1-3 Piezocomposites Based on Super-Cell Structuring for Transducer Applications

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***Abstract*—In ultrasound transducers, the most popular fabrication method for 1-3 piezocomposites is the « dice and fill » method where lateral periodicity *p* is introduced and leads to the occurrence of lateral modes. These spurious modes can drastically damage the performance of the device if they appear near its thickness (*h*) mode, thus limiting the operational frequency range. In order to overcome the previous limitations while maintaining a good electromechanical efficiency for the 1-3 piezocomposites, a new fabrication method based on lamination is proposed. The piezocomposite is partially regular with a super-cell structure composed of five piezoelectric rods and two different pitches in one direction. The chosen cell shape allows numerical modeling to be performed (ATILA software). This study is made in the frequency range 0.4-1.3 MHz. Experimental results (electroacoustic responses in water) confirm those obtained with the numerical simulations, showing that the super-cell composite can be used in a larger range of frequencies than regular composites, while keeping similar sensitivity and bandwidth.**

Keywords—Piezoelectricity; Composite; Transducer; Fabrication method, Numerical modeling.

I. Introduction

Piezoelectric composite materials are currently used in a wide range of applications. Among all these developed materials, aligned piezoelectric rods embedded in a polymer matrix deliver the highest performance in thickness mode for transducer applications. These materials are defined as 1-3 piezocomposites using the connectivity concept [1]. The dice and fill method [2] is the most popular method for their fabrication but a lateral periodicity with a pitch (*p*) is introduced and leads to the existence of spurious lateral modes at frequencies inversely proportional to the pitch. This limits the use of such composites to frequencies that are significantly lower than that of the spurious modes. In this study, the main objective is to design and fabricate a 1-3 piezocomposite in which the effect of lateral modes is reduced so that the frequency range in which the material can be efficiently used is increased. To this aim, the concept of super-cell structure used in phononic crystals [3,4] is introduced. The choice of the size, acoustic properties and spatial arrangement of the materials in the super cell must be made in order to encourage or suppress the propagation of specific modes. In our case, the super-cell structure is designed in order to attenuate lateral modes in the 1-3 piezocomposite. In the next section, the design of the super-cell is detailed. The interest is confirmed through numerical simulations comparing the behavior of this new design with standard regular structures. Then, the fabrication of the corresponding optimized piezocomposite is described. Experimental set-up for the measurements of electroacoustic responses in water is also described. In particular, the fabricated composites are successively lapped to reduce their thickness and thus increase their operating frequency (thickness mode) to progressively reach the frequency of the spurious modes. The relevance of this new design is demonstrated through the measurement of bandwidth. In section III, these experimental results are shown for three thicknesses and confirm the interest of this new material for a use in a wide range of frequencies.

II. Design and Fabrication of 1-3 Piezocomposite

A. *Design of Super-Cell Structure*

The proposed structure is only partially regular in order to minimize the effects of lateral modes. In regular structures (i.e. typically fabricated with the "dice and fill" method [2]), the first lateral mode corresponds to standing waves along the diagonal between piezoelectric rods (two arrows in Fig. 1(a)). To avoid this symmetry, a spatial shift of piezoelectric rods is introduced in the structure leading to the so-called super-cell structure. This representative cell is composed of 5 piezoelectric rods with the same square section (a^2) and distributed on two horizontal lines (Fig. 1(b)). The upper line contains three rods with *a/3* spacing while the lower line is composed of two rods with a *a* spacing. The whole cell can be defined by two spatial periodicities (*Px* and *Py*) of the 1-3 piezocomposite defined by *Px=4a* and *Py=8a/3* respectively. This configuration leads to a fixed value of the ceramic volume fraction (piezoelectric phase) at 47%. Other configurations can also be obtained with a higher number of rods to modify this ceramic volume fraction [5]. In the super-cell structure, two different kerfs widths are used, which also contributes to minimize the second lateral mode.

(a)

(b)

