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Multiphysics analysis and experimental validation of an air coupled piezoelectric micromachined ultrasonic transducer with residual stresses

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Abstract

In this work, we present a complete multiphysics modelling (via the Finite Element Method, FEM) of an air coupled piezoelectric micromachined ultrasonic transducer (PMUT) with preliminary experimental validations. The PMUT is a suspended layered membrane, in which one of the layers is made of piezoelectric material. By means of an applied voltage over the piezoelectric layer thickness, the device emits acoustic waves in air. The model takes into account the multiple interactions between electrical, mechanical and acoustic fields, and in particular gives a realistic estimation of the device quality factor by means of a proper modelling of thermo-viscous losses in the fluid domain. The complexity of the model is increased by the presence of initial large deformations in the membrane and fabrication induced residual stresses. Preliminary experimental matchings are presented for static pre-deflection of the membrane due to residual stresses and for the eigenfrequency corresponding to acoustic wave emission.

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Keywords: MEMS; dynamic analysis; Piezoelectric Micromachined Ultrasonic Transducers; Residual stresses; Static predeflection

1. PMUT device: numerical modelling and experimental validation

PMUTs are widely used for many practical purposes. Medical acoustic imaging and hydrophones exploit the in-water propagation of ultrasonic pulses; rangefinders and fingerprint recognition [1] use the in-air propagation; further applications are represented by non-destructive testing, velocity sensing and three dimensional object recognition. This work is focused on a single membrane air-coupled PMUT [2] clamped over a closed cavity (Fig. 1) characterized by a vibration frequency around 50 kHz, in the absence of a packaging structure.
The PMUT membrane is characterized by high aspect ratio (being the radius r=750 μm and thickness t=8 μm), in order to have a natural frequency at the desired value for the application exploiting the use of the piezoelectric thin film technology. The active material is represented by lead zirconate titanate (PZT) actuated by a 0 V-2 V harmonic voltage. PZT in the past has been avoided for such applications, in spite of its good figures of merit, because of

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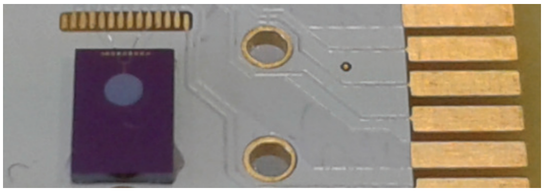

Fig. 1. PMUT: single layered membrane for in air application, diameter 1.5*mm*.

technological issues related to the integration of PZT thin films in MEMS [3]. In recent years, much progress has been made in improving PZT thin films and their properties [4], so that PZT can now be effectively adopted in MEMS.

The membrane presents an initial static predeflection due to the presence of residual stresses [5] in each layer from the fabrication process.

In order to simulate the static and dynamic behaviour of the device surrounded by air, we present a brand new complete multiphysics model by means of the solver COMSOL Multiphysics which incorporates four physics and their mutual interactions, namely: mechanical modeling of the membrane, piezoelectric effect in the PZT layer, fluid thermo-viscous dissipative modeling and fluid non dissipative modeling. The membrane is clamped over a cilindrical closed cavity of diameter equal to the membrane diameter and height of 400 μm; the membrane plus the cavity are inserted in a spherical thermo-viscous acoustic fluid domain of radius equal to λ, where $\lambda = v_s/f_0$ is the ratio between the sound velocity in air (v_s) and the first operating natural frequency of the device (f_0); outside of the thermo-viscous acoustic fluid domain there is a 4λ thickness spherical pressure acoustic domain in which there are no losses; outside the pressure acoustic domain to simulate the infinite fluid domain there is a Perfectly Matched Layer (PML) of thickness equal to λ. The model studies are organized as follows: an initial non linear mechanical static analysis which permits to calculate the initial predeflection due to fabrication residual stresses, an additional static electro-mechanical analysis which takes into account the static voltage of 1 V applied in the harmonic perturbation of the device and an electro-mechanical-fluid frequency domain analysis to calculate the behaviour of the entire system in presence of small vibrations aroud the deflected configuration of the membrane.

The results of the first study described above are presented in Fig. 2 and Fig. 3: the predeflection due to fabrication residual stresses presents a typical bending-like shape.

