Electrostatic actuator for creating pressure waves against the ear drum

Gene Fridman*, Larry Lai*, Jeffrey Yee**
*Department of Biomedical Engineering
** Department of Electrical Engineering
University of California at Los Angeles, 405 Hilgard Ave, Los Angeles, CA 90095-1594, U S A

SUMMARY

A micromechanical electrostatic actuator is introduced for the propagation of sound waves. The idea behind this actuator is that we can create pressure waves by actuating several thousand modified cantilever beams. The modification consists of creating paddles at the ends of the cantilevers to create air vibration. By positioning these devices close to the eardrum, we can send the pressure wave, which will cause the eardrum to vibrate at specified frequencies. The power consumption needed to actuated these devices is , and the force needed to create these pressure waves is .

Keywords: acoustic, electrostatic actuator, MEMS

INTRODUCTION

Out of the 260 million people living in the United States, 28 million are hearing impaired. Of this population, 51 percent wear hearing aids, and there are many "shades of gray" losses (moderately and moderately severe), which also need to be addressed. Statistics support doctors' observations that people are suffering from hearing loss at younger ages. Between 1971 and 1990, the number of people between the ages of 46 and 64 with hearing loss increased 26 percent, and the number between the ages of 18 and 44 increased 17 percent, according to the National Health Interview Survey.

80 percent of hearing-impaired adults presently are not using amplification to take some action regarding their hearing. Currently, only about 20 percent of adults with hearing loss wear hearing aids. The reasons for shunning the aids include personal vanity, the stigma associated with the devices, their cost and the fact that hearing aids are imperfect devices.

The MEMS hearing aid gives users the benefit of having a semi-disposable device that cannot be visually seen by the outside world. By using batch fabrication techniques, these hearing aids will be cheap, so a user will not have to worry about spending thousands of dollars on a device that will be obsolete within the next year.

The semi-disposable hearing aids will cost about \$100 each, which equals to about a dollar a day based on their expected life span. First-rate digital hearing aids cost more than \$2,000 per aid, and have a life expectancy of three to five years. In comparison, the consumer may save more than a \$100 per year with the disposable aids.

REQUIREMENTS

The goal of the MEMS speaker in our application is to amplify the sound near the eardrum to aid a deaf person. The requirements resulting from the application are based on the following:

Threshold of hearing:

(1) $P_0 = 2e\text{-}5\ \text{N/m}^2$

Desired maximum amplification: ~100 dB

$$\text{dB} = 20 \log \frac{P_s}{P_0}$$

To ease the calculation, we set:

(2) $P_s = 1\ N/m^2$

This makes it 94 dB, which is about 100 dB as desired.

Assuming the eardrum is 5mm radius, the total area of the eardrum is:

(3) A_d= 8e-5 m^2

The assumed range of human hearing of speech is from 20Hz to 10kHz

The constraints imposed by our feasibility study stem from the desire to use the standard MUMPS process for the device and project the sound using the proposed set of cantilevered paddles (see fabrication portion of this document).

We define A_p as the area of the individual paddle and x as the distance that the paddle will need to move. The force that the cantilevered paddle will need to overcome is based on the standard spring-dashpot model.

(4) $F_0 = F_s + F_a + F_m$

In this equation, F_s=restoring force of the cantilever, F_a = air dampening, F_m= momentum force due to the mass of the paddle.

(5) $F_s = k*x$

k is based on the assumption of using a 2x2x100 μm cantilever of poly-silicon.

(6) k = 0.64 N/m

The force due to the air dampening is the function of paddle velocity:

(7) $F_a = b*x'$

b is based on the dampening effect of a micro-device pushing air from the surface (from a number of MEMS references):

$$(8) b = \frac{96 * \mu_0 * A_p{}^2}{\pi^4 * x^3}$$

μ_0 is the air viscosity constant and is equal to 1.5e-5 Ns/m^2.

Momentum force is due to the acceleration of the mass of the plate:

(9) F_m=m*x''

The plate mass is determined based on the area of the plate and the thickness and density of Poly2 and electroplated nickel.

(10) m=A_p*2e-6*(2330+8908)

Since the paddle is very close to the eardrum, the work done by the paddle is assumed to be conserved and delivered to the eardrum.