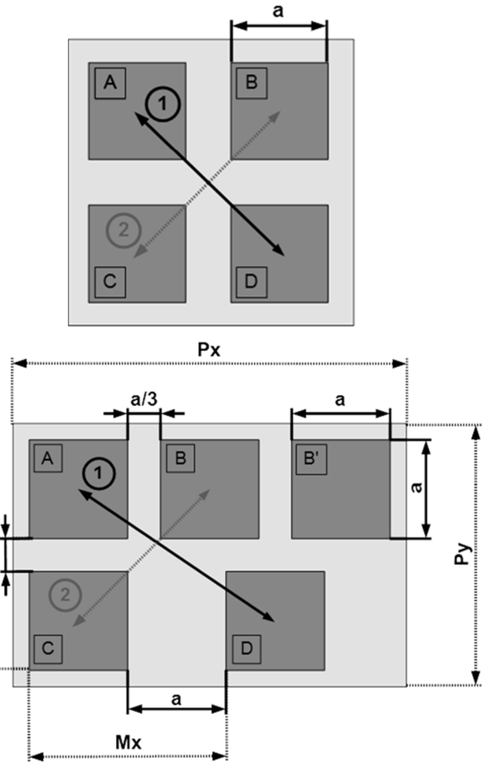

Fig. 1. Schematic representations (top views) of (a) regular and (b) super-cell structure for 1-3 piezocomposites (dark grey : piezoelectric rods, light grey : polymer).

B. Numerical study

This subsection is devoted to numerical calculation using the finite element method (FEM) with the ATILA code [6]. This theoretical study is performed to evaluate the interest of the super-cell concept compared to standard regular 1-3 piezocomposites. Comparisons are performed on electroacoustic responses of the immersed materials. For that, transfer functions in emission and reception in water are simulated using periodicity conditions. The previous description of the super-cell structure takes into account two additional criteria. First, the corresponding 1-3 piezocomposite must have sufficient symmetry planes to simplify the modeling and reduce the calculation time. Secondly, the corresponding design must be compatible with a fabrication method, which will be discussed in the next subsection. For the calculation, the chosen material database are those of a PMN-34.5PT [7] for the piezoelectric phase and of an epoxy resin [8] for the inert phase. The chosen rod size is a=1 mm leading to a size of the super-cell of 4 mm×2.67 mm. For comparison purposes, three regular 1-3 piezocomposites are defined with different fixed pitch values to cover those defined in the 1-3 super-cell piezocomposite. For that, the two pitches *Mx* and *My* (Fig.1(b)) are used and a third configuration with an intermediate value of pitch (i.e. (*Mx+My)/2*) is added. For all of these, the same ceramic volume fraction is kept (47%) imposing the size of the piezoelectric rods. Table I summarizes the four configurations with all the geometrical specifications. For the three regular structures, only the thickness *h* corresponding to a ratio *h/p=1* is considered while for the super-cell piezocomposite, the three same thickness values are used for comparisons. In all cases, this ratio corresponds to a low value that does not verify the classical criterion for which lateral modes do not disturb the thickness mode (*h/p>3*) [9].

TABLE I. GEOMETRICAL SPECIFICATIONS AND FRACTIONAL BANDWIDTH (IN WATER) OF THE FOUR 1-3 PIEZOCOMPOSITES.

	Piezocomposite configurations[a]	*p (mm)*	*a (mm)*	*h (mm)*	BW_{-6dB} *(%)*
1	Super-Cell	1.33-2	1	1.33 1.67 2	7 29 18
2	Regular	1.33	0.91	1.33	5
3	Regular	1.67	1.14	1.67	5
4	Regular	2	1.37	2	4

[a]p: pitch (two values in the super-cell structure), a: side value of the square piezoelectric rods, h: retained thickness(es) for each simulated piezocomposite behavior, BW_{-6dB}: corresponding fractional bandwidth at -6dB deduced in water.

Fig. 2 represents the six numerical frequency responses. For the three simulated regular structures (with *h/p=1*), the first lateral mode disturbs the response with a significant decrease of the bandwidth compared to those obtained with super-cell 1-3 piezocomposite (Table I). For example, the bandwidths for configurations 1 (with 1.67 mm thick) and 3 are respectively 29% and 5%. For configurations 1 and 2, similar bandwidths are obtained (around 6% for a thickness of 1.33 mm). These results show that the 1-3 super-cell piezocomposite can be used in a larger range of frequencies (with an adapted thickness) than a regular structure with similar pitch values, which confirms the interest of the proposed new design.

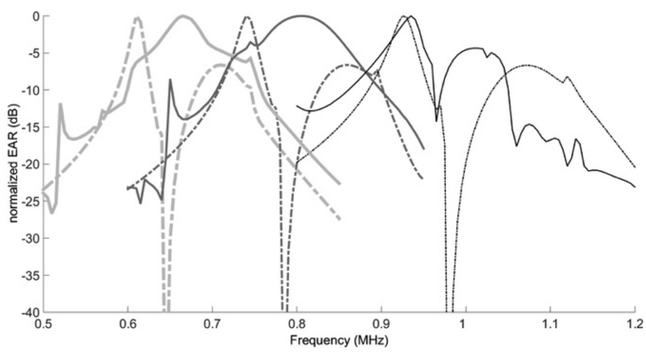

Fig. 2. Theoretical electroacoustic responses of the four piezocomposites for three different thicknesses: 1.33 mm (thick lines for configurations 1 and 2), 1.67 mm (medium line for configurations 1 and 3) and 2 mm (thin lines for configurations 1 and 4). Dashed line for regular and solid lines for super-cell structures.

