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Influence of 1-3 piezocomposite fabrications on lateral modes

Rémi Rouffaud^{*†}, Anne-Christine Hladky-Hennion[†], Mai Pham-Thi[‡], Claire Bantignies[§] and Franck Levassort^{*}

^{*}GREMAN, CNRS UMR7347, 10 boulevard Tonnellé, BP3223, 37032 Tours Cedex 1, FRANCE

[†]IEMN, CNRS UMR8520, 41 boulevard Vauban, 59046 Lille Cedex, FRANCE

[‡]THALES Research and Technology, 1 avenue Augustin Fresnel, 91767 Palaiseau Cedex, FRANCE

[§]VERMON, 180 rue du Général Renault, BP93813, 37038 Tours Cedex 1, FRANCE

E-mail: remi.rouffaud@univ-tours.fr

Abstract—Properties of 1-3 piezocomposites with periodic structure were characterized. This material can be typically fabricated in using the "dice and fill" method (DFM) and two phases were used (PMN-34.5PT ceramic and epoxy resin). The corresponding numerical simulations allowed to study the influence of spurious lateral modes on electromechanical performance of the thickness mode. This was performed in calculating the bandwidth and the sensitivity of the piezocomposite in water (emission-reception) in the frequency range 1-5 MHz. Moreover, three ceramic volume fractions between 25% and 60% were used. Finally, a comparison of these results with those obtained with a pseudo-periodic 1-3 piezocomposite was made. This composite can be fabricated by a lamination technique (LMT) and the use of a pseudo-periodic structure leads to a minimized effect of the lateral modes (confirmed on the simulated electrical impedance). Thanks to these results an optimum structure was discussed.

I. INTRODUCTION

1-3 piezoelectric composites are often used for the fabrication of ultrasonic transducers. The main interests of these structures are a very high electromechanical thickness coupling factor, in particular when piezoelectric single crystals are used (typically 90%) and a decrease of the acoustical impedance with the introduction of a polymer phase. These composites are often fabricated in using the standard "Dice and Fill" Method (DFM) which mostly delivers a periodic structure and leads to the existence of spurious (lateral) modes. These lateral modes were widely studied few years ago [1], [2] and several solutions were proposed to minimize their effects. On the one hand, an important work on the pillar geometry was performed by Hossack *et al.* [3]. The contribution of different pillar geometries on the electromechanical coupling factor of the composite was studied. More practically, the design of a piezocomposite with triangular pillars was manufactured and the measurements showed that this geometry improves some essential characteristics, in particular for high frequency imaging applications [4].

On the other hand, a Lamination Technique (LMT) was used to obtain large area 1-3 piezocomposite (well adapted for the use of single crystals)[5]. This method offers the possibility to fabricate irregular structure which can be an alternative way to reduce the effect of spurious lateral modes. The LMT allows many degrees of freedom such as the pillar shape (square or rectangular) and size but also the dimensions of the spacing

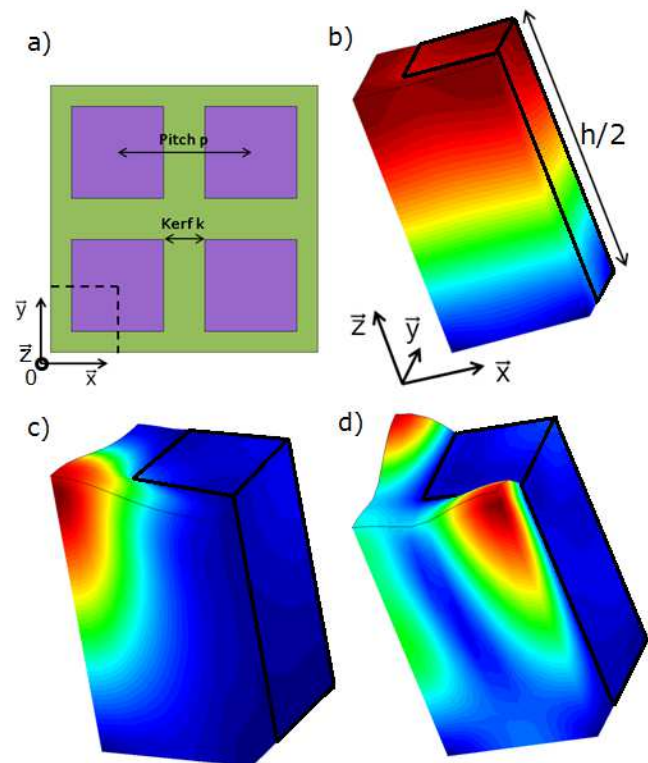


Fig. 1. a) Top view of simulated 1-3 piezocomposite (purple: piezoelectric rod; green: polymer); From this periodic structure, a quarter mesh is used for the simulation (black dashed line) of the three first vibration modes and the displacement fields are represented for b) the thickness mode; c) the first lateral mode and d) the second lateral mode.

width (kerf). This paper gives in the following section II a complete study for a regular 1-3 piezocomposite and in section III, a comparison is made with a pseudo-periodic structure. Finally, several configurations are discussed and planned to minimize the spurious effect of the lateral modes.

