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SMART MATERIALS AND METAMATERIALS FOR MEMS: A GROWING TREND IN MICROSYSTEMS TECHNOLOGY

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Abstract. The rapid development of microsystems technology on one side and the impressive progresses in the fields of smart materials and metamaterials on the other side open the possibility to create a new field of innovative Smart and Meta -Microsystems or Micro Electro Mechanical Systems (MEMS). Smart materials and metamaterials can give to MEMS unprecedented properties for sensing and actuation. The potentialities of this new class of Microsystems are discussed and put in evidence in this paper starting from recent works of the Authors' group related to piezoelectric actuated Microsystems and to micro-scale Metamaterials endowed with band-gap and auxetic properties.

Key words: Smart Materials, Metamaterials, Microsystems, MEMS.

1 INTRODUCTION

In the last decades, there was an exponential growth of research activities in the field of smart materials and mechanical metamaterials, see e.g. the two books [1, 2]. Metamaterials and metastructures, possibly combined with smart materials, are now being transformed into engineering products. In parallel, the world of Micro Electro Mechanical Systems (MEMS), or Microsystems [3], has evolved from academic research to a fast growing industrial sector representing one of the enabling technology for Internet of Things and for the new industrial revolution 4.0.

The cumulated experiences in the field of smart materials and metamaterials on one side and the improvement of fabrication processes in the world of Microsystems on the other side, enable a fruitful merge of smart materials and metamaterials in MEMS, thus enabling the creation of smart meta-MEMS as a new trend in Microsystems technology [4].

As meaningful and recent examples of the use of smart materials in microsystems we can cite here piezoelectric actuated micro-mirrors [5, 6], micro-speakers [7, 8], and micro-ultrasonic transducers (PMUT) [9 - 12].

Micro-lenses [13], metaplates for vibration isolation [14] and auxetic structures [15, 16] are innovative recent examples of the use of acoustic metamaterial concepts in microsystems.

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This work focusses on recent results obtained in the above field of smart materials and metamaterials for MEMS, selecting a couple of meaningful examples of Smart-MEMS and Meta-MEMS. Section 2 discusses peculiar features of PMUTs with particular reference to the influence of residual stresses in the dynamic response of a single PMUT and cross-talk effects among various PMUTs in arrays configurations. Section 3 shows how auxetic configurations can be used for efficient double axis movements in microsystems. The final Section 4 contains closing remarks and future prospects for Smart and Meta -Microsystems

2 MECHANICAL FEATURES OF PMUTS BEHAVIOUR

PMUTs are usually designed as circular plates, suspended on a back-chamber, with their first-mode eigen frequency higher than 20 kHz, the audible sound threshold. The actuation of the membrane is caused by the response of a thin piezoelectric layer deposited on top of the plate, usually in the central portion, to the application of an electric potential across two metallic electrodes, as schematically shown in Fig. 1.

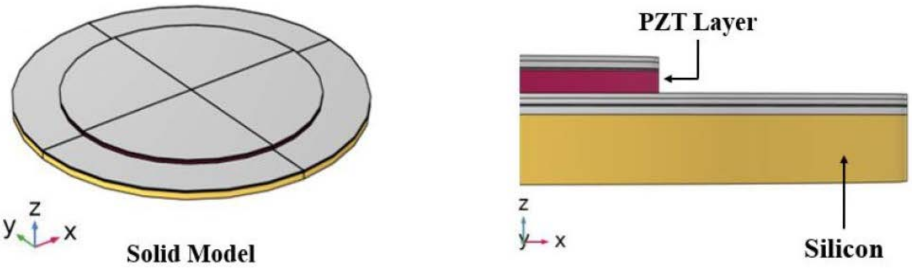
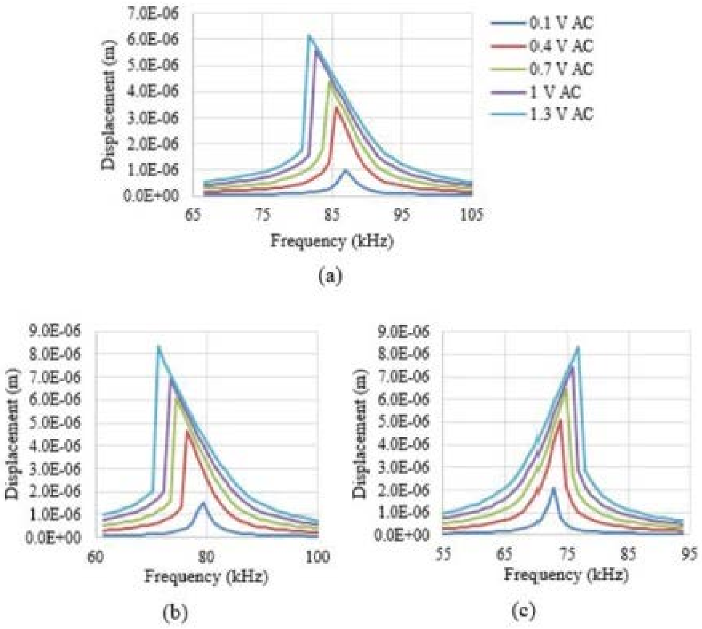


Figure 1: a typical PMUT plate and its solid model, from [10].