C. Fabrication

The retained fabrication method has to be compatible with the design described in previous subsections. The "dice and fill" method could not be used since it cannot deliver two different kerf width values in one direction. The lamination technique is used [10] since it adds degrees of freedom for the fabrication, in particular the possibility to avoid alignment of the rods in one direction. The basic concept of this method is first the fabrication of two 2-2 piezocomposites with the same thickness of the piezoelectric plates (*a*) but two different thicknesses of the polymer plates (*a* and *a/3*). Fig. 3 represents the cross-sections of these two 2-2 piezocomposites (called 1 and 2). Transverse cuts (with 90° turns of the initial 2-2 composites) are performed and plates are alternatively glued with a new intermediate polymer layer which has the same thickness (*a/3*) as that included in the second 2-2 piezocomposite, in order to obtain the final 1-3 super-cell piezocomposite.

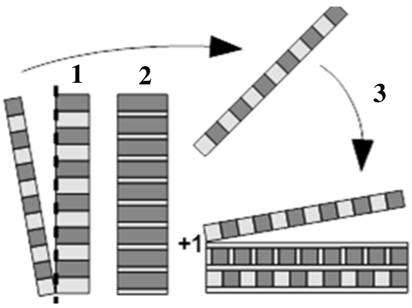

Fig. 3. Schematic representations (cross-sections) for the fabrication of the super-cell 1-3 piezocomposite.

MEGGITT-Ferroperm Piezoceramics Pz27 plates [11] and epoxy resin E501 [8] are used for this fabrication. The final dimensions of the fabricated samples are 37.1×22.5×12.1 mm^3 (the last value corresponds to the thickness). This sample is cut in two pieces to reduce its thickness. Fig. 4 presents pictures of the two samples.

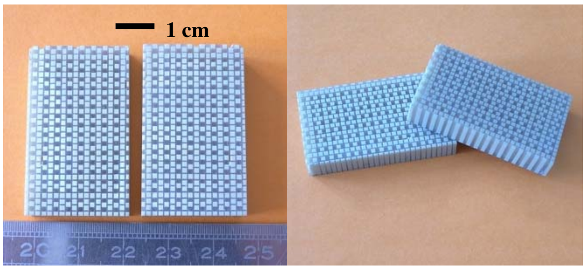

Fig. 4. Pictures of fabricated super-cell 1-3 piezocomposites.

Before experimental characterizations, two regular 1-3 piezocomposites using the "dice and fill" method have been fabricated with the same materials corresponding to configurations 2 and 4 (Table I,). The three samples are lapped to have the same thickness at 2.78 mm. Gold electrodes are sputtered on each side of the three samples. Finally, they are poled using an electrical field of 2kV/mm.

D. Characterization

For the experiments, each sample is successively lapped to have the same thickness and this procedure is repeated nine times (from 2.78 mm to 1.1 mm). After each machining, new electrodes are deposited and poling is performed. For each thickness, the electroacoustic response in water is measured to deduce the evolution of the bandwidth in a wide range of frequencies. For these measurements, each 1-3 piezocomposite is alternatively immersed in a water tank in front of a metallic target and excited with an electrical signal of 14-cycle burst (10V peak-to-peak) at a fixed frequency and repeated for several frequencies around its resonance (with a step of 10kHz). The studied thickness range corresponds to a *h/p* ratio range of 1.42-0.57 for configuration 4 and 2.18 to 0.87 for configuration 2 (Table I). Before measurements, a preliminary theoretical study with ATILA had been made to define the limit value of the *h/p* ratio where the thickness mode begins to be disturbed by the first lateral mode for the two regular piezocomposites (with a significant decrease of the bandwidth). The corresponding value was found at 1.25. For the highest thickness (i.e. 2.78mm) this ratio is higher and confirms that a pure thickness mode will be measured.

