Optimization of Device Geometry of a Fully Implantable MEMS Hearing Aid Microphone by Genetic Algorithm

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Abstract: The paper presents the performance optimization of a MEMS accelerometer based microphone for the fully implantable hearing application. A genetic algorithm is employed to optimize the device geometry parameters satisfying the design constraints. The analytical model run on MATLAB and the simulation model implemented in COMSOL MULTIPHYSICS 4.2 show good agreement. Optimization with Genetic algorithm shows enhanced capacitance of 3.14 pF, displacement sensitivity of 2.49 nm/g and capacitive sensitivity of 2.48 fF/g.

Keywords: Implantable microphone, microelectromechanical systems (MEMS) accelerometer, middle ear microphone.

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1. Introduction

The hearing impairment is affecting more than 360 million people all over the world [1].In India alone, 63 million people suffer from significant auditory loss [2]. Considerable interest in middle ear implants has emerged over the years to facilitate patients who do not receive benefits with conventional hearing aids. Moreover, the social stigma of wearing external hearing aids discourages some users from even considering the conventional devices.The totally implantable devices provide freedom from the social and practical difficulties of using conventional hearing aids [3]. In this paper, a MEMS capacitive accelerometer is demonstrated as a middle ear implantable microphone for the fully implantable hearing application. The accelerometer is proposed to be attached to the middle ear bone structure, umbo to convert the bone vibration to an electrical signal representing the original acoustic information. This paper attempts to enhance the sensitivity of the fully implantable middle ear microphone by optimization of the device geometry using the Genetic algorithm. The optimized model satisfies the required design considerations with respect to the surgical implantation of the fully implantable microphone.

The comb drive accelerometer in this work consists of four folded beams, a proof mass, and movable fingers as shown in Figure 1. The fixed parts include two anchors and left/right fixed fingers. The movable central mass is connected to both anchors through four folded beams. Here x_1 is the distances of fixed finger from left movable finger and x_2 from the right movable finger as shown in (Figure1).

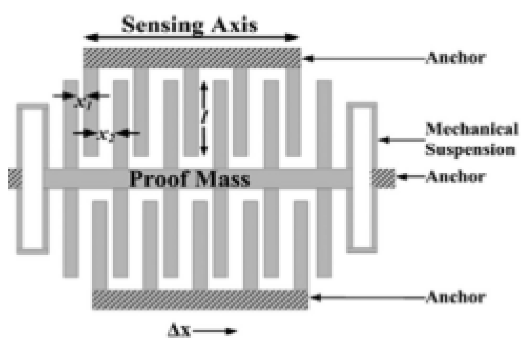

Figure 1. Prototype of the capacitive accelerometer

Under external acceleration, the proof mass with the movable fingers moves in the direction of body force, which changes the capacitance between the movable and the fixed fingers.This change capacitance is measured using electronic interface circuitry.

2. Sensor Design

2.1 Design Considerations

Certain important design considerations [4-6] need to be considered for implantation and efficient working of the sensor. The total packaged mass of the sensor cannot be more than 20 mg. At frequencies above 1 kHz, mass exceeding 20 mg can potentially cause an appreciable damping effect on the frequency response of the middle ear ossicular chain. A minimum proof mass of 2.5 µg is required to ensure low Brownian noise. The overall prototype microsystem should exhibit a packaged dimensions less than 3.5mm×6.5mm for it to be implanted on the umbo without touching other structures inside the middle ear cavity. The microphone should be within 1mm ×1mm. The acceleration of umbo is measured in the frequency range from 250 Hz to 10 kHz with input tones between 70 and 100 dB Sound Pressure Level (SPL) [7]. The resonant frequency clearly needs to be greater than the speech signal frequency range. For our present design, the resonant frequency is kept at 10,000 Hz.

2.2 Theoretical Calculation

The input acceleration a from the umbo causes a body force F to act on the proof mass m. This force causes the proof mass to displace by Δx under the effect of spring with spring constant k.

$$F = ma \quad (1)$$

$$F = k\Delta x \quad (2)$$

where k is the effective spring constant. Hence,

$$\frac{\Delta x}{a} = \frac{m}{k} \quad (3)$$

which represents the displacement sensitivity of the device.