From a structural point of view, PMUTs are composite plates with a complex lay-up, dependent on the microfabrication process. When built as circular membranes, their thickness to diameter ratio defines the first-mode eigen frequency which in turn depends on the kind of envisaged applications: in the order of hundreds of kHz for air, while in the order of MHz for liquids. The thickness to diameter ratio can be very low for “low-frequency, large diameter” air-tuned PMUTs, thus enhancing the tendency to nonlinear regimes induced by bending-membrane coupling and the high sensitivity to fabrication-induced residual stresses. In addition to this, as recently proved in [9], the dynamic spectral response of PMUT membranes highly depends on the level of poling of the piezoelectric layer, thus showing a complex panorama of possible responses, from softening to hardening, as shown in Fig. 2.



(a)

(b)

(c)

Figure 2: softening and hardening dynamic responses of a PMUT plate, at fixed V_{dc} = 2 V and varying V_{ac}; (a) pristine, (b) partially poled, (c) poled piezoelectric material. From [9].

The transmission and reception of ultrasonic signals emitted and received by PMUTs plates must be experimentally and numerically studied with reference to the surrounding fluids and to the specific application. Usually, a pressure acoustic formulation is enough to capture the overall response; in some meaningful cases, viscous-thermo-acoustic formulations are necessary to correctly capture the response in the proximity of vibrating plates. PMUTs can also be used, similarly to ultrasonic testing at the macro-scale, for the detection of internal defects and internal stress states in solids and small structural components, as recently shown in [11]; in this case, elasto-acoustic effects must be carefully taken into account for the simulation of acoustic wave propagation in stressed solids.

A single PMUT can be used to measure distances by means of the time of flight of the signal transmitted, reflected back and received by the same vibrating plate. A couple of PMUTs can be used for signal transmission, e.g. for intrabody communication. The potentiality of PMUTs can be better exploited when arranged in arrays [10]. The small dimensions of the single membranes (the diameter can be in the order of a millimeter for a “large” PMUT vibrating in air) allow to condense in a small surface hundreds or thousands of plates, possibly grouped in clusters that can emit and receive ultrasonic signals, see Fig. 3. PMUTs arrays can highly increase the emitted Sound Pressure Level at non negligible distances, can enable acoustic beam forming and even image reconstruction as done in macroscale medical ecography.

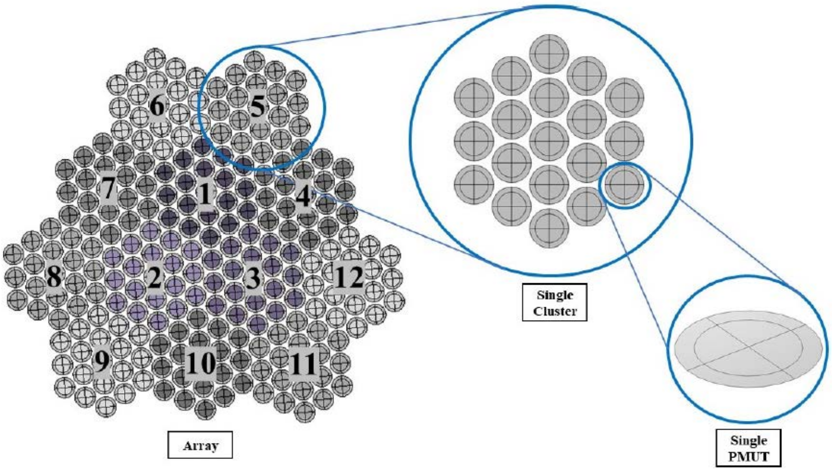


Figure 3: a typical PMUT array organized in 12 cluster of 19 PMUTs each. From [10].

A series of intriguing mechano-acoustic problems arise when trying to interpret the complex behaviour of PMUTs arrays. The high number of vibrating plates represents per se a real challenge for modelling and simulation, which calls for innovative reduced order models possibly combined with domain decomposition strategies. Another relevant and difficult phenomenon to control comes from cross-talk effects which create unwanted coupling among distinct plates. This dynamical coupling can be generated by the supporting substrate on top of which PMUTs plates are built and/or from a purely acoustic coupling as recently shown in [12].