III. Results and Discussion

Fig. 5 shows the evolution of the electroacoustic responses as a function of frequency for three representative thicknesses (2.78 mm, 2.2 mm and 1.1 mm). On each figure, the behaviors for the three samples (the two regular and super-cell structure) are superimposed. The regular piezocomposites with large and low pitches are respectively called R1 and R2. The super-cell piezocomposite is called SC. In Fig. 5(a), all the *h/p* ratios are higher that the calculated limit and fractional bandwidths at -6dB are comparable with 16.4%, 19.3% and 19% for R1, R2 and SC samples, respectively. The lower sensitivity for the SC sample is mainly due to a lower k_t value (58%) compared to 63% for R1 and R2 samples. In Fig. 5(b), the *h/p* limit is reached for R1 sample and the effect is clearly observed with a significant decrease of the bandwidth (11%). For the two other cases, bandwidths are close (24% and 21% for R2 and SC respectively). Finally, for the lowest thickness (1.1 mm) presented in Fig. 5(c), R2 sample exceeds the *h/p* limit value leading to a slight decrease of the bandwidth and dissymmetrical frequency response, not suitable for transducer applications. This phenomenon is even more highlighted for sample R1. However, for the SC sample, bandwidth is stable (23%) with a symmetrical behavior. Moreover, in this last case, the thickness coupling factor value (k_t%) of the SC sample is 63%, which is identical to those of the regular structures. The increase of k_t value for the SC sample as a function of the decrease of the thickness is due to a more efficient poling. The consequence is an increase of the sensitivity, which becomes comparable to that of regular samples. Finally, in the whole studied frequency range, the super-cell 1-3 piezocomposite delivers quasi-constant properties such as bandwidth while exhibiting a symmetrical frequency response.

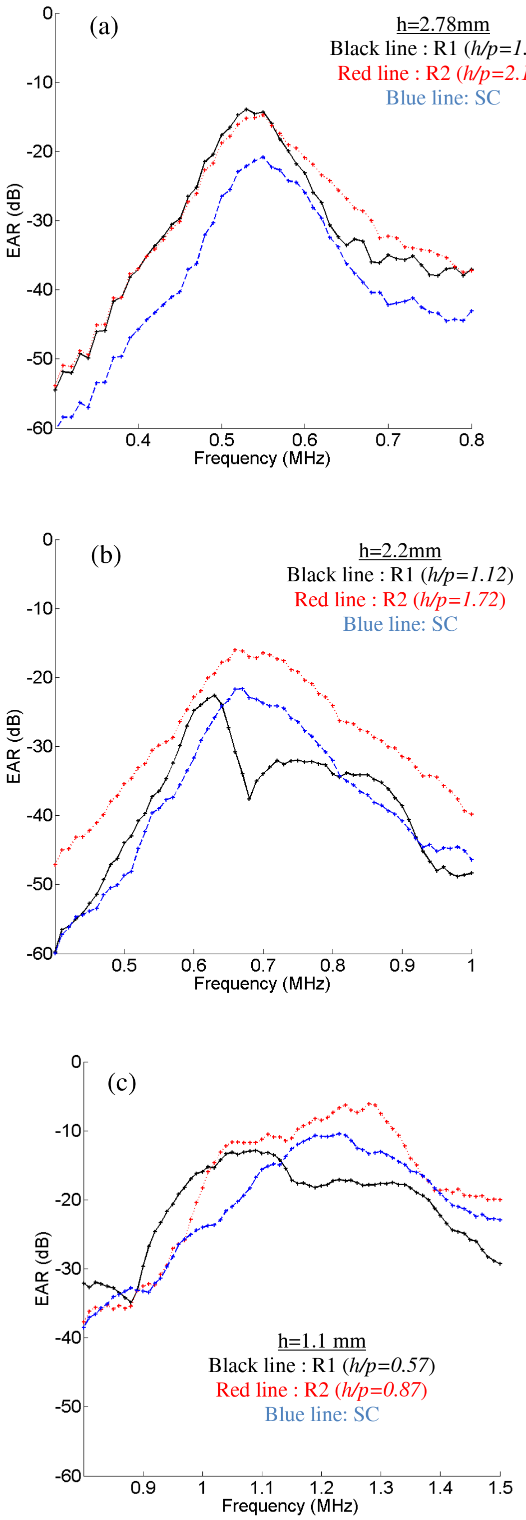

Fig. 5. Experimental electroacoustic responses (EAR) as a function of frequency for the three fabricated 1-3 piezocomposites (R1: regular with 2 mm pitch value, R2: regular with 1.33 pitch value, SC: super-cell): for a thickness of (a) 2.78 mm, (b) 2.2 mm and (c) 1.1 mm.

IV. Conclusion

A piezoelectric composite with 1-3 connectivity based on a super-cell structure has been designed and fabricated in order to minimize the effect of lateral modes. The lamination method has been used for the fabrication. This new 1-3 piezocomposite allows an efficient use, with bandwidth and sensitivity comparable to those of standard periodic structures, even when the standard criterion of h/p ratio is no longer respected (typically lower than 1.25). Consequently, this material can be used in a wider range of frequencies than standard piezocomposites.

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