Piezocomposite transducers built using ultrasound micromachining techniques

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ABSTRACT

The manufacture of one- and two-dimensional arrays of piezoelectric transducer elements devoted to the fabrication of piezocomposite devices is mainly based on saw-dicing techniques, appropriate for piezocomposite transducers exhibiting simple and regular patterns. However more complicated patterns cannot be obtained using these techniques.

In the present paper, an alternative technique to manufacture two-dimensional piezoelectric transducer arrays is investigated. Quincunx distributed cylinder patterns have been manufactured using an ultrasound micromachining process on PZT discs.

Piezocomposite materials are then built using these arrays and tested experimentally (electrical and optical measurements).

In parallel, a specific finite-element program, built using the ModuleF toolbox, has been developed to address the problem of two-dimensional periodic piezoelectric transducers. Comparison between theory and experiments is reported to try and identify the excited vibration modes.

INTRODUCTION

During the last ten years, piezocomposite transducers have been developed for medical ultrasound imaging and non destructive evaluation to overcome the limitations of standard one-dimensional probes [1]. The manufacture of one- and two-dimensional arrays of piezoelectric transducer elements devoted to the fabrication of piezocomposite devices is mainly based on saw-dicing techniques [2]. These are well appropriate for rapid and accurate production of piezocomposite transducers exhibiting simple and regular patterns. However more complicated patterns like honeycomb or cylinders cannot be obtained by the use of these techniques.

In the present paper, an alternative technique to collectively manufacture two-dimensional piezoelectric transducer arrays is investigated. Quincunx distributed cylinder patterns have been manufactured by the use of an ultrasound micromachining process on PZT discs. Cutting tools, consisting in the counter-form of the structure to be patterned, are manufactured following two different ways: standard mechanical processes and clean-room techniques. These technological developments are described in the 1st section of this article.

The ultrasound micromachining process is applied on PZT plates, providing cylinder arrays then embedded in a polymer matrix, yielding piezocomposites. These devices are measured by the use of a network analyzer. The obtained admittance shows the different acoustic modes such as the fundamental longitudinal mode or the first lateral mode. The devices are then measured optically with an interferometric heterodyne laser probe. Modulus and phase images of vibration modes are performed. These results are reported in the second section.

In parallel, a home-made finite-element program, built on the ModuleF toolbox [3] (INRIA Rocquencourt), is used to compute the admittance and the vibration shapes of such materials. A specific program has been developed to address the problem of two-dimensional periodic piezoelectric transducers, in which rectangular and hexagonal unit cells are considered. Computations are then compared to experimental results.

As a conclusion, future developments of this work are proposed.

GENERAL PHILOSOPHY

The main objective of the presented work is the fabrication of piezocomposite materials (more particularly 2-2 or 1-3 connectivity transducers). A massive PZT substrate is first machined by the use of a collective process, then the structure is filled in with a polymer. The material in excess is finally suppressed. Figure 1 gives a scheme of the proposed approach.

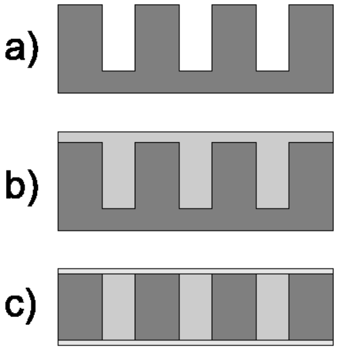

Fig. 1. a) deep etch of the PZT, b) fill in with a polymer, c) lapping and metallization of the plate.

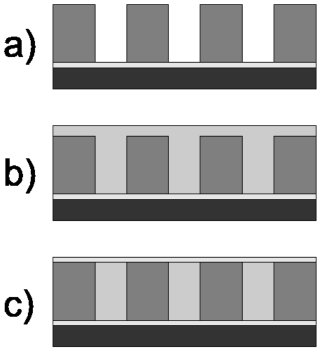

Fig. 2. a) top-down etch of the PZT glued on a backing, b) fill in with a polymer, c) lapping of the surface and metallization.

An alternative approach consists in gluing the massive PZT plate on a backing, for instance with a conducting glue. The PZT is etched top-down over the whole thickness of the plate, before being filled in with the polymer. The advantage of this process is that only polymer in excess has to be eliminated. This second approach is represented in Fig. 2. Its main difficulties consist in a fine control of the etching depth and also in addressing the electrical pixels across the backing.

