Optimization of MEMS Capacitive Accelerometer as Fully Implantable Middle Ear Microphone for Hearing Aid

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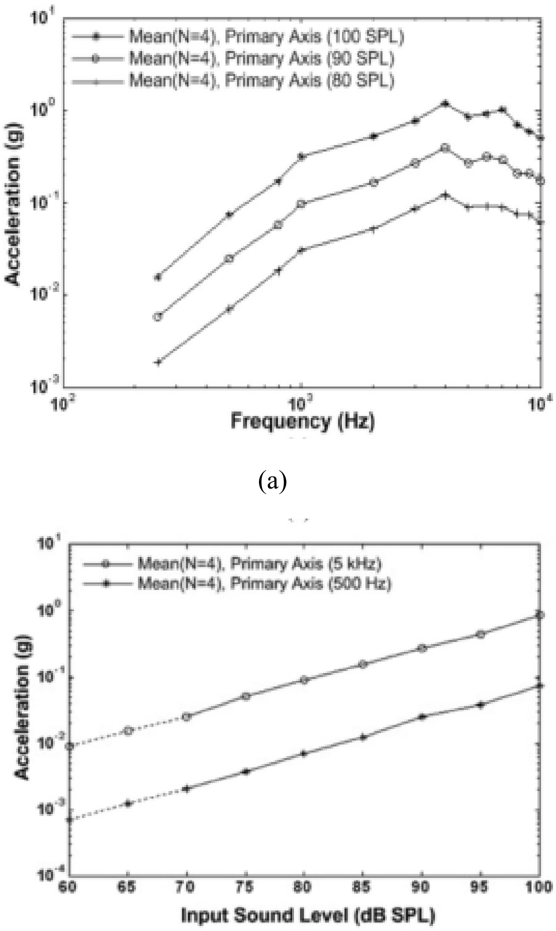
Abstract: This work describes the design and optimization of three prototypes of microelectromechanical systems (MEMS) capacitive accelerometer-based middle ear microphone. The microphone is intended for middle ear hearing aids as well as future fully implantable cochlear prosthesis. The analysis is done using COMSOL Multiphysics. The maximum applied acceleration was considered 1g. Human temporal bones acoustic response characterization results are used to derive the accelerometer design requirements. The accelerometer can be attached to the middle ear bone structure, umbo to convert the bone vibration to an electrical signal representing the original acoustic information. The acceleration of umbo is measured in the frequency range from 250 Hz to 10 kHz with input tones between 70 and 100 dB SPL. The capacitance sensitivities and capacitance values of three different prototypes with different gap spacing between fixed and movable electrodes is considered for optimizing the design.

Keywords—Implantable microphone, micro electromechanical systems (MEMS) accelerometer, middle ear hearing aid, middle ear microphone.

1. Introduction: Over 30 million people in the U.S. and millions more around the world are affected by sensorineural hearing loss. In India, 63 million people (6.3%) suffer from significant auditory loss. Contemporary acoustic hearing aids can achieve moderate rehabilitation in a large number of sensorineural hearing loss cases. Partially implantable middle ear and cochlear prosthetic systems have become increasingly accepted. However, the use of external accessories such as microphones and electronics presents reliability, practicality, and social stigma concerns. Therefore, it is highly desirable to develop fully implantable high-performance prosthetic systems. While progress has been made in developing and improving middle ear implantable systems that rely on piezoelectric effects [1], [2] and electromagnetics [3],[4] for compensation of hearing loss, these approaches do not address cochlear hair cells damage, which causes sensorineural hearing loss and is responsible for the majority of all hearing loss cases. Modern semi implantable cochlear implants address hair cells damage by direct stimulation of the auditory nerve; these implants, however, continue to rely on external microphone, speech processor, and radio-frequency (RF) coils [3].The speech processor can be potentially integrated as a part of the existing implant unit [4].



(a)

(b)

Figure. 1. Acceleration response curves of umbo along the primary axis after medial wall removal. (a) Acceleration frequency response at 80-, 90-, and 100-dB SPL. (b) Loudness response at 500 Hz and 5 kHz. Dashed lines below 70-dB SPL represent the projected acceleration amplitude based on 20 dB per decade slope. [5]

However, a significant challenge is presented in realizing a high performance implantable microphone. In this paper, a microelectromechanical systems (MEMS) capacitive accelerometer is demonstrated and optimised as a middle ear implantable microphone for future fully implantable cochlear prosthesis.