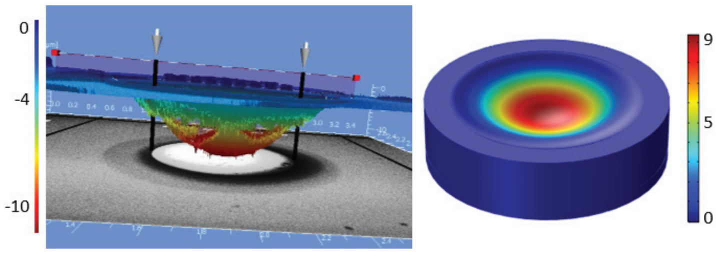

Fig. 2. Initial static non linear deflection, 3D representation: experimental measurement by Polytec MSA-500 Micro System Analyzer (left), mechanical static non linear simulation result by COMSOL multiphysics (right). The units are in μm.

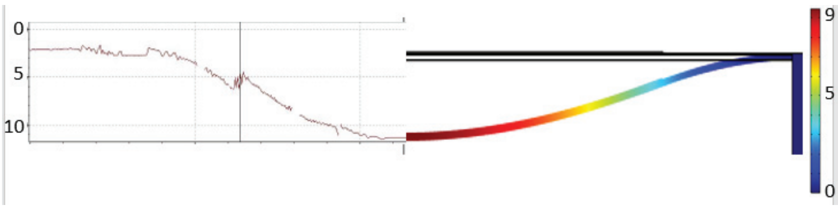

Fig. 3. Initial static non linear deflection, 2D axi-symmetric representation: experimental measurement by Polytec MSA-500 Micro System Analyzer (left), mechanical static non linear simulation result by COMSOL multiphysics (right). The units are in μm.

Together with the initial deflection, the residual stresses due to fabrication process have another important effect, namely the contribution to the stiffness of the membrane that changes significantly the first natural frequency of the PMUT. The same PMUT device in terms of geometry and materials, without residual stresses, presents a natural frequency around 40.9 kHz, when the stresses are considered it shifts to 53.8 kHz. In order to demonstrate this shift a frequency spectrum analysis has been conducted with applied voltage varying between 0 V and 2 V by means of an oscilloscope and measured by the Polytec MSA-500 Micro System Analyzer (see Fig. 4) together with the corresponding electro-mechanical-fluid frequency domain analysis simulation in COMSOL multiphysics. The results (see Fig. 5) show a good agreement between the experimental and the numerical spectra. It must be noticed that the presence of the 1 V static voltage value in the harmonic actuation of the piezo layer decreases the stiffness of the membrane, in opposition of what happens for the residual stresses described above, with less impact in the natural frequency being the shift from 53.8 kHz to 53.3 kHz. This effect varies proportionally to the static applied voltage and therefore can be used to tune properly the natural frequency of the device.

The PMUT device analyzed in this work presents a quality factor aroud 60 (see Fig. 5). This Q factor is calculated in the frequency domain [6] as $Q = f / f_{bw}$ where f_{bw} is the 3 dB bandwidth at resonance. The device Q-factor depends on several sources of losses: structural losses Q_{struct}, such as thermoelastic, support, surface layers losses, and fluid losses Q_{fluid}, such as the radiation of the energy in the infinite domain and the thermo-viscous losses in the air. By means of the thermo-viscous modelling of the fluid domain it is possible to define, at least numerically, the amount of the losses Q_{fluid}, which results equal to $Q_{fluid} = 100$. The fluid region in which the thermal and viscous losses [7] are greater is the so called boundary layer (see Fig. 6), which is the fluid area that sorrounds the membrane on the two sides (thickness of 9.7 μm): it is important to notice that its dimension is comparable with the oscillations of the membrane due to the applied harmonic voltage.

The $Q_{struct} = 150$ is extimated subtracting the inverse of Q_{fluid} to the inverse of the total Q factor, and extracting the inverse of the result, as common in parallel impedance calculations. Further experiments must be conducted

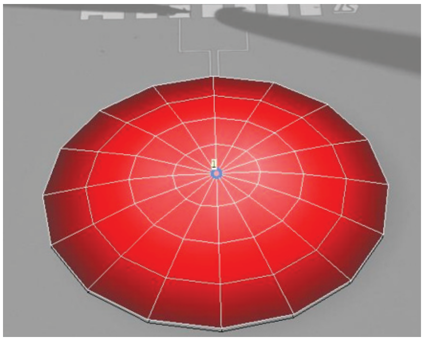

Fig. 4. Polytec MSA-500 Micro System Analyzer vibrometer image.

