A Surface-Micromachined Levitating MEMS Speaker

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***Abstract*—This paper presents the design and simulation of a levitating MEMS speaker. The device is composed of a levitating membrane actuated through electrostatic forces using several electrodes and a control system. The absence of supporting anchors allows for a drastic reduction of damping losses and therefore promises higher power efficiency. Simulation results indicate very promising performance.**

Keywords—MEMS, speaker, levitation

I. INTRODUCTION

Throughout the past three decades, numerous electromechanical devices existing at the macro scale have been successfully miniaturized to benefit, similarly to electronic integrated circuits (IC), from bulk fabrication processes and economies of scale. For examples, one only has to think of microelectromechanical system (MEMS) accelerometers, gyroscopes, or pressure sensors. Despite these advances, the ubiquitous device that is the audio speaker remains quite bulky and inefficient, awaiting viable commercial miniaturization solutions.

While, for many device types, micro-scale physics are beneficial to performance, such is unfortunately not the case for speaker applications. Because MEMS devices typically rely on deformation-based motion of stiff materials, there is usually a strong tradeoff between power and frequency bandwidth. Furthermore, operation at low frequencies is reliant on a very large device footprint. For audio applications, both low frequencies and a bandwidth covering all audible wavelengths are critical requirements, all without sacrificing output power, i.e., sound volume.

Despite these challenges, in recent years, MEMS speakers have generated substantial research interest due to their enormous potential for portable electronics.

In [1], a piezoelectric MEMS loudspeaker fabricated using a PZT thin film and capable of generating a sound pressure level (SPL) of 119 dB at 1 cm has been presented, with a device footprint for a single membrane smaller than 50 mm^2. However, its efficiency significantly drops for sound frequencies below 4 kHz.

In [2], electrostatically actuated micro-speakers are demonstrated, with the transduction electrodes positioned on the sides of the membrane to achieve peripheral actuation and allow an augmented range of deflection (and increased SPL) without risking pull-in. However, because the membrane is excited at resonance, the frequency response is not flat, which is essential for a high-fidelity speaker.

In [3,4], MEMS speakers are presented, which consist in a micro-coil supported by a suspended diaphragm, held above a permanent magnet. While the device presents excellent performance at low frequency, the fabrication process is complex and difficult to scale due to the need for integrating a magnetic material.

Some attempts have been made to overcome the low frequency limitation of small MEMS devices, such as digital sound reconstruction. In this approach, an array of membranes is used, where each element produces a series of discrete pulses of acoustic energy. The total energy emitted by the array is the combination of the energy generated by each element. Hence, one can control the intensity and frequency of the sound produced by dynamically adjusting the number of simultaneous active sources [5-7]. With this approach, reconstructing higher frequency sound waves can be more challenging, as it requires a faster sampling rate, and for the membrane elements to be able to start up sufficiently quickly.

Alternatively, this work attempts to avoid the usual limitation of deformation-based MEMS devices altogether by presenting a novel architecture for a MEMS speaker based on the principle of electrostatic levitation.

Levitation in MEMS has not yet been extensively explored. In [8], a contactless wafer manipulator is presented. The device uses direct electrostatic force to make a wafer levitate and move around. In [9], electrostatic forces are used to induce levitation of the rotor of an electrical micro-motor, to minimize friction and increase power efficiency. In [10], a levitating dual-axis gyroscope and a levitating tri-axis accelerometer are presented, using a closed loop control system.

To the knowledge of the authors, this paper is the first to propose a levitating MEMS speaker, as well as present its design and simulation results.

II. SYSTEM OVERVIEW

A. Device Concept and Working Principle

The objective of this work is to implement a levitating membrane speaker that can be actuated merely through electrostatic potential differences. The absence of any mechanical support eliminates anchor loss damping and has the potential for superior power efficiency even if operating out of band.

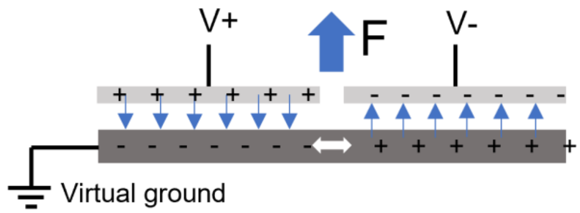

Figure 1: Working principle of the device

Fig. 1 illustrates the actuation mechanism used in this work to generate electrostatic forces on a floating-potential body in order to make it levitate. Connecting two electrodes to a differential voltage (V+ / V-), when placed adjacent to a free membrane, by virtue of the electric field generated, causes a redistribution of the electric charges within the membrane. As such, negative charges drift towards V+ and positive charges drift towards V-, in turn creating an upward electric force on the entire membrane, which pulls it up.