In that matter, an ultrasound micromachining technique has been investigated and is described in the next part.

THE ULTRASOUND MICROMACHINING TECHNOLOGY

The machining part of the apparatus consists in a vibrating head. This latter is in touch with particles in suspension in a liquid. The movement of the particles, created by the vibration of the head, cuts the PZT plate, so that the head of the apparatus is never in touch with the substrate to be machined. Diamond powder as well as Bore Carbide particles are used to etch the PZT. For more details, see Ref. [4].

The ultrasound micromachining technique requires the fabrication of cutting tools consisting in the counter-form of the structure to be transferred in the piezoceramic.

A first "sonotrode" head of the ultrasound micromachining apparatus was manufactured using standard mechanics means. A twenty millimeter diameter steel cylinder was patterned by conventional drilling. The pattern was a quincunx distributed cylinder hole array, with holes of 250 µm radius, 3 mm depth and separated by a 200 µm large wall, yielding a 700 µm period. The corresponding tool is shown in Fig. 3.

Fig. 3. Cutting tool of the ultrasound micromachining apparatus.

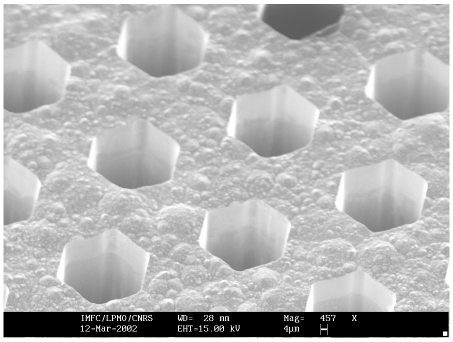

Fig. 4. SEM view of an electroplated Nickel cutting-tool. The Nickel counter-form is glued on the head of the sonotrode.

Standard mechanics manufacture does not easily provide tools allowing dimensions smaller than several hundred microns. For this reason, clean-room technologies have been investigated, especially electroplating of Nickel with a UV-LIGA [5] technique in order to micromachine metallic sonotrodes. A electroplated Nickel cutting-tool is shown in Fig. 4. The hexagonal holes are about 45 µm diameter large and 120 µm deep.

EXPERIMENTAL RESULTS

A massive PZT substrate was processed with the first presented cutting tool. SEM views of the machined PZT plates are shown in Figs. 5 and 6. Because of the thickness of the plate (500 µm), the PZT cylinder height is 400 µm and the width over thickness ratio close to one is not well suited for imaging applications. However, due to the depth of the sonotrode holes, high aspect ratios can be obtained.

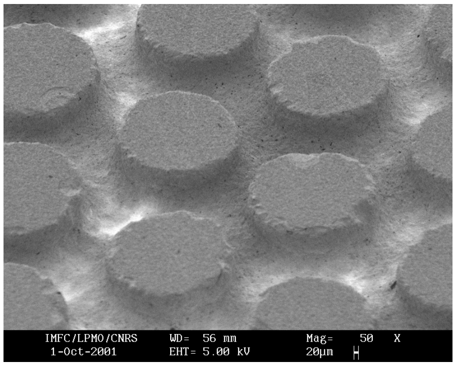

Fig. 5. SEM view of the patterned PZT plate. Such a non conventional quincunx pattern can not be obtained with a standard saw-dicing technique.

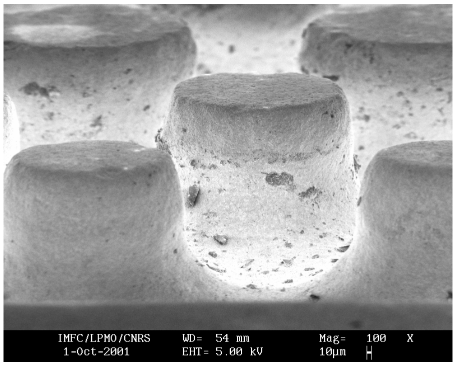

Fig. 6. Second SEM view of the patterned PZT. The sides of the pillars are well defined.

A piezocomposite array of PZT transducer elements was then built using an epoxy-based photoresist. The previous machined PZT plate has been filled in with the photoresist, namely the SU-8® [6], also used for deep etch UV lithography. The grooves are filled in without any particular difficulties such as air bubbles trapped in the resist matrix. It is then hardened by successive bakings and an exposure to UV light. Finally the PZT and the polymer in excess are lapped in order to obtain PZT cylinders in a polymer matrix. The obtained piezocomposite transducer (Fig. 7) is about 350 µm thick.