Single and in arrays PMUTs are miniaturized smart structures and a meaningful example of Smart Microsystems with potential applications like local signal transmission, echolocation, fingerprint recognition and image reconstruction.

3 MICRO-SCALE AUXETIC STRUCTURES

The second example briefly discussed in this work relates to a periodic distribution of unit cells each characterized by an auxetic response in their plane. The single cell, shown in Fig. 4, expands laterally when pulled vertically, thus spontaneously creating a two-axis movement.

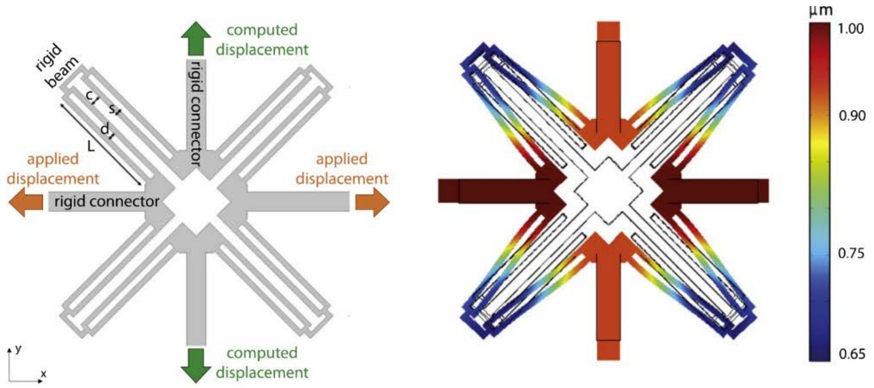


Figure 4: auxetic micro unit cell in the undeformed (left) and deformed (right) configurations. From [16].

This interesting feature was exploited in [16], designing and fabricating a whole auxetic Microsystem, as shown in Fig. 5. The device was experimentally tested and the results confirmed the optimal response of the designed auxetic cells.

This is a meaningful example of Meta-MEMS which can today be designed and fabricated thanks to new micro-fabrication processes combining new materials with extremely high precision.

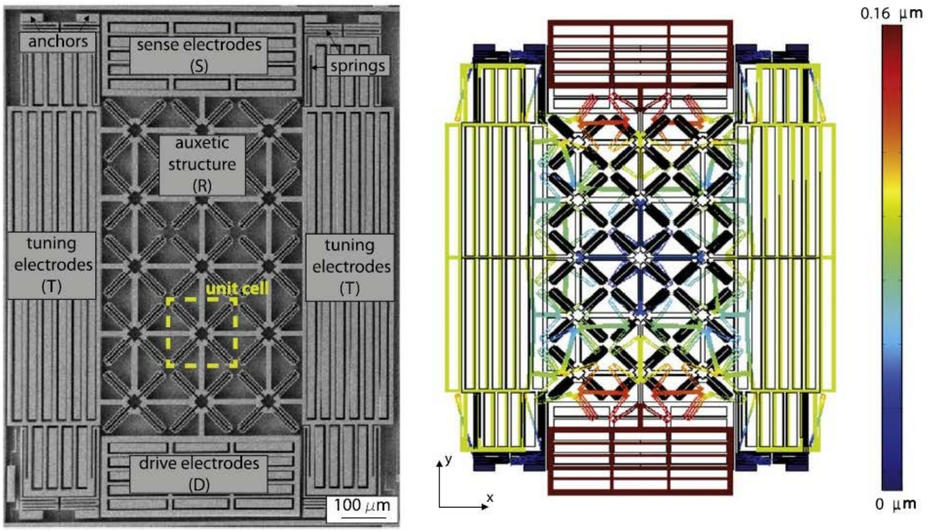


Figure 5: Auxetic Microsystem with two-axis motion. From [16].

4 CLOSING REMARKS

The purpose of this work is to put in evidence an interesting and promising trend in Microsystems technology: the combination of smart and metamaterials at the micro-scale for the creation of MEMS with unprecedented properties. This unique opportunity is made today possible by the fast development of micro-fabrication technologies which allows for the introduction of thin layers of piezoelectric and possibly other smart materials in MEMS and for the creation of complex shapes with very high geometrical precision. Two meaningful examples have been briefly presented and discussed referred to single and in arrays PMUTs and to auxetic structures for bi-axial motion. Many innovative configurations for innovative applications can be conceived in the world of Smart and Meta – MEMS as will be shown in future publications of the Authors' and of other research groups sharing the interest for this new research field.

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