II. PERIODIC STRUCTURE

In this section, the properties of a periodic 1-3 piezo-composite are simulated with ATILA finite element software[6]. Here, with the DFM, a square pillar shape is retained. Thus, due to the symmetry conditions, only a quarter

TABLE I
ELASTIC, PIEZOELECTRIC AND DIELECTRIC CHARACTERISTICS OF
MATERIALS USED.

Material	PMN-34.5PT (ceramic)	E501 (polymer)
C_{11}^E (GPa)	174.7	7.84
C_{12}^E (GPa)	116.6	3.90
C_{13}^E (GPa)	119.3	3.90
C_{33}^E (GPa)	154.2	7.84
C_{44}^E (GPa)	26.7	1.97
C_{66}^E (GPa)	29.0	1.97
$\epsilon_{11}^S/\epsilon_0$	2373	3
$\epsilon_{33}^S/\epsilon_0$	2610	3
e_{13} (C/m ²)	-6.4	-
e_{15} (C/m ²)	17.1	-
e_{33} (C/m ²)	23.3	-

of the cell is meshed (dashed lines on Fig.1(a)). Moreover, the plane of symmetry (oxy) allows working on half-thickness composite ($h/2$) for a faster calculation. The fixed parameters are the pitch p (see Fig.1(a)) and the ceramic volume fraction v_f . The corresponding chosen values are respectively $483\mu m$ and 47%. Frequential behavior of the resonance modes as a function of the thickness h (along the direction of the z -axis) of the composite is studied. In the simulation, the composite is assumed infinite in the (xy)-plane. Data used for the two phases are given in Table I [7].

A. Characterization of the structure modes in air

The thickness mode has a displacement field related to an half-wavelength resonator. In this case, both phases in the piezocomposite have an homogeneous z -displacement (Fig.1.b). The first lateral mode is due to the Bragg scattering effect. In the frequency domain, the first stationary wave appears in the $[110]$ -direction (Fig.1.c) and the displacement field has a higher value in the epoxy resin than in the ceramic phase. The second lateral mode (Fig.1.d) has a $[100]$ - and $[010]$ -directions. Figure 1 shows the displacement field for these three modes. Figure 2 illustrates the frequency dependence of the three modes as a function of the ($1/h$). For low values of ($1/h$) (until $2\mu m^{-1}$), the thickness mode has a standard frequency dependence (proportional to $1/h$) whereas the first and second lateral modes have stable resonant frequencies independent of the thickness of the piezocomposite.

The critical behavior for our configuration is around $1/h = 2\mu m^{-1}$ where frequencies of the thickness and first lateral modes are close. Consequently, a decrease in the electromechanical performance of the thickness mode is observed. A previous study was performed for a 1-3 piezocomposite with a ceramic volume fraction of 25% [8]. A decrease of performance through the calculation of the thickness coupling factor was made around the critical configuration and finally, a minimum ratio h/p was determined (in this case 3) to avoid this disturbing configuration.

This last study can be generalized in introducing the ceramic volume fraction as a variable. In Figure 2, calculations were

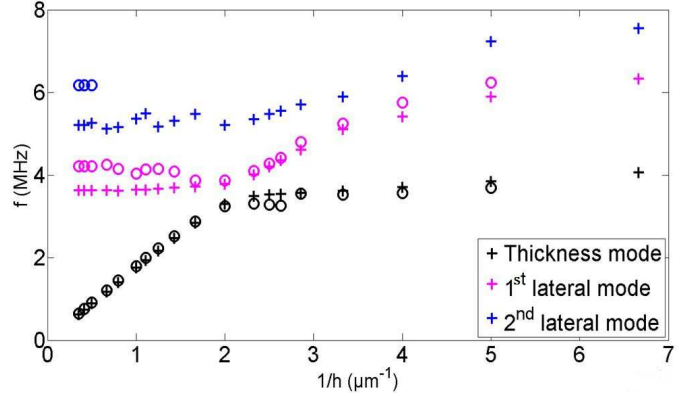


Fig. 2. Frequency dependence as a function of the inverse thickness ($1/h$) (+ symbol for a ceramic volume fraction of 47% and O symbol for 65% ceramic volume fraction).

also performed for two ceramic volume fractions in keeping the same pitch and consequently, the kerf value changes. As expected, the results show that the decrease of the kerf value allows to increase the resonance frequency of the spurious mode and tends toward a minimization of the spurious effect of the lateral modes on the thickness mode in the critical behavior.