(11) $W_p = W_d$

(12) $W_p = F_p*x$

(13) $W_d = (F_d*x_d)/n$

x_d = displacement of the eardrum = 150e-9 m, n = number of devices (paddles), F_d = force on the eardrum due to the desired pressure P_d. n is idealized to be the following:

(14) $n = A_d/A_p$

(15) $F_d = P_s*A_d$

Combining (11) – (15) and solving for F_p, we have the following:

(16) $F_p= (P_s* A_d*x_d)/(n*x)$

The total force that we need to generate then becomes:

$$(17)\ F_t = F_0 + F_p$$

The combined dynamic form of this equation then becomes:

$$(18)\ F_t(s) = kx + bsx + ms^2x + (P_s{*}A_d{*}x_d)/(n{*}x)$$

Making $s = j\omega = j{*}2{*}\pi{*}f$, we have a force as a function of frequency of oscillation and distance that we wish to move the cantilever. This model of the force was inserted into MATLAB and was plotted as a function of x and frequency. As the two MUMPS oxide layers allow us 2.75 μm of motion – choice of 2.75 μm provides us with a reasonable frequency - force dependence, and a force to the order of 10's of μN, which is reasonable to accomplish using either magnetic or electrostatic actuators.

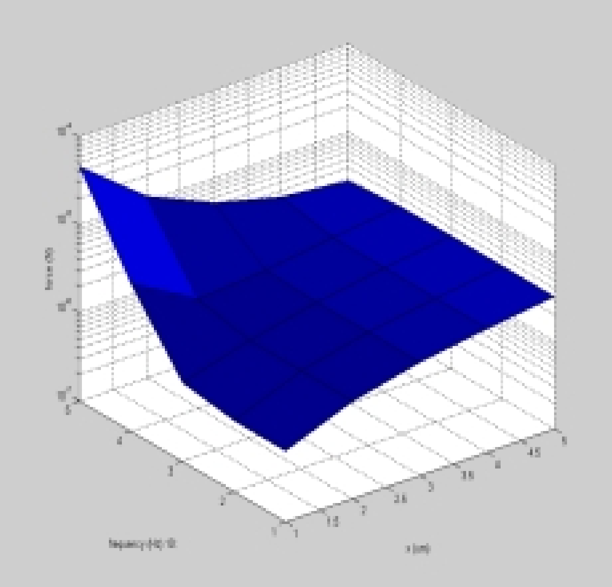


Figure plots force as a function of the allowed displacement of the paddle and the desired frequency of motion (see equation (18)).

ACTUATION DESIGN

We examined the use of electrostatic actuation for this device because this appears intuitive considering the large area of the paddles. We can consider the cantilever/substrate as a parallel plate capacitor, with the substrate as one plate and the paddle as the other plate. This assumption is warranted because the vertical motion of the beam is small with respect to its length, thus the beam and the substrate will remain relatively parallel to each other.

We can thus use the parallel plate capacitor model to find the voltage required to generate this input force given a desired value of x. To do this, we need to consider the capacitance created by the two different dielectric levels: air and nitride.

$$(19)\ \left(\frac{1}{C_{air}} + \frac{1}{C_{nit}}\right) = \frac{1}{C_{total}}$$

The input force will be generated by applying voltage across this capacitor such that the plates are drawn together by electrostatic attraction. When we have created the desired displacement at constant force, we will remove the voltage. The force attracting the two plates when voltage is applied is

$$(20)\qquad F = \frac{\varepsilon{*}A{*}V^2}{g^2}$$

where ε is the permittivity of free space ($8.854{*}10^{-12}$ F/m), V is the voltage in Volts, and g is the distance between the plates in meters.

If we calculate using our desired values of f and g, it will give us the amount of Voltage necessary

(21) $$V = \sqrt{\frac{2F * g}{C_{total}}}$$

At the gap distance, the beam will experience pull-in when x = 1.00 µm. We believed we could use this to our advantage. by placing 0.75 µm dimples on the bottom of the paddle, thus getting a 3 µm displacement when we have only put in the voltage required for a 1.25 µm displacement.

After this analysis was done, we realized several problems with the above characterization. The problems arise from the use of the pull-in. The first one is that the force can no longer be controlled during the pull-in condition and a constant force is required by the system. The second problem is that contact with the wafer, resulting from the pull-in will cause acoustic noise to be propagated into the eardrum.

We decided to stay with the MUMPS design but only actuate the device for 1µm. This would allow us to avoid pull-in, but would necessitate larger forces for higher frequencies.