The resonant angular frequency is given as

$$\omega_0 = \sqrt{\frac{k}{m}} \quad (4)$$

From equations (3) and (4), it is clear that the displacement sensitivity is inversely proportional to the square of the resonant angular frequency.

$$\frac{x(t)}{a(t)} = \frac{1}{\omega_0^2} \quad (5)$$

The spring constant is given as

$$k = Et\left(\frac{w}{l}\right)^3 \quad (6)$$

where E is the Young's modulus of elasticity, t is the device thickness; w is the width of the spring beam, and l is the length of the spring beam. The nominal capacitance value from each side can be expressed by

$$C_0 = \left(\frac{K\varepsilon_0 L_{f0} t}{x_1} + \frac{K\varepsilon_0 L_{f0} t}{x_2}\right) \times N_f \quad (7)$$

The change in sensing capacitance value under displacement Δx of proof mass is given by

$$\Delta C = \left(\frac{K\varepsilon_0 L_{f0} t}{x_1}\frac{\Delta x}{x_1} - \frac{K\varepsilon_0 L_{f0} t}{x_2}\frac{\Delta x}{x_2}\right) \times 2N_f \quad (8)$$

where L_{f0} is the finger overlap length, K is the dielectric constant, ϵ_0 is the permittivity of free space and N is the total number of sensing fingers.

Capacitive Sensitivity is given as change in capacitance with respect to applied acceleration $\Delta C/a$ (fF/g).

2.3 Device Optimisation

We can see that the sensitivity depends on so many parameters that are conflicting with each other. For performace enhancment, these parameters need to be optimised. Also, the device parameters need to follow the constraints that need to be considered for the desigining of the middle ear implantable microphone.The design considerations are:

1) The length of the sensor is within 1 mm.

2) The width of the sensor is within 1mm.
3) The resonant frequency is 10,000 Hz.
4) The total mass of the sensor is greater than 2.5 µg and less than 25 mg.

Hence we use Genetic algorithm, an evolutionary optimisation technique inspired by Darwin's theory of evolution for achieving this optimisation.

The following is the flowchart of the procedure followed.

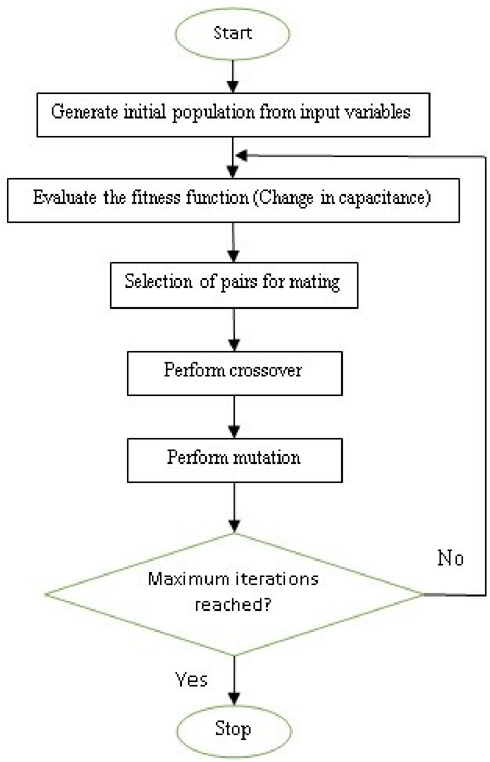

Figure 2. Flowchart of Genetic Algorithm

It is based on the pricniple of natural selection and the survival of the fittest. So the solution we obtain will be a close approximation of the best solution. Algorithm is started with a set of solutions (represented by chromosomes) called population. Solutions from one population are taken and used to form a new population. This is motivated by hope, that the new population will be better than the old one. Solutions which are selected to form new solutions (offspring) are selected according to their fitness - the more suitable they are, the more chances they have to reproduce. This is repeated until some condition (for example number of populations or improvement of the best solution) is satisfied.

2.3 Use of COMSOL Multiphysics®:

This model is simulated using COMSOL Multiphysics in 2D as a plate structure. The physics include electrostatics, solid mechanics, and moving mesh. The geometry parameters of the model optimized using Genetic Algorithm are given in (Figure 2). Corresponding to the input voice signal, the acceleration values from 0 g to 1g are applied to the designed structures. The structures have been analyzed using silicon material and air as dielectric. The proof mass along with movable fingers is kept at 1 V and the fixed fingers with the ground.