Posing a significant challenge to this general approach, Earnshaw's theorem states that a charged object cannot be restrained at a steady position using only a constant electrostatic field. Instead, either a variable field configuration exhibiting natural stability, or an active control system are necessary to maintain the object in a set location. For this speaker application, the latter approach is selected as it is more appropriate for a membrane for which the position needs to be dynamically controlled, i.e., according to the audio signal to be generated.

To be able to control the position of the membrane in space, electrodes are required to act in five of the six possible degrees of freedom (DOF): linear displacement in x, y, and z, as well as rotation around the x- and the y-axes. Rotation around the z-axis (i.e., the membrane spinning) is not problematic for an out-of-plane speaker application and does thus not need to be actionable. Fig. 2 illustrates the electrode configuration necessary to act upon the 5 desired DOF. Because the electrostatic actuation method presented can only generate unidirectional force, the electrode configuration of the device must be doubled in order to permit actuation in any orientation and direction. Actuation along the x-axis is enacted by two differential lateral electrodes on the left (x_l+/-) and right (x_r+/-) of the levitating membrane; along the y-axis by two differential lateral electrodes on the top (y_t+/-) and bottom (y_b+/-) of the levitating membrane; along the z-axis and around rotational axes x/y by three pairs of differential vertical electrodes above ($z_{1,t}$+/-, $z_{2,t}$+/-, $z_{3,t}$+/-) and below ($z_{1,b}$+/-, $z_{2,b}$+/-, $z_{3,b}$+/-) the levitating membrane. Only one differential electrode of each pair should receive a potential difference at a time, depending on the desired direction of motion in that DOF.

Stabilization of the membrane is implemented using 5 sets of proportional-integral-derivative (PID) controllers. Each of the PID controllers is connected to one of the pairs of differential electrodes, although only one of these two differential electrodes can be actuated at a given time. For example, the controller responsible for stabilizing along the x-axis provides its differential output either to the x_l+/- or to the x_r+/- electrode, the former if the command is to move left, the latter if the command is to move right.

B. Fabrication Process

The device is designed to be fabricated using the commercial technology PolyMUMPS by MEMSCAP, which is a three-layer polysilicon surface micromachining process that allows for lateral and vertical transduction gaps. As shown in Fig. 3, the levitating membrane is realized using *Poly1*, the bottom electrodes using *Poly0*, the lateral electrodes using *Poly1*, and the top electrodes using *Poly2*. The performed simulations respect all material and design rules of the technology.

