

MEMS Acoustic Pixel

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Abstract: In this work we use COMSOL Multiphysics 4.4 to simulate the behavior of a micro-membrane (Acoustic Pixel) to be used as a potential acoustic transducer. The MEMS and Piezoelectric devices modules are used to aid the design process of such transducer. A four-cantilever spring configuration was initially proposed; each cantilever has a width of 30 μm and is connected to a central circular plate with a diameter of 300 μm . From simple analytical calculations, a single Acoustic Pixel is required to generate approximately 18 dB of acoustic pressure to be able to hear it at a distance of 1 m away from the membrane. Such acoustic pressure could be produced with approximately 5 μm of total displacement in the z-axis of the proposed membrane area. The simulated piezo actuated cantilevers and membrane had a response time of 34 μs using 17 V between the electrodes.

Keywords: Acoustic Pixel, MEMS, PZT, membrane, microspeaker.

1. Introduction

The world has evolved to a point where digital media and electronic play an important role in everyday life. The electronic industry is continuously growing month after month; where more improved components such as speakers, microphones, sensors and cameras among others are in high demand. These components require improved characteristics (i.e. smaller dimensions, low power consumption and better quality) in order to keep up with the technological evolution.

It has been approximately 91 years [1-5] since the appearance of the first loudspeaker drive, which is similar to the current transducer used nowadays. Nevertheless, in a world dominated by digital media and electronics, the acoustic transducer design remains to be the last analog component in the audio systems.

In 2003, Diamond et al. [6] reported the development of a direct digital method of sound reconstruction using CMOS-MEMS arrays as micro-speakers in a single chip. They previously described the theory behind their sound reconstruction method in 2002 [7], with the development of individual electrostatically actuated membranes and joining seven chips to create a 3-bit array. In their last work, they presented experimental results of both projects. Each transducer in the array has a fixed electrode with a dome shape membrane. When voltage is applied between the membrane and the electrode, the membrane buckles down and comes into contact with the electrode. When the voltage is removed, the membrane buckles up and springs to its idle position. Therefore, there is an inherent asymmetry with the configuration between the negative and positive pulses. The negative pressure pulse is shorter than the positive pressure pulse, because the bottom electrode stops its displacement. When the membrane is released to create the positive pressure pulse, the displacement (pulse) is longer because of the spring constant force and it continues to oscillate until the vibration decreases because of the damping of the air.

2. Systematic design

Due to the significance of the shape of the pulse that is needed by each element, asymmetry is a concern for the membrane actuation. The digital sound reconstruction of individual pulses is linear. In order to produce a desired frequency, the frequency must exist in each of the individual pulses. An ideal pulse would be represented by a delta function; ideally this pulse should last for one clock of the system. Most of the known acoustic transducers do not have a very short impulse. The membrane has a certain inertia, when a voltage is applied the membrane usually overshoots to its final position, producing a sine wave that will gradually decrease in amplitude until it stabilizes. The stabilization time depends on the quality factor of the system. The

membrane typically oscillates at its resonance frequency. This kind of pulse has much narrower frequency content, containing the resonance frequency and its closest harmonic.

In order to produce a symmetric impulse we selected the piezoelectric effect as the driving mechanism of the membrane. When a positive voltage is applied to the piezoelectric transducer the membrane will displace in the positive z-axis and when a negative voltage is applied the membrane will displace the same distance in the opposite direction from its idle position. For initial design parameters a relatively large surface area of the membrane was selected. Instead of a square membrane used by Diamond et al. [6,7], a circular membrane with radius of 150 μm is used. A top view of the proposed design is shown in Figure 1.

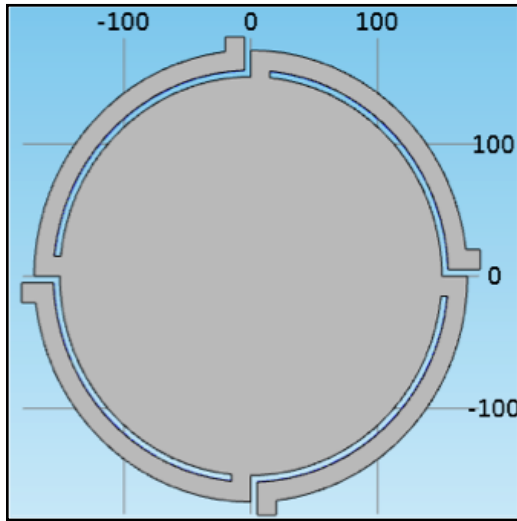


Figure 1. Top view of the Acoustic-pixel. Four curved cantilevers with a width of 30 μm connected to a circular plate with a radius of 150 μm . The material stack is Pt/PZT/Pt [100 nm/500 nm/100 nm].