3. Results And Discussions

The analytical and the simulation results from COMSOL are compared for validation. The material used is Silicon. The dielectric used is air. The modulus of elasticity of Silicon is 131 GPa. The poisson's ratio of Silicon is 0.30. The length of finger is 116 µm, the width of finger is 2 µm, the length of finger overlap is 96 µm, the number of fingers is 64 on each side of the proof mass, the thickness of the device is 25 µm and the gap ratio is 4.5 (x1 = 2 µm, x2= 9 µm) [4].The spring constant and dimensions of the proof mass are selected so as to maintain the resonant frequency around 10,000 Hz and to satisfy the design constraints. The length and the width of the proof mass are 700 µm and 905 µm respectively. The length and the width of the of the spring are 140 µm and 2 µm respectively.

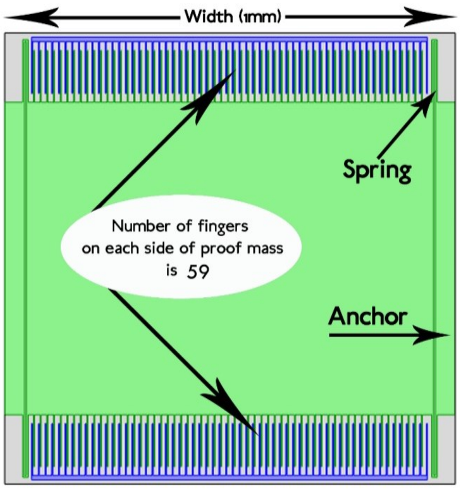

Figure 3. The accelerometer structure designed in COMSOL MULTIPHYSICS

The simulation and analytical results for the main parameters show a variance of less than 10%. The input acceleration is provided in terms of g (g=9.8msec^{-2}).

Table 1. Comparison of Analytical and Simulated Values

Parameter	Analytical Value	Simulated Value	Error (%)
Resonant Frequency (Hz)	10524	10785	2.48
Capacitance (pF)	1.55	1.63	5.41
Displacement Sensitivity (nm/g)	2.24	2.37	5.84
Capacitive Sensitivity (fF/g)	1.34	1.44	7.49

Now we go for optimisation of the device parameters so as to enhance the performance. We have performed 500 iterations 50 times with a crossover probability of 0.8 and mutation probability of 0.01 to obtain the best result. The population size is taken as 500. The number of input variables is seven which are presneted in Table 2.The gap spacing between the first movable and fixed finger is 2 µm. The position of the first fixed finger on the proof mass is 10 µm from the spring. The other input variables which are optimised are presented in the follwing table.

Table 2. The input variables which form the chromosome string

Input Variables	Range of values
Length of finger	[90 µm 130 µm]
Length of proof mass	[710 µm 760 µm]
Width of proof mass	[925 µm 940 µm]
Thickness of device	[25 µm 50 µm]
Length of spring beam	[0 µm 145 µm]
Gap between spring beams	[4 µm 8 µm]
Gap ratio between fingers	[1 10]
Applied acceleration	[0g 1g] g = 9.8 m/sec2

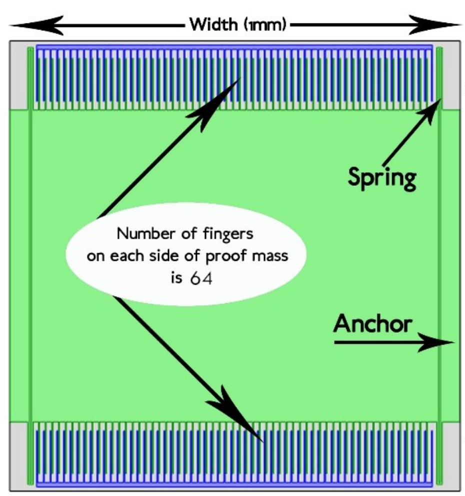

Figure 4. The optimised accelerometer prototype designed in COMSOL MULTIPHYSICS

The best set of input parameter values obtained is presented in Table 3.