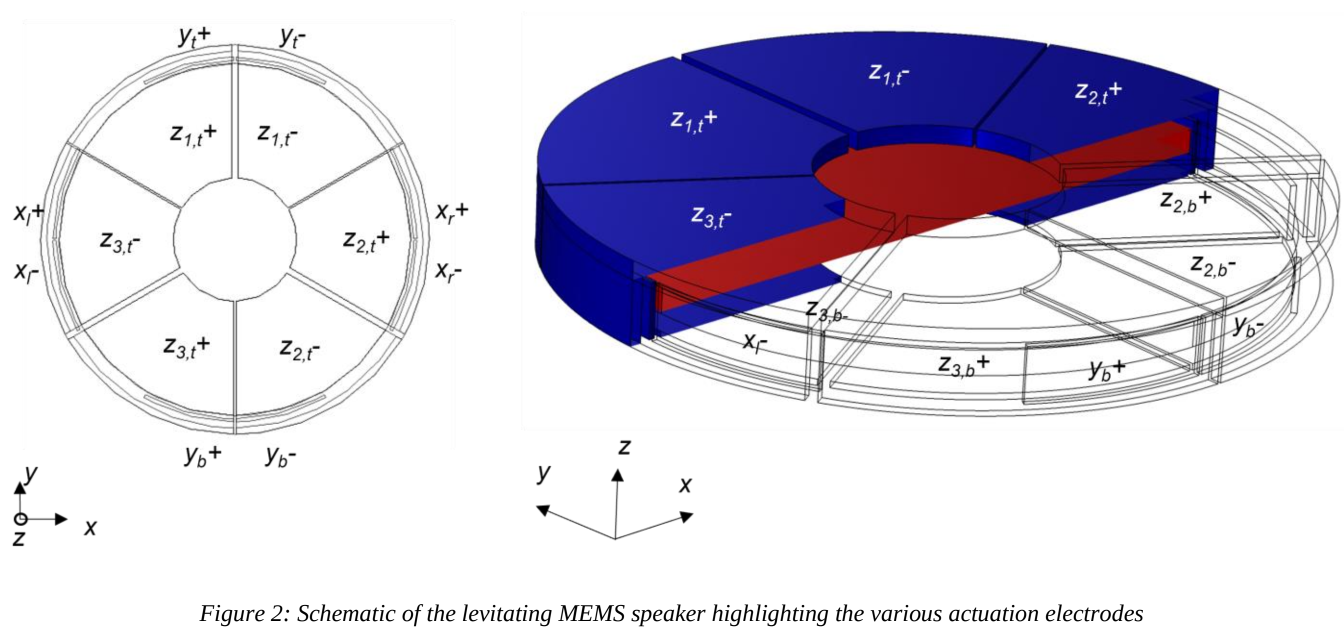

Figure 2: Schematic of the levitating MEMS speaker highlighting the various actuation electrodes

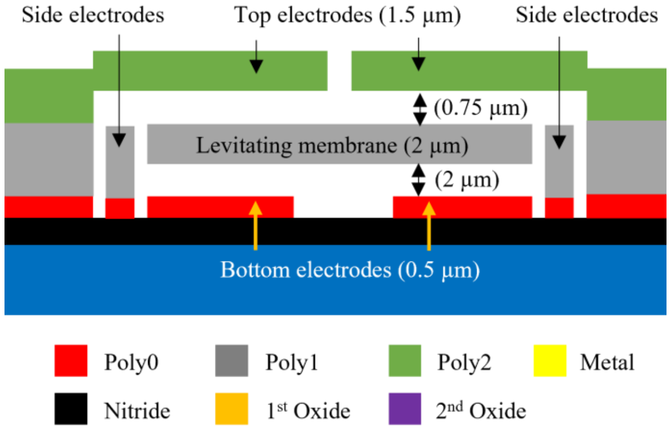

Figure 3 : Schematic of the device prepared using PolyMUMPS layers

III. Simulation Results

A. Model Description

COMSOL Multiphysics is used to perform finite-element simulations, simultaneously considering the solid mechanics, electrostatic, pressure acoustics and thermoviscous acoustics domains. To reduce simulation load, the following simplifications are made: 1) gravity is ignored due to the very low mass of the membrane; 2) membrane motion is disabled along the x and y axes; 3) the membrane begins at the center of the gap (1.375 µm elevation from the bottom electrodes).

B. Step Response

Ideally, stabilization of the membrane should be at least ten times quicker than the shortest period of interest, which is 50 µm for a maximum audible frequency of 20 kHz. To assess the stabilization time of the membrane, the step response of the device was simulated: a command is provided to the PID controller to displace the membrane by 0.5 µm along the z-axis. As shown in the results of Fig. 4, the membrane is well stabilized 50 µs after the input step. Further tuning of the PID could reduce the stabilization time even more if necessary.

Fig. 5 demonstrates the position of the membrane after stabilization showing a settling position corresponding to the PID command of 0.5 µm.

C. Harmonic Response

The step response of the device has shown that its reaction time is fast enough to handle audio frequency. To examine the behavior of the device when excited by a sound wave, two cases are simulated in which sine waves at 5 kHz and 20 kHz are respectively fed as command signal to the z-axis PID controller.

As a first step, the behavior of the device right after applying the command signal is verified. Fig. 6 shows the electric potential distribution on the electrodes and on the levitating disk 10 µs after the signal is applied, highlighting