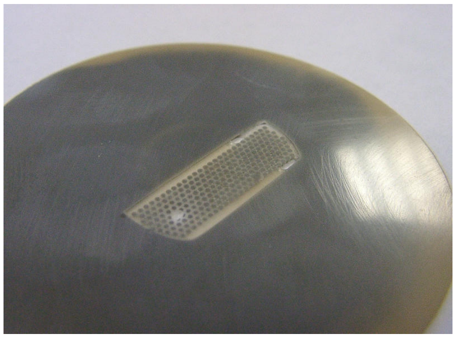

Fig. 7. The manufactured PZT substrate was filled in with an epoxy-based photoresist. The PZT and the photoresist in excess were eliminated.

Two different measurements have been performed. The transducer elements are excited synchronously. The measured admittance is displayed in Fig. 8. The thickness mode is found close to 3.63 MHz. The antiresonance frequency, given by the maximum of the impedance curve, is found at 4.28 MHz. One can deduce an electromechanical coupling factor equal to 0.569, from these two frequencies.

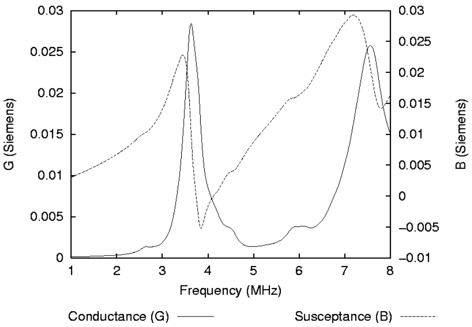

Fig. 8. Real (solid line) and imaginary (dashed line) parts of the admittance.

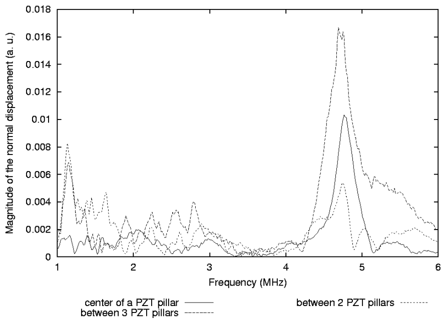

Fig. 9. Magnitude of the normal displacement measured for three particular points of the hexagonal structure.

Measurements of the normal displacement of the structure have been then performed using an interferometric heterodyne laser probe. Figure 9 shows the normal displacement versus the frequency for three particular points of the vibrating device: the center of a PZT pillar, the polymer matrix between two PZT pillars and finally between three PZT pillars.

Due to the bad aspect ratio of the PZT cylinders and the defects of the finite periodic structure, a lot of vibrating modes appear for low frequencies and the thickness mode can not be easily identified. Nevertheless an image of the surface normal displacement is performed for a frequency of about 4.7 MHz, where the magnitude of the displacement seems to be relatively important. Magnitude and phase of the normal displacement for a 1 mm² zone are shown in Figs. 10 and 11. This vibrating mode can be compared with the well-known first lateral mode for classical biperiodic piezocomposites with square section PZT pillars.

The points of the polymer matrix, of maximum connectivity between the PZT pillars, as well as the centers of the pillars, appear as vibration maxima. Moreover, the PZT pillars and the polymer matrix do not vibrate in phase.

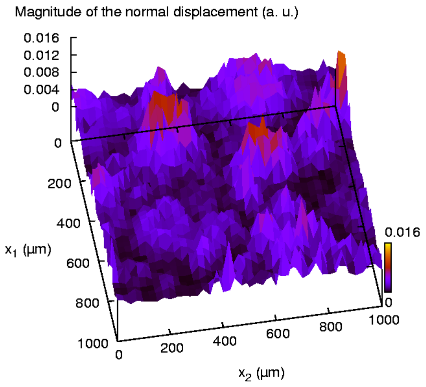

Fig. 10. *Magnitude of the normal displacement at about 4.7 MHz, corresponding to the first lateral mode.*