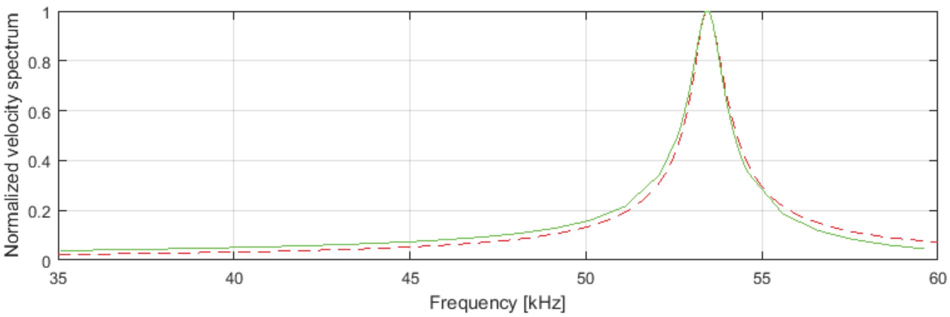

Fig. 5. Normalized velocity spectrum in frequency domain for the center point of the membrane: experimental measurement by Polytec MSA-500 Micro System Analyzer (red dashed line), electro-mechanical-fluid frequency domain analysis simulation result by COMSOL multiphysics (green solid line).

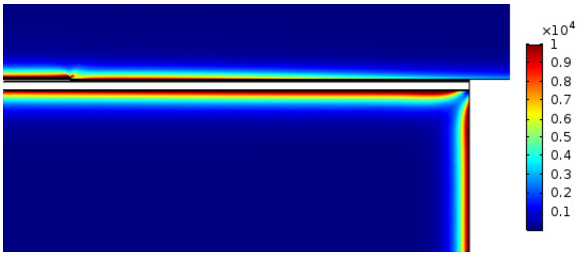

Fig. 6. Total thermo-viscous power dissipation density [W/m^3] in the fluid domain, in white the solid domain. The region sorrounding the membrane that presents the greatest dissipation is the so called boundary layer.

to validate such numerical result; for example in order to measure the Q_{struct} one possible setup could be the same frequency domain harmonic perturbation test described in this work inserting the membrane in a vacuum space.

2. PMUT device: further in the acoustic field

Due to the modeling adopted in the acoustic field the estimates of the Sound Pressure Level (SPL) can be performed in every point of the fluid domain and further outside of it (in the so called "far field"). Because of the absence of any obstacle for the fluid (such as packaging of the PMUT) the SPL versus frequency response presents the maximum value in correspondance of the resonance of the membrane (see Fig. 7, left). The polar SPL (see Fig. 7, right) describes a non directional emitted pressure wave which is typical of a PMUT device not inserted in a packaging structure. The polar SPL is not symmetric with respect to the orizontal axis because of the presence of the closed cavity.

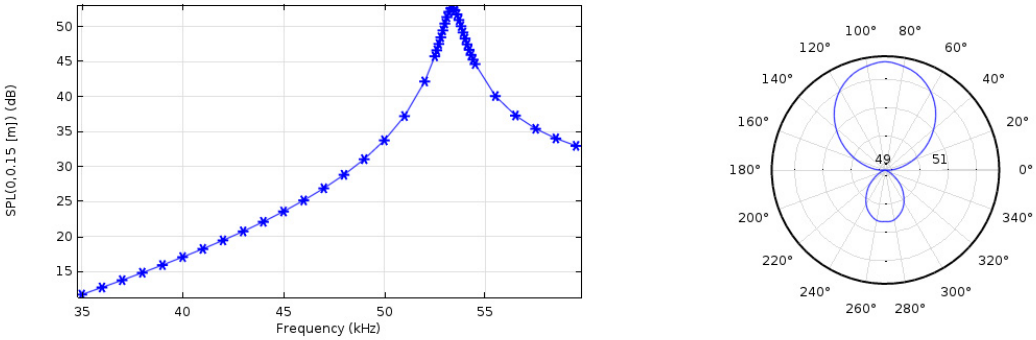

Fig. 7. Sound Pressure Level in the far field (15 cm on the positive direction along the axisymmetric axis of the membrane): frequency sweep analysis (left), polar plot calculated at the corresponding peak value in the SPL versus frequency (right).

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