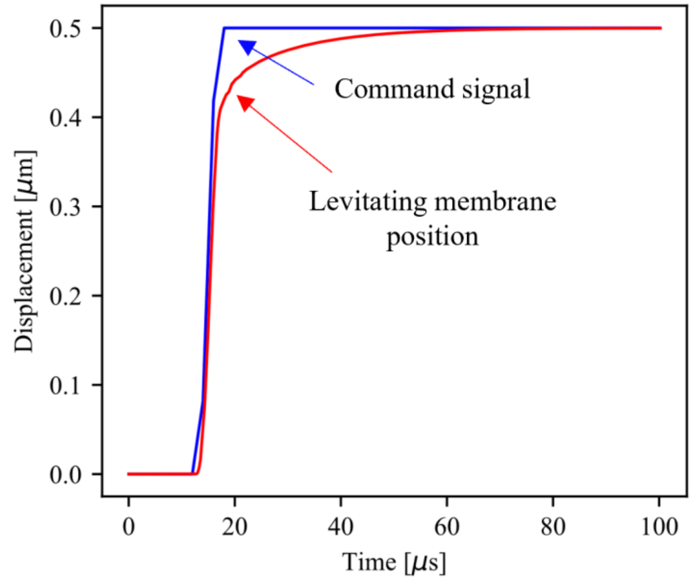

Figure 4: Step response of the device

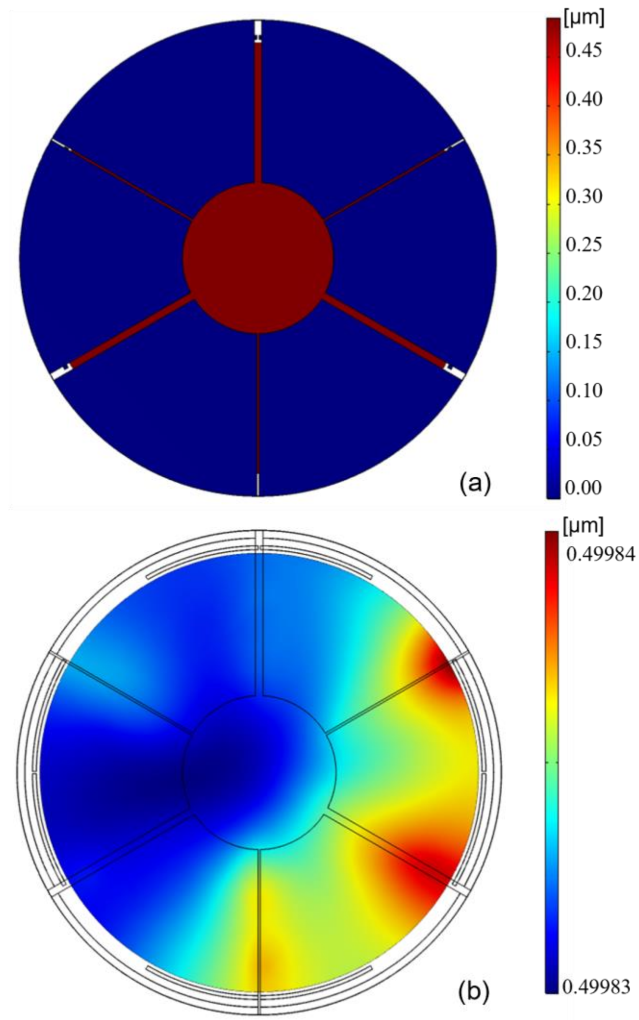

Figure 5: Position of the membrane after stabilization from the step response of the PID at time 50 µs (a) showing membrane and electrodes displacement (b) showing only membrane displacement