Frequency	Voltage (3µm gap)	Voltage (2µm gap)
1Hz	23.167	15.559
10Hz	23.167	15.559
100Hz	25.739	17.287
1kHz	62.714	42.12
10kHz	197.343	132.54

Table 1. Swing necessary for 3 µm gap and 2 µm gap at varying frequencies.

We can see that a large initial voltage is required to generate the desired force at small displacement. As the paddle moves towards the substrate, less voltage is required to create the same force because the gap size has decreased. The force required decreases linearly with gap size, so our control circuit for the device will have to calculate the bend time for different frequencies and decrease with time to match the decrease in gap size.

We can also see from the table above that the amount of voltage required to power the device increases as the desired frequency increases. This is because higher frequencies necessitate faster movement and acceleration of the paddle head, creating larger inertia and a larger damping due to air. As all the paddles are connected in parallel, voltage sufficient to drive one will drive all of them. The current across the paddle/substrate system will be minimal because it behaves as a capacitor.

After seeing such high voltages necessary for, we decided to look at magnetic actuation as an alternative. By electroplating a coil underneath each pad, we believed that we could generate enough torque on the beam to actuate it.

Given that

Torque = Ms*Hfield*Volume*sin (x)
Torque = Force * distance
Force=Ms*Hfield*Volume*distance*sin(x)

Sin(x) = 1um/100µm, Ms = 1T, Volume = 50µm*50µm, distance = 100µm

Field is calculated by

$$\mathrm{Hfield}(\mathrm{radius}, \mathrm{NI}) := \mathrm{NI} \cdot \frac{\mathrm{radius}^2}{2\left(100\mathrm{um}^2 + \mathrm{radius}^2\right)^{\frac{3}{2}}}$$

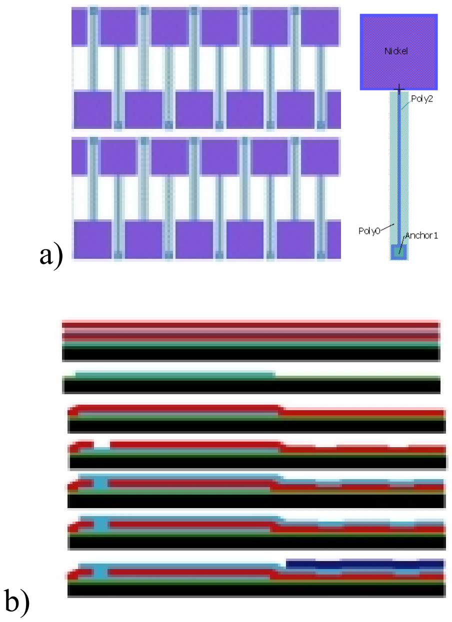
This method also did not yield well as well, since we ended up with an NI of 100 for a 25 µm radius, in order to actuate the 1Hz case!

Also power ended up being a huge issue, since we can never effectively turn the device off.

FABRICATION

The fabrication of these devices will utilize similar design rules and steps as MUMPS. The layers will consist of Si Substrate, .6µm of Nitride, 0.5 µm Poly 0 layer, 2.0 µm SiO_2 layer, 2.0 µm Poly 1 layer, 0.75 µm SiO_2 layer, 1.5 µm Poly 2 layer, and 2.0 µm of Cr/Nickel (post processing).

The following cross sectional views and layout of our cantilever system are shown below.



a) Spacing of Cantilever beams and b) cross section of a beam.

In our design we opted to use MUMPs due to its quick turnaround time. We stack both oxide layers together to form a 2.75µm gap layer between Poly2 and nitride.

Etch holes will be added in subsequent designs to allow easy integration with circuits

Level	Minimum Feature (um)	Necessary Enclosure and Spacing Rules	
Poly0	2	Poly0 Enclose Poly2	5µm
Anchor2	2	Poly0 Enclose Anchor2	5µm
Poly2	2	Poly0 Space Anchor2	5µm
Metal	2	Poly2 Enclose Metal	3µm

CONCLUSION

We have analyzed the use of a micromechanical electrostatic actuator for incorporation into a hearing aid device that would be more cost-effective and aesthetically pleasing than the current hearing aid device. However, the micromechanical electrostatic actuator requires a high voltage at high frequencies. This may cause discomfort for the user and cause problems for power consumption. We looked at utilizing a magnetic actuator, but this method had the same problems that we faced using the electrostatic actuator and was magnified.

ACKNOWLEDGMENTS

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