The acceleration of umbo is measured in the frequency range from 250 Hz to 10 kHz with input tones between 70 and 100 dB SPL [5]. The figure 1 presents the relationship of umbo acceleration with input sound pressure levels and frequency

The paper is subdivided into 5 main sections. The first section introduces the subject, the second section deals with the dynamics of the device, the third discusses the results and findings. The fourth section gives the concluding remarks and the firth one contains the references.

2. Dynamics of the device: Comb drive accelerometer consists of fixed fingers attached to the accelerometer frame and movable fingers fixed to the proof mass and suspended by springs [6]. Any external acceleration causes the proof mass and movable fingers to move along the direction of body force, the fixed comb remains stationary. This movement changes the capacitance between the fixed and the movable finger. The capacitance is measured using electronic circuitry. The fixed finger has two movable finger on either sides. The input acceleration *a* from the umbo causes a body force *F* to act on the proof mass *m.* this causes the proof mass to displace by Δx under the effect of spring with spring constant *k*.

$$F = ma \tag{1}$$

$$F = k\Delta x \tag{2}$$

$$\Delta x = \frac{ma}{k} \tag{3}$$

The resonant frequency ω_0 is given by

$$\omega_0 = \sqrt{\frac{k}{m}} \tag{4}$$

In this paper, different prototypes of accelerometer (using different spring topologies) are presented in figure 3. Let's say, x_1 is the distances of fixed finger from left movable finger and x_2 from the right movable finger. For each prototype, x_1 has been kept 2 µm and x_2 has been varied from 2 µm to 20 µm. Their sensitivity and nominal capacitance (C_0, when no acceleration is applied) have been plotted against x_2. The geometry of proof mass and spring for each parameter is designed for resonant frequency of 10 KHz. The geometry parameters of the device are shown in Table 1 [5]. The total area of the sensor (excluding the electronics interfacing) has been kept 1000 µm ×1000 µm.

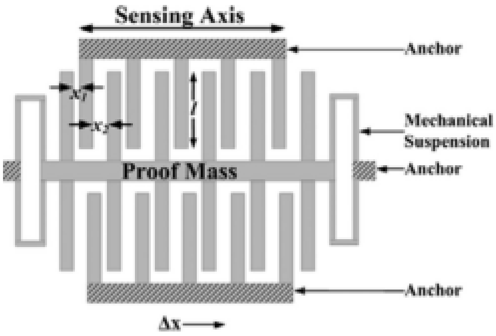
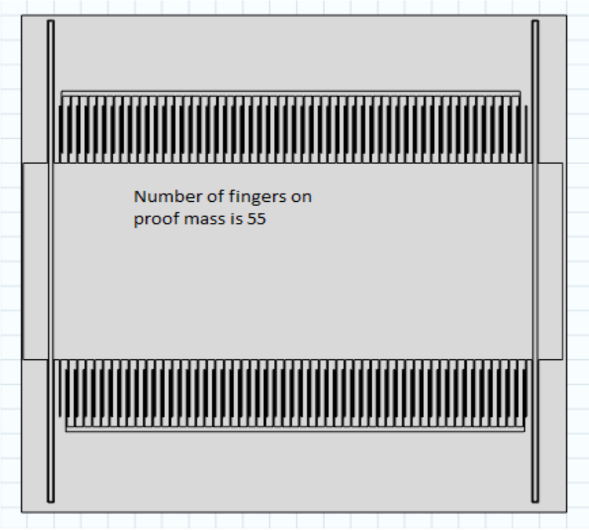