The first calculations are intended to check the feasibility to generate audible pressure change with the proposed membrane size. The pressure that can be produced by the proposed membrane can be calculated using the simplified equation of a circular vibrating piston on an infinite baffle [8], as shown below:

$$P = \frac{\sqrt{2} \cdot \pi \cdot \rho \cdot S \cdot \varepsilon \cdot f^2}{r} \quad (1)$$

Where,

- P:** Sound Pressure RMS [Pa]
- ε :** vibration amplitude [m]
- ρ :** air density [kg/m^3]
- f:** vibration frequency [Hz]
- S:** membrane surface area [m^2]
- r:** distance to listener [m]

It is known that the human audible pressure range goes from $\sim 20 \mu\text{Pa}$ to $\sim 100 \text{kPa}$ of sound pressure and frequencies of 20Hz to 20 kHz for a healthy young ear. The lowest pressure limit is 20 μPa at 1 kHz. For instance, the sound pressure in normal conversation between two people at a distance of 1m, ranges from $2 \cdot 10^{-3} \text{Pa}$ to $20 \cdot 10^{-3} \text{Pa}$. By using the smallest value, we can use Eq. 1 to solve for ε to calculate the required membrane vibration amplitude that needs to be displaced by the Acoustic Pixel in order to contribute in an array of 255 identical membranes to perceive an overall Sound Pressure Level (SPL) of $\sim 40 \text{ dB}$ at a distance of 1m and a frequency of 1 kHz. We first calculated the SPL required for a single Acoustic Pixel. To remove intermodulation components the selected sampling rate is 40 kHz, which would give the lowest intermodulation component at 20 kHz (audible threshold).

The overall SPL for the entire chip would be:

$$\begin{aligned} SPL_{f=20000} &= \\ SPL_{f=1000} + 20 \cdot \log_{10} \frac{f_{\text{half sampling rate}}}{f_{\text{lowest range}}} & \quad (2) \\ SPL_{255} = SPL_{f=20000} &= \\ 40 + 20 \cdot \log_{10} \frac{20000}{1000} &= \mathbf{66 \text{ dB}} \end{aligned}$$

Therefore we can calculate the SPL for a single membrane:

$$\begin{aligned} SPL_n = 20 \cdot \log_{10} \frac{P \cdot n}{P_0} & \quad (3) \\ SPL_1 = SPL_{255} + 20 \cdot \log_{10} \frac{1}{255} &= \mathbf{17.87 \text{ dB}} \end{aligned}$$

$$P_1 = P_0 \cdot 10^{\frac{SPL_1}{20}} = 156.5 \mu\text{Pa}$$

Solving for the vibration amplitude ϵ :

$$\epsilon = \frac{P \cdot r}{\sqrt{2} \cdot \pi \cdot \rho \cdot S \cdot f^2}$$

$$= \frac{156.5 \times 10^{-6} \cdot 0.1}{\sqrt{2} \cdot \pi \cdot 1.2 \cdot \pi \cdot (150 \times 10^{-6})^2 \cdot (1000)^2}$$

$$= 2.5 \mu\text{m}$$

$$\epsilon_{pk-pk} = 5 \mu\text{m}$$

That means that we would need to develop a chip with 255 Acoustic Pixels each of them with a radius of 150 μm and they would have to provide a peak-to-peak displacement of approximately 5 μm .

3. Use of COMSOL Multiphysics

COMSOL Multiphysics was used to simulate the behavior of the driving mechanism for the proposed transducer. The transverse d31 mode configuration for the piezoelectric effect was selected [9]; such mode is shown in Figure 2 below.

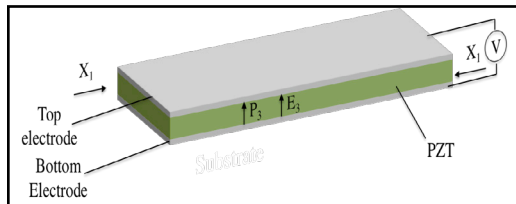


Figure 2. d31 Transverse piezoelectric effect mode.

As it can be seen, the piezoelectric material is between two electrodes. When a voltage is applied the piezoelectric material extends creating a bimorph effect bending the cantilever beam. The cantilever was simulated with the following parameters: 100 nm for the electrode's thickness, 500 nm for the piezoelectric material thickness and a 3 μm thickness for the structural material. The cantilever had a 30 μm width and 120 μm length and a voltage of 10 V was applied between the electrodes. A total displacement of 2.95 μm was obtained. A simulation result is shown in Figure 3 below. The displacement result is enough for what is needed for the Acoustic Pixel displacement that was calculated previously. If we apply a positive voltage the

cantilever will bend away from the substrate and if we invert the polarity the cantilever bends towards the substrate, getting a peak-to-peak amplitude of approximately 6 μm .

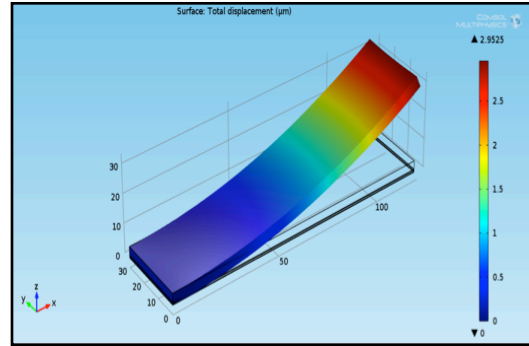


Figure 3. d31 mode simulation (deformation is scaled by a factor of 10 for display purpose).