Table 3. The Optimised Set of Values

Parameter	Value
Gap Ratio (x_2/x_1)	6
Number of fingers	64
Length of finger	105 µm
Thickness of device	43 µm
Length of proof mass	747 µm
Width of proof mass	940 µm
Length of Spring Beam	119 µm
Capacitive Sensitivity	2.48 pF

Table 4. Comparison of Ga Optimised and Non-Optimised Results

Parameters	GA Optimised Value	Non-optimised value	Difference (%)
Resonant Frequency (Hz)	9986	10524	-5.17
Capacitance (pF)	3.14	1.55	102.58
Displacement Sensitivity (nm/g)	2.49	2.24	11.17
Capacitive Sensitivity (fF/g)	2.48	1.34	85.07

The optimised values are compared with the previous set of values obtained as mentioned in Table 1. It is clear that the capacitive sensitivity is greatly enhanced.

Table 5. Comparison of Simulation and Analytical Results

Parameters	Analytical Value (GA)	Simulated Value (COMSOL)	Error (%)
Resonant Frequency (Hz)	9986	10023	0.37
Capacitance (pF)	3.14	3.32	5.73
Displacement Sensitivity (nm/g)	2.49	2.37	7.23
Capacitive Sensitivity (fF/g)	2.48	2.72	9.68

The optimized results are now compared with the simulated results from COMSOL Multiphysics for validation. They show good agreement (within 10%). The displacement vs. acceleration plot and change in capacitance vs. acceleration plot are presented in Figure 5 and Figure 6 for three different frequencies of 500 Hz, 2000 Hz and 3500 Hz.

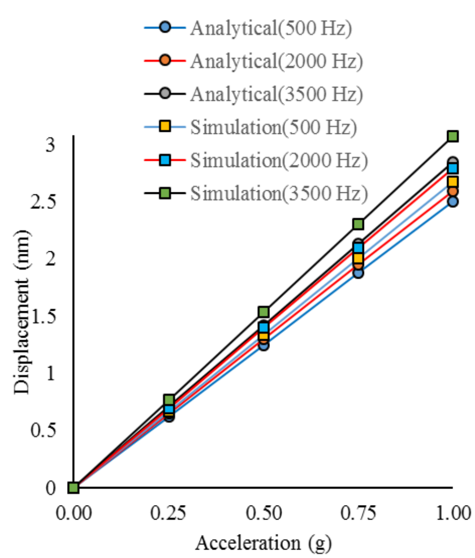

Figure 5. Displacement vs. acceleration plot at frequencies of 500 Hz, 2000 Hz, and 3500 Hz

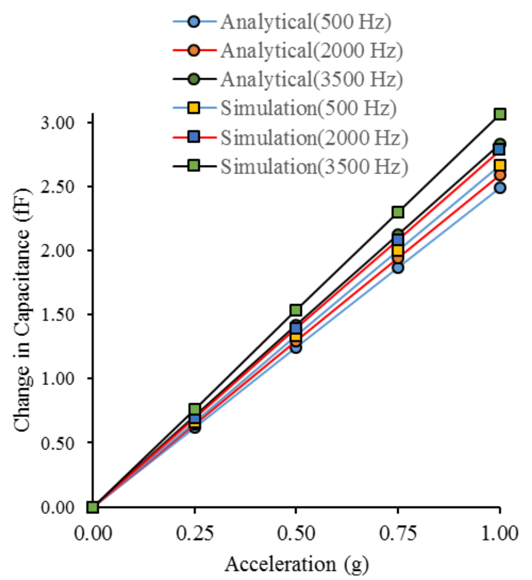

Figure 6. Change in capacitance vs. acceleration plot at frequencies of 500 Hz, 2000 Hz, and 3500 Hz.

4. Conclusion

This paper presents a comprehensive mathematical model of a MEMS capacitive accelerometer based microphone for the fully implantable hearing application. The model is developed and is validated with simulation results from COMSOL MULTIPHYSICS. A genetic algorithm is employed to optimize the performance. The optimized capacitance of 3.14 pF, displacement sensitivity of 2.49 nm/g and capacitive sensitivity of 2.48 fF/g is obtained with total 128 number of sensing fingers.

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