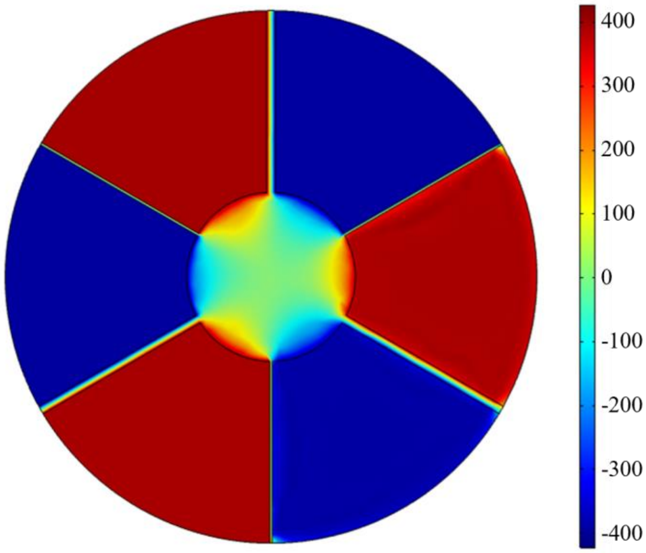

Figure 6: Voltage on the electrodes at 10 us from the start of the command

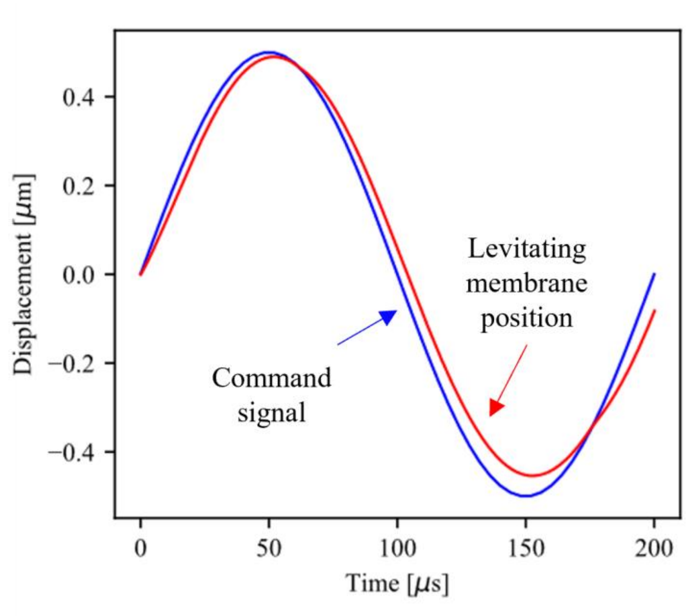

Figure 8: Comparison of the 5 kHz input signal and the displacement at the center of the membrane

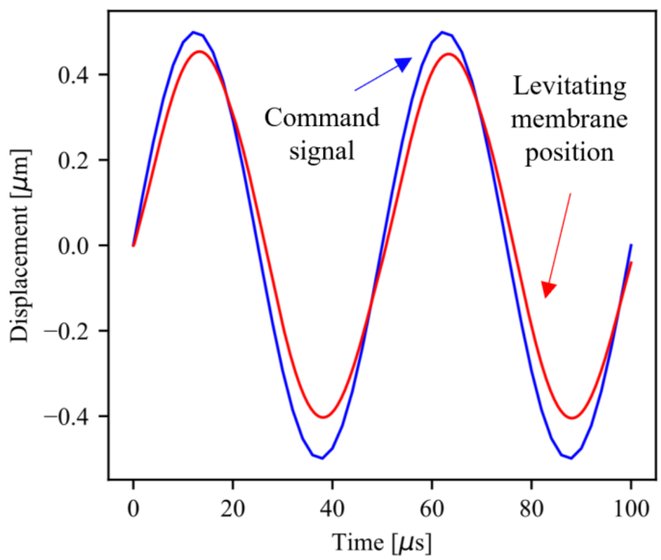

Figure 7: Comparison of the 20 kHz input signal and the displacement at the center of the membrane

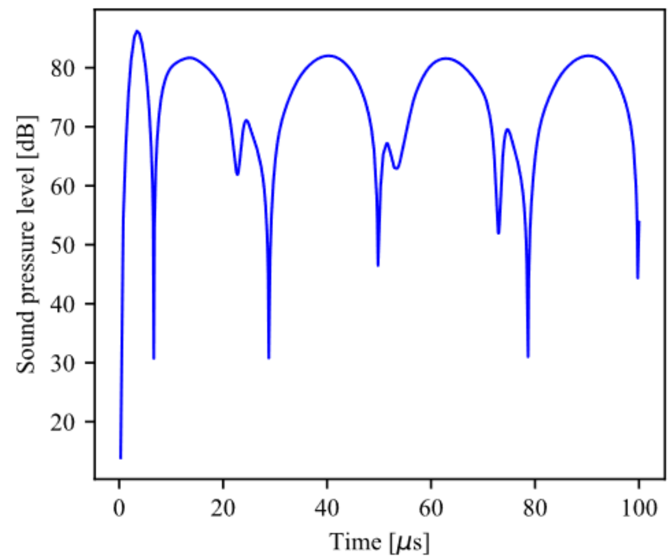

Figure 9: Sound pressure level at 1 mm from the center of the membrane

differential electrodes $z_{1,t}$, $z_{2,t}$, and $z_{3,t}$ in action, as explained in section II.

Fig. 7 shows the z displacement of the center of the membrane for a command signal with an input frequency of 20 kHz, exhibiting good tracking.

Fig. 8 shows the z displacement of the center of the membrane for a command signal with an input frequency of 5 kHz, also exhibiting good tracking, and suggesting that the proposed speaker device architecture is suitable for efficient audio emission over a large range of frequencies.

By simulating in the acoustic pressure domain in air, the sound pressure is determined as received at a point location 1 mm away from the center of the membrane, as presented in Fig. 9. The maximum received SPL is about 85 dB at 1 mm, which corresponds to a SPL of 65 dB at 1 cm.

IV. Conclusion

This paper has presented a levitating MEMS speaker controlled by electrostatic transduction forces. The proposed working principle was explained, and working simulation results were presented, showing that the device could generate a sound pressure level of 85 dB at 1 mm, while keeping very good track of the input command signal. It is important to point out that this design is implemented as a functional proof of concept and is not yet optimized for performance. Hence, the suggested approach is very promising as a novel speaker architecture for high fidelity, high efficiency applications, even for low sound frequencies.

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