For transducer applications, a trade-off must be defined between an increase of ceramic volume fraction (consequently higher acoustic impedance value) and the minimization of the disturbing effect of the spurious modes. To quantify more precisely these effects on transducer properties, electroacoustic frequency responses of 1-3 piezocomposites in water were calculated. Corresponding sensitivity and bandwidth were deduced to define for our configuration a functional limit.

B. Transducer properties

Figure 3 represents the normalized electroacoustic frequency responses calculated in water by FEM. These electroacoustic responses were obtained by the product of the two transfert functions (emission and reception). This was performed with the same 1-3 piezocomposite previous configuration (with a fixed ceramic volume fraction of 47% and a pitch of $483\mu m$) and for 4 different thicknesses (from 1.5mm to $642\mu m$) corresponding to a ratio h/p from 3 to 1.33. From this figure, the resonance frequency of the first lateral mode is measured at around 2.8MHz. As expected, this frequency value is lower than the value observed in Fig.2 (3.5MHz) due to the different surrounding media (air and water). From these theoretical results, -6dB relative bandwidths were deduced in each case. For the three first thicker samples, the -6dB bandwidth is constant at 23% whereas for the last case (the thinnest sample), the value decreases under 20%. This allows to define a first limit of $h/p = 1.3$ for the design of the 1-3 piezocomposite.

The second transducer characteristic is the sensitivity. It was obtained from the maximum amplitude of the electroacoustic response at the center frequency. Figure 4 shows the behavior of the normalized sensitivity as a function of the ratio h/p

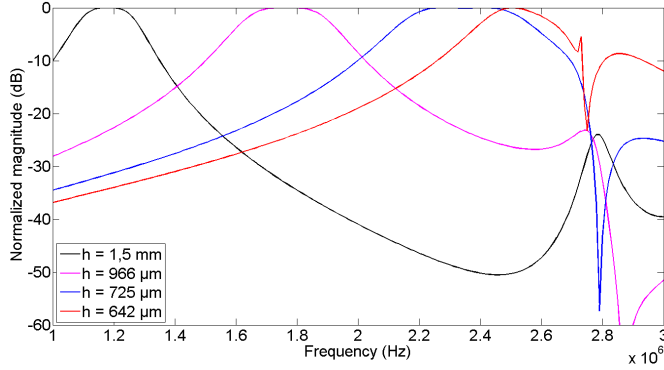


Fig. 3. Normalized electroacoustic frequency responses in water, simulated by FEM, for 4 different thicknesses (for a fixed ceramic volume fraction of 47%).

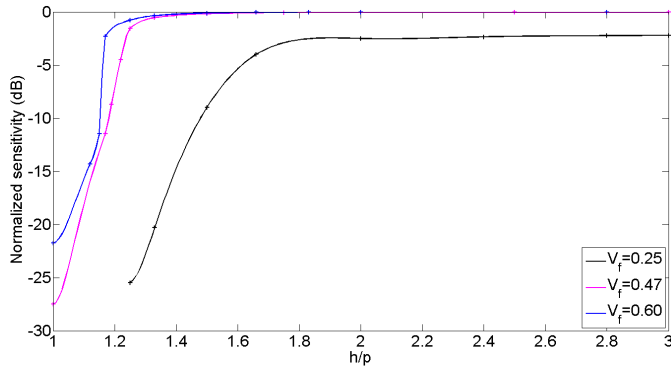


Fig. 4. Normalized sensitivity of 1-3 piezocomposites (with three ceramic volume fractions) as a function of the ratio h/p (h : thickness; p : pitch).

for three ceramic volume fractions ($v_f = 0.25; 0.48$ and 0.60). As observed on Figure 4, the sensitivity of the 1-3 piezocomposite with 25% of ceramic volume fraction is lower than the two others (typically for a ratio h/p higher than 2). This is mainly due to a lower thickness coupling factor for this composite. Moreover, the decrease of sensitivity is observed for a ratio h/p of around 1.3 for the two highest ceramic volume fractions, while for the third sample this limit value is around 2. This result confirms that for our configurations, a higher ceramic volume fraction (in keeping the pitch constant and consequently a decrease of the kerf) leads to a possible higher operating frequency (thickness mode).