Figure. 2 Prototype MEMS accelerometer architecture

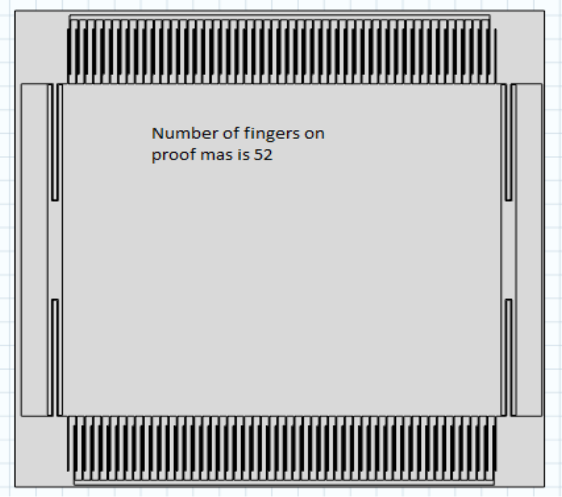
Table 1 Geometry parameters of the accelerometer model

Geometry Parameters	Values (µm)
Thickness of the plate	25
Width of finger	2
Finger overlap length	96
Width of spring beam	2
Length of finger	116

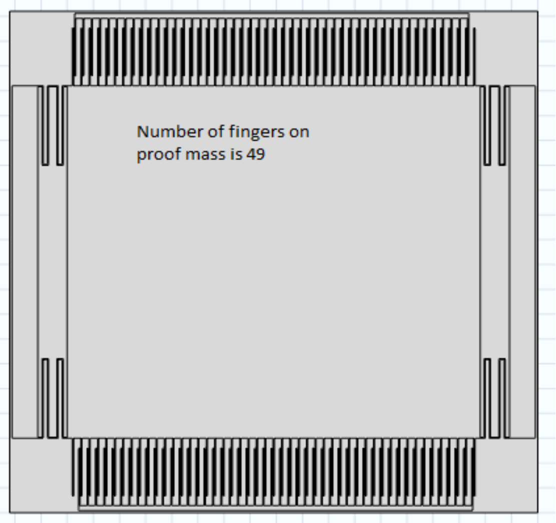
There are certain important design considerations that need to be taken care. The mass of the umbo and long process of the malleus is about20–25mg.It has been shown that adding a mass greater than 20 mg can potentially result in a significant damping effect on the frequency response of the middle ear ossicular chain, particularly at frequencies above1kHz. Therefore, the total packaged mass of the sensing system needs to be kept below 20 mg. The average length of the long process of the malleus is between 6.5 and 8mm and the size of the umbo tip is typically between 1.5 and 2 mm, which is comparable to the height of the eardrum cone. The spacing between the umbo and the oval window of the cochlea varies between 2 and 3mm. Therefore, the overall prototype microsystem should exhibit a packaged dimension less than3.5mm×6.5mm so that it can be implanted on the umbo without touching other structures inside the middle ear cavity [5].



(a) Prototype 1



(b) Prototype 2



(c) Prototype 3

Figure 3. Different prototypes (a), (b) and (c) of accelerometer based on different spring topologies with gap ratio of 5

These models are simulated using COMSOL 4.2 in 2D as a plate structure. The physics used includes electrostatics, solid mechanics, and moving mesh. The geometry parameters of the model are given in table 1. Corresponding to this input voice signal, the acceleration values from 0g to 1g are applied to the designed structures [5]. The structures have been analysed using Silicon as material and dielectric as air. The proof mass along with movable fingers is connected to 1 V supply and the fixed fingers with ground.

For different gap ratios a number of combinations of dimensions of proof mass and spring are selected to have a resonant frequency of 10 kHz.

The nominal capacitance value from each side is a function of the finger overlap length l, device layer thickness t, air gap between adjacent fingers x_1 and x_2, and the number of sensing finger sets N. The nominal capacitance value for C_{s+} can be expressed by

$$C_{s+nom} = \left(\frac{\varepsilon_0 lt}{x_1} + \frac{\varepsilon_0 lt}{x_2}\right) \times N = C_{s+1} + C_{s+2} \quad (7)$$

where ε_0 is the permittivity of vacuum. The proof mass moves along the direction of acceleration and thus changes the gap spacing between the interdigitated fingers by Δx, which results in a corresponding change in sensing capacitance value as

$$\Delta C_{s+} = \left(\frac{\varepsilon_0 lt}{x_1}\frac{\Delta x}{x_1} - \frac{\varepsilon_0 lt}{x_2}\frac{\Delta x}{x_2}\right) \times N \qquad (8)$$

