A 256 MEMS membrane digital loudspeaker array based on PZT actuators

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Abstract

This paper reports on the development of a unique Digital Loudspeaker Array solution, based on Pb(Zr0.52,Ti0.48)O3 (PZT) thin-film actuated membranes, arranged in a matrix and which operate in a binary manner by emitting short pulses of sound pressure. Using the principle of additivity of pressures in the air, it is possible to reconstruct audible sounds. For the first time, electromechanical and acoustic characterizations were reported on 256 MEMS membranes DLA. Sounds audible as far as several meters from the loudspeaker have been generated using low-voltage.

Keywords: Digital, Loudspeaker, PZT, actuator

1. Introduction

A Digital Loudspeaker Array (DLA) is an electromechanical transducer which receives a numerical signal as input data and allows the analogical conversion directly in the air. Previous work about MEMS-DLA used electrostatic actuation, which presents pull-in limitation [1]. We designed high performances PZT actuated membranes in order to obtain the higher acoustic pressure as possible. In this
paper, the actuation principle is first presented. Then the generic technology used to build demonstrators based on thin-film PZT actuator is detailed. Finally, electromechanical and acoustic characterizations are presented. Digital acoustic reconstructions have been demonstrated using low actuation voltage.

2. Actuation principle and technological realization of demonstrators

Through a mixt Finite Element Method (FEM) and analytical study, we designed high performances PZT actuated membranes, in order to obtain the higher acoustic pressure as possible. We focused on membranes (radius \( R = 1300 \mu m \)) which theoretically present a resonant frequency of 18 kHz. Due to the ferroelectric properties of PZT, we implement a double-actuator design able to generate positive or negative acoustic pulses (Fig. 1) [3]. The actuation principle consists in stacking the piezoelectric layer and electrodes together with an elastic layer clamped on its periphery. When an electric field is applied between the top and the bottom electrode, the PZT layer shrinks in-plane (\( d_{31} \) coefficient effect) and a bending motion of the membrane is therefore induced by the bimorph effect. Our design is compatible with a multiple-level command of membranes, as described in [4]. It opens the perspective of 16-bits-DLA using a limited number of membranes.

![Fig. 1. Thin-film PZT actuated membrane schematic view. The double actuator design allows to obtain positive and negative acoustic pulses.](image)

We used a generic technology to build demonstrators, compatible with RF MEMS [5] or haptic interfaces [6]. Devices were manufactured out of 200 mm standard silicon wafers. First the structural layer was deposited (1.9 \( \mu m \) silicon-oxide and 4 \( \mu m \) poly-silicon). Then we deposited and etched the piezoelectric stack (Fig. 2-a). It consists of 2 \( \mu m \) thick sol-gel PZT in between 200 nm thick Pt bottom electrode and 100 nm thick Ru top electrode. We deposited and patterned a passivation silicon oxide layer followed by gold lines and pads. Then, membranes were released by back side etching the substrate. Finally, we sawed the substrate to obtain individual ultra-thin DLA, presenting a thickness finer than 735 \( \mu m \) (Fig.2-b).

![Fig. 2. (a) Schematic cross section of the technological stack and SEM cross section of the sol-gel thin film PZT actuator and (b) Photography of a 256 MEMS membrane DLA (4x4 cm²).](image)
In parallel, an electronic board was designed and manufactured using discrete components. It consists in a microcontroller, two FPGA, and 512 drivers (one driver per actuator). Moreover, a socket with 576 micro-pins was used to electrically connect the 576 pads of the DLA. Fig. 3 gives a view of the system.

3. Electromechanical and acoustic characterizations

Electromechanical characterizations were performed on MEMS-DLA. We used a WYKO optical profilometer to measure the maximum deflection experienced by the membrane. We calculated the differential displacement amplitude (DDA), which is the measured membrane deflection under a given voltage minus the membrane position at 0 V, in order to get rid of the residual stress. Fig. 4 shows the DDA for internal and external actuators of three membranes (R = 1300 µm). One can note that the DDA reaches 4 µm using only 10 V. Internal and external actuators allow obtaining symmetric response insuring symmetric negative and positive acoustic pulses as expected. We also measured the resonant frequency of the fundamental mode of the membrane using laser vibrometry, namely 17.3 kHz (quality factor = 500). The discrepancy between the expected resonant frequency and the measured one can be explained by the residual stress that must be taking into account for predictive model.

Acoustic characterizations were performed on 256 membranes MEMS-DLA. We measured the response spectrum of the DLA playing in the digital reconstruction mode a 5.5 kHz sinus with a sampling rate of 44.1 kHz. It shows a satisfactory limited number of harmonic parasitic peaks and a high SPL value of about 100 dB at 13 cm (Figure 5). The acoustic pressure generated by the MEMS-DLA in its analogic mode was also investigated using an actuation voltage of only 8 V. Figure 6 compares the acoustic
pressure measured by a microphone placed 13 cm face to our MEMS-DLA, with the acoustic pressure of a 64-membranes MEMS-DLA [3] when we play a sinus with frequency ranging from 500 Hz up to 50 kHz. It shows an acoustic pressure increase of about 40 dB, coming from membrane surface and number increase but also actuator optimization. Sound quality was also improved per a factor 3 (Total-Harmonic-Distortion criteria). Sounds audible as far as several meters from the loudspeaker have been generated. Digital acoustic reconstructions using our MEMS-DLA have been demonstrated using low actuation voltage. These results are promising for the development of ultra-thin DLA.

![5.5 kHz sinus to be digitally reconstructed](image)

**Fig. 5.** Response spectrum of the 256-MEMS DLA (R = 1300 µm) playing in digital mode a 5.5 kHz sinus.

![Comparison of measured acoustic pressure](image)

**Fig. 6.** Comparison of the measured acoustic pressure between a 256-MEMS DLA and a 64-MEMS DLA.

4. Conclusion

Electromechanical and acoustic characterizations were reported on a 256 MEMS membranes DLA based on PZT actuators. Sounds audible as far as several meters have been generated with sound pressure levels higher than previous works and using low actuation voltage (8 V). These results are very promising for the development of ultra-thin DLA.

References