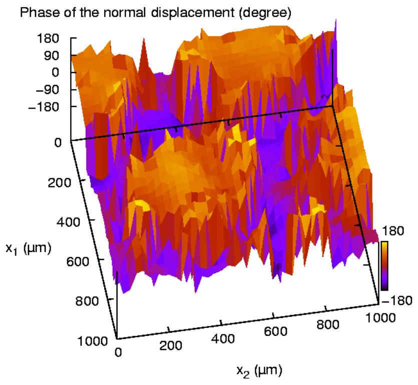

Fig. 11. *Phase of the normal displacement for the first lateral mode.*

FINITE ELEMENT METHOD COMPUTATIONS

Since the behavior of such complicated structures is difficult to predict in a simple manner, a finite-element program, built on the ModuleF toolbox from INRIA Rocquencourt, has been developed to simulate piezoelectric transducers. Some of the last developments are particularly devoted to the simulation of periodic piezoelectric transducers such as piezocomposites. Only one elementary cell of the device is meshed and boundary conditions, based on the Bloch-Floquet theory [7], are applied at the frontiers of the cell in order to compute the harmonic admittance (or impedance) of the device. In fact, rectangular and hexagonal unit cells are considered in our developments.

The calculated admittance is shown in Fig. 12. Because of the constant sets of the used materials, which do not exactly correspond to the actual materials, and the approximation made about the mean dimensions of the structure, it is difficult to obtain a quantitatively exact estimate of experimental measurements. However the thickness mode and the first lateral mode are identified. The deformed shapes of this modes are represented in Figs. 13 and 14.

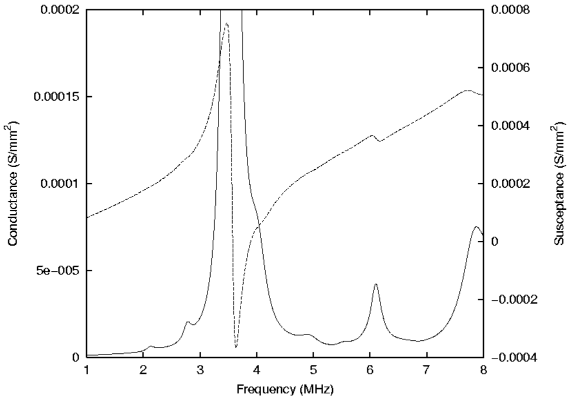

Fig. 12. *Computed admittance for the considered structure. Real part (solid line) and imaginary part (dashed line) are both represented.*

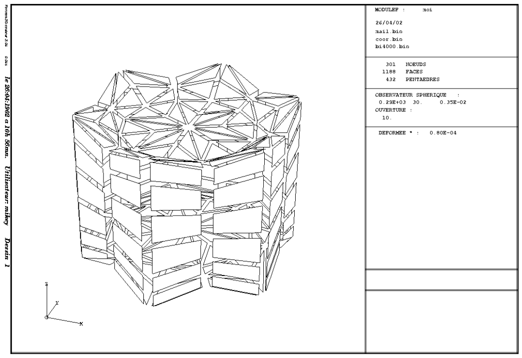

Fig. 13. Deformed shape of the thickness mode.

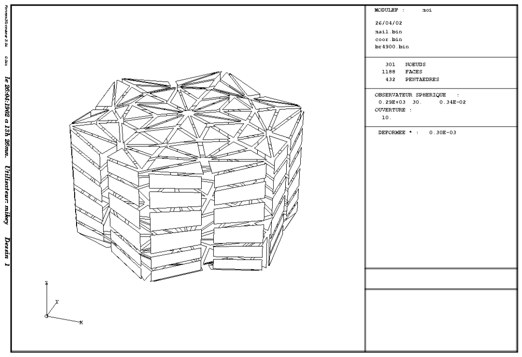

Fig. 14. Deformed shape of the first lateral mode.

CONCLUSION

A new method to manufacture non conventionally patterned piezocomposite transducers was investigated. A first test device was fabricated by the use of the ultrasound micromachining process. Electrical and optical measurements of the device were performed. The thickness mode and the first lateral mode were identified. The fabrication process seems to have not affected the piezoelectric properties of the PZT. At the same time, finite-element computations were performed in order to compare with the experimental results and to validate our periodic piezoelectric transducer simulation program.

Future devices will be manufactured with the electroplated Nickel cutting-tool in order to obtain smaller dimension piezocomposite transducers and so higher frequency operating conditions. Cross-talk effects will be investigated.

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