III. RESULTS AND DISCUSSION

The periodic structure in a 1-3 piezocomposite implies several limits in the design. These limits were defined for our specific configurations from bandwidth and sensitivity values of the simple corresponding transducer (only the piezocomposite in water). According to the results, the introduction of a pseudo-periodic structure in the piezocomposite could modify these limits in reducing the spurious effect of the lateral modes. Thus such 1-3 piezocomposite was fabricated by Thalès Research and Technology with a lack of regular periodicity. In this case, material properties of the two phases were exactly the same as those used in the previous

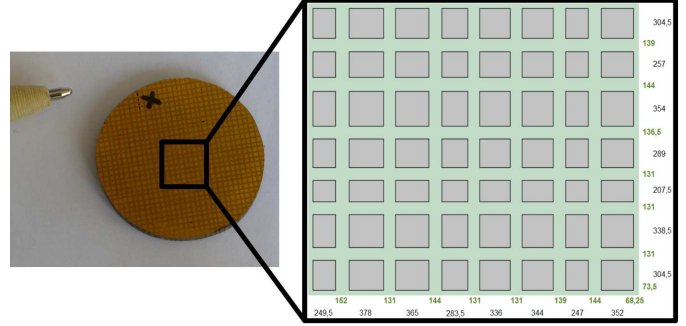


Fig. 5. Photograph of the pseudo-periodic 1-3 piezocomposite (in the square, the simulated area).

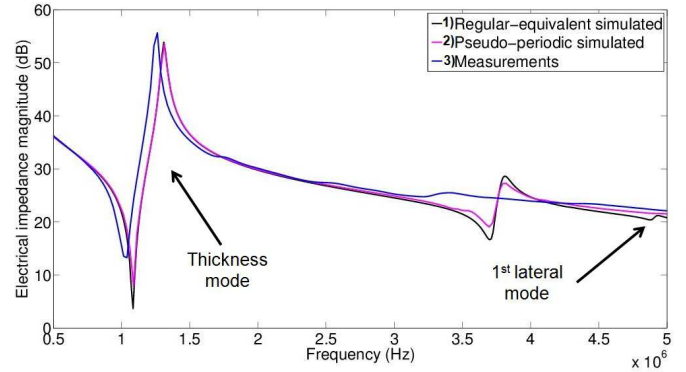


Fig. 6. Electrical impedance magnitudes as a function of frequency for: 1) simulated regular equivalent, 2) simulated pseudo-periodic and 3) measurements of 1-3 piezocomposites.

simulations. In this sample, all the rods have not the same dimensions (Fig.5) on contrary to the kerf which is identical in the whole sample. The rods can vary from $247 \times 207 \mu m$, for the smallest, to $378 \times 354 \mu m$, for the largest. Because of a memory limitation of the computer, only a representative part of the real sample is meshed ($1/10^{th}$) as shown in Figure 5. The thickness of this sample is 3.5mm and the ceramic volume fraction is 48%. A first simulation was performed to calculate the electrical impedance in air as a function of frequency for this 1-3 piezocomposite. This result was compared to the experimental electrical impedance of the whole sample. Moreover, an equivalent periodic 1-3 piezocomposite with the same ceramic volume fraction and material phases was defined and theoretical electrical impedance was also simulated. The three curves are superimposed in Figure 6. For these configurations, the mean ratio h/p has a value around 8 where the thickness mode is not disturbed by the lateral modes. The first lateral mode appears at 4.9MHz for the regular sample whereas, for the simulated pseudo-periodic part, the corresponding resonance is clearly minimized.

To increase the pseudo-periodic aspect in the 1-3 piezocomposite structure, several kerf values can be used. This will lead to minimize, one more time, the effect of spurious lateral modes. For the fabrication of such 1-3 piezocomposite, the lamination technique (LMT) is well adapted. Moreover,

transducer properties must be evaluated (bandwidth and sensitivity) to define limits of the ratio h/p for these new configurations. Results must be compared to an equivalent regular 1-3 piezocomposite.

IV. CONCLUSION

A theoretical study was made to evaluate the performance of periodic 1-3 piezocomposites (in air and water). For several given configurations, a limit of the ratio h/p (h : thickness; p : pitch) was defined for an optimal use of these materials (at the highest frequency as possible). This limit was defined in calculating the corresponding transducer properties (the piezocomposite is immersed in water) such as bandwidth and sensitivity. The introduction of a pseudo-periodic structure in the piezocomposite delivered a significant reduction of the effect of the first lateral mode. This was, in a first time, verified with a kerf constant value. Finally, in using the LMT, new structures could be designed in order to break the periodicity of the kerf and consequently, defined a new low limit of the ratio h/p .

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