After the cantilever simulation a more complex design for a circular membrane was simulated. A four cantilever configuration springs that was initially proposed was used for the simulation. The displacement results from the simulation of the membrane using the transverse piezoelectric effect at 10V are shown in Figure 4.

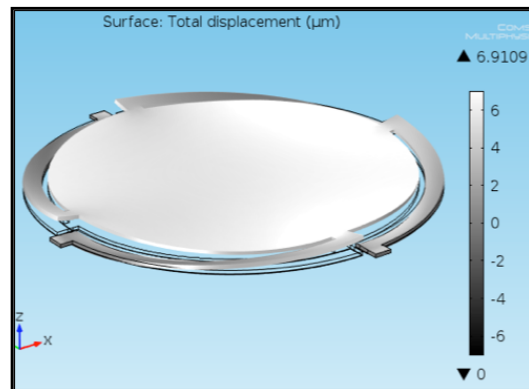


Figure 4. Membrane displacement at 10V.

Both simulations had similar boundary conditions. The cantilevers were fixed at their free end in the case of the 4 cantilever and membrane configuration. The remaining structure was left free to move. One of the faces of the PZT cantilever was set to be the ground and the opposite face was set to be a terminal where we applied 10 V. Four different studies were performed in order to get relevant

information of the system. A stationary study was done to calculate the immediate displacement after applying a voltage. An Eigen-frequency and Frequency-Domain studies were used to calculate the frequency modes of the membrane and the displacement of the membrane at a particular frequency. Finally a time-dependent modal study was done to be able to see the time response of the actuator.

4. Modal analysis

The first six frequency modes are shown in Figure 5. From these modes we can see that the motion of the first resonant frequency mode at 8.67kHz, is the desired mode for our actuator displacement. Also, we can see that the first three modes are within the audible range, but it is not a concern, because the membranes will not be actuated at the specific resonance frequencies. Nevertheless, by changing the parameters of the device we can modify its resonance frequencies. For instance, the current design has the following parameters: 394.173 μ g of mass and a spring constant of 1.17 N/m, using the resonant frequency mode of interest of 8.67kHz. It would be a matter of changing its geometry by increasing layer thicknesses or materials used.

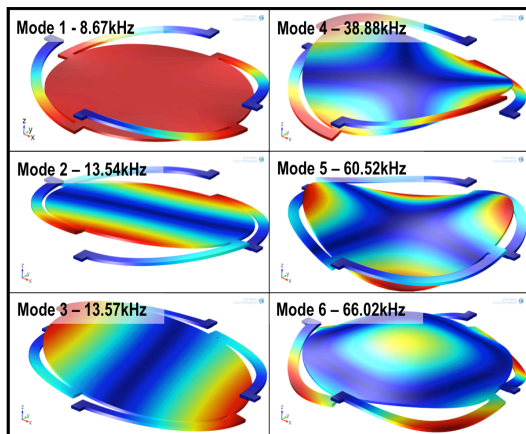


Figure 5. First six frequency modes of the membrane.

A time response graph was obtained from the simulations. The cantilevers were actuated with a potential of 10V and the response time was of 34 μ s, which is below the sampling time that we are trying to aim of 20kHz (50 μ s). Figure 6 shows the time response graph of the actuated membrane.

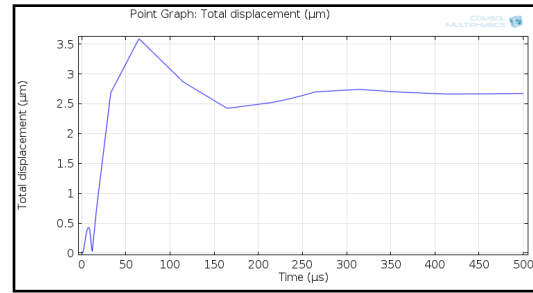


Figure 6. Total Membrane center Displacement vs. Time. Membrane was actuated with 10 V.

8. Conclusions

COMSOL Multiphysics has helped in better understanding the system presented in this work. The next step in this project is to fabricate an array of similar membranes to create a digital micro loudspeaker. The development and innovation of a Digital Micro-Loudspeaker would directly impact the electronics industry, by creating new components that utilize less power and space on a circuit board, decreasing its fabrication costs without compromising the sound quality, but rather improving it. The field of Audiology, which studies human hearing, balance, and related disorders, could also potentially benefit from such advancements. The aim of this field is to establish if a person can hear within the normal human audible range, if not, determine the affected frequencies (i.e. high, middle or low) and the degree of the damage. Several corrective actions can be taken depending on the diagnosed results, such as hearing aid apparatus or cochlear implants. These devices could substantially benefit of acoustic MEMS advancements and directly improve a person's quality life.

9. References

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