion of the layer guaranteeing no lateral mode in the bandwidth of the transducer. The criterion has been experimentally tested. Then, the FEM has been used to calculate the electrical potentials needed to minimize acoustic cross-coupling. The feasibility of the algorithm was successfully tested using a simple 5 elements array.

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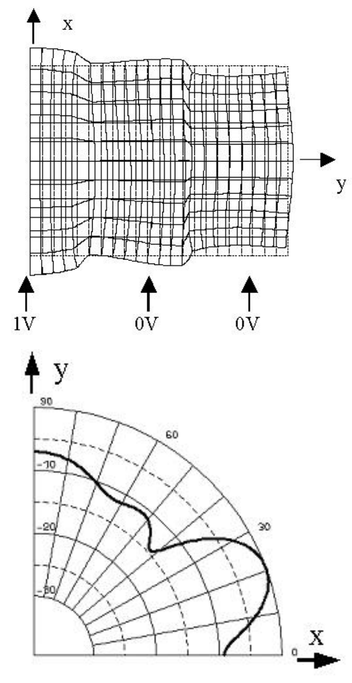

Figure 7: Numerical displacement field and far-field directivity pattern of a set of five piezoelectric bars radiating in water. The middle element is active (1V) and the others are passive (grounded)

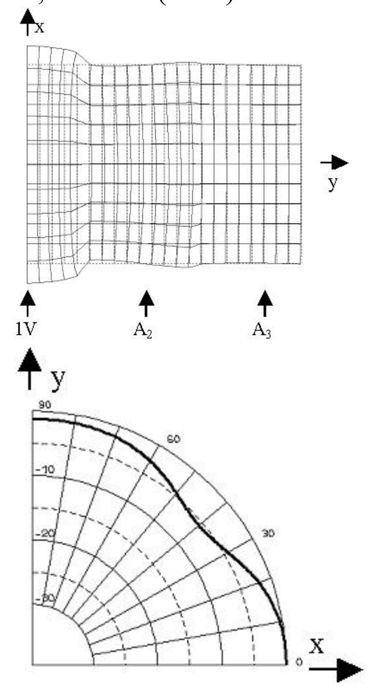

Figure 8: Numerical displacement field and far-field directivity pattern of a set of five piezoelectric bars radiating in water. The middle element is active (1V) and the others are excited by electrical potential A_i (i=2,3)