where Δx is assumed to be much smaller than x_1 and x_2. If the gap spacing of x_1 and x_2 is identical, then there will be no capacitance change. By extending x_2 much larger than x_1, the second term in (2) can be greatly minimized, thus enhancing the sensitivity if N is unchanged. On the other hand, enlarging x_2 would reduce the number of fingers that can be fabricated within a given length, thus causing a sensitivity degradation. Analysis reveals that the device sensitivity ΔCs/Δx, as a function of gap ratio, x_2/x_1, can be maximized with a gap ratio of approximately 2.5 based on a device length of 1 mm, finger overlap length and thickness of 100 and 25 µm, respectively [5]. For our analysis we have taken the gap ratio from 1 to 5.

3. Results and Discussions:

The variation of nominal capacitance and capacitive sensitivity with gap ratio (x_2/x_1) are plotted in figures 4 and 5 respectively.

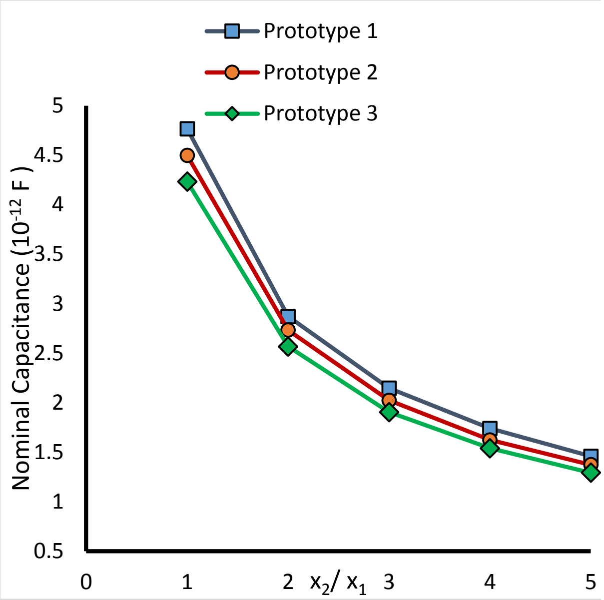


Figure 4. Nominal Capacitance vs gap ratio

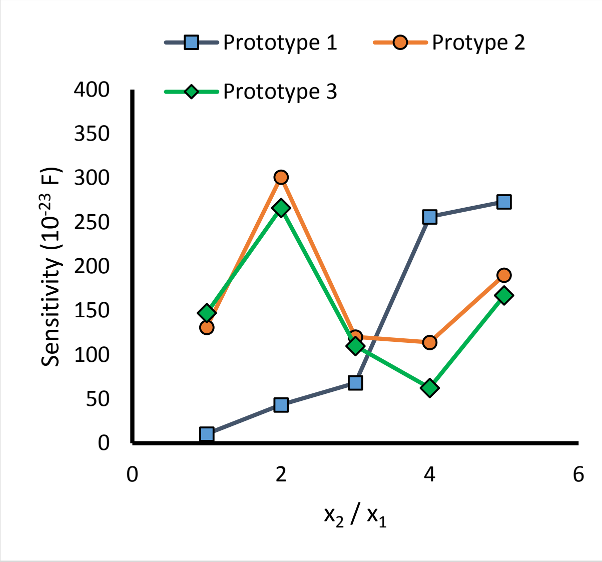


Figure 5. Capacitive sensitivity vs gap ratio

The plot of nominal capacitance vs variable gap ratio in figure 3 shows that the number of fingers and hence the capacitance decreases with increasing gap spacing. But the plot of sensitivity vs variable gap spacing in figure 5 varies randomly. So we have optimised the gap spacing which gives higher sensitivity and higher capacitance as well. Figure 5 clearly shows that the prototype 2 gives the best sensitivity at gap ratio of 2.

4. Conclusion: The optimum value of sensitivity is obtained at gap ratio of 2 for prototype 2.The optimised results will be used in selecting the prototype structure for designing high performance MEMS accelerometer for fully implantable hearing aid applications.

5. References

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