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Development of a Cochlear Biomodel Using Micro-Electromechanical Systems (MEMS) †

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Abstract: The human cochlea is undeniably one of the most amazing organs in the body. One of its most intriguing features is its unique capability to convert sound waves into electrical nerve impulses. Humans can generally perceive frequencies between 20 Hz and 20 kHz with their auditory systems. Several studies have been conducted on building an artificial basilar membrane for the human cochlea (cochlear bio model). It's possible to mimic the active behavior of the basilar membrane using micro-electromechanical systems (MEMS). This paper proposes an array of MEMS bridge beams that are mechanically sensitive to the perceived audible frequency. It was designed to operate within the audible frequency range of a set of bridge beams with 0.65 μm thickness, width of 50 μm and varying lengths between 200 μm and 2000 μm. As the material for bridge beam structures, Platinum (Pt), Molybdenum (Mo), Chromium (Cr), and Aluminium (Al) have been considered. For the cochlear bio model, platinum has proven to be the best material, closely mimicking the basilar membrane, based on the finite element (FE) and lumped element (LE) models.

Keywords: MEMS; cochlear bio model; finite element (FE); lumped element (LE)

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1. Introduction

Sound can be heard and manipulated by humans only through their auditory system. There are three parts to the human ear: the outer ear, middle ear, and inner ear. As sound waves travel from the surrounding area to the middle ear, they are carried by ear flaps and canals in the outer ear. Anvil, stirrup, and hammer are three miniature ear bones in the middle ear. An eardrum is a thin membrane that the sound waves bump into at this point. A hammer is attached to an eardrum. This will cause the hammer to move when the eardrum vibrates. A stirrup and anvil will be used to transfer these movements. Stirrups are connected to basilar membranes in the inner ear. Consequently, the basilar membrane vibrates by the movements of the ear bones. In the meantime, the nerve cells detect the movement from the basilar membrane and transmit nerve impulses to the brain [1]. Different biomimetic approaches have also been reported [2–4] to detect sound using MEMS technology.

A basilar membrane within the cochlea is one of the essential parts of the hearing process. It may hold the key to the mechanism responsible for the unknown adaptive cochlear mechanism. Researchers have developed artificial basilar membranes, i.e., cochlear biomodelling, to mimic the active cochlea filtering characteristics. A basilar membrane has a stiff, narrow base that is the opening part. As sound waves propagate from the base to the apex, the basilar membrane responds mechanically depending on their frequency, amplitude and time [5]. When high-frequency sounds are received, it responds.

In contrast, the apex is the flexible part of the basilar membrane. There is more flexibility and a larger area in this part. Sound waves with lower frequencies are responded to by it. The sensitivity decreases when the distance between the basilar membrane and the base increases [6]. The micro-

electromechanical system (MEMS) combines miniaturized mechanical and electromechanical elements, such as resonators and microphones [7]. The advantages of MEMS resonators are that they closely mimic the cochlea in terms of measurement and characteristics.

A tonotopic organization factor within the cochlea has been mimicked by artificial basilar membranes [8,9]. Many of them are bulky, heavy, and fluid-surrounded artificial basilar membranes. Based on advances in microfabrication technology, micro resonators could be fabricated with a life-size, nonfluidic and unsophisticated surrounding artificial basilar membrane [10–13].

An array of MEMS bridge beam resonators of various lengths is used in our study to work at audible frequencies of 20 Hz to 20 kHz. Each resonator of the bridge beam series is known to have a thickness of 0.65 μm and a width of 50 μm, varying in length from 200 μm to 2000 μm. Moreover, four different materials structures are investigated for MEMS bridge beam resonators: Platinum (Pt), Molybdenum (Mo), Chromium (Cr), and Aluminium (Al). The MEMS bridge beam resonators have been designed and analyzed using finite element (FE) and lumped element (LE) models. Comsol Multiphysics is used for FE modelling, and the results are compared with the LE model.

2. Lumped Element Model

An analysis of the dynamic behavior of a bridge beam structure using lumped element models may be represented as a vibrating system with a single degree of freedom. In Equation (1), a series of bridge beams can be designed that resonant within a certain frequency range, where fundamental mode vibration γ is equal to 4.73, the cross-sectional area is $Ab = w_b t_b$ where tb and w_b are the bridge beam thickness and width respectively, E is material 's Young's modulus, $\mathbf{I = \frac{w_b t_b^3}{12}}$ is the moment of inertia, ρ represent the density, and lb is the length. In our work, we have used

t_b =0.65 μm and w_b =50 μm with l_b = 200–2000 μm.

$$\boldsymbol{fo = \frac{\gamma^2}{2\pi}\sqrt{\frac{EI}{\rho A_b l_b^2}}} \tag{1}$$

$$\boldsymbol{fo = 1.028\frac{t^b}{l_b^2}\sqrt{\frac{E}{\rho}}} \tag{2}$$

3. Finite Element Model

A novel array of bridge beam resonators shown in Figure 1 resembles the basilar membrane in the human cochlea in terms of its characteristics. Bridge beams with a length of 200 m indicate the opening area of the membrane (base), which will be highly responsive to high-frequency sound waves. The longest bridge beam, which has a length of 2000 m, indicates where the membrane ends (apex), which is responsive to the lowest frequency of the audible sound wave, and moves upwards [14]. Comsol Multiphysics 4.3 was used to construct the finite element models, and the resonators' desired frequency response was verified and designed. Comsol Multiphysics has been used in our work to develop MEMS cochlear biomodel. The finite element model of the microbridge structures has been created, and the model analysis has been performed. In the simulation model, the study includes Platinum 5 (Pt), Molybdenum (Mo), Chromium (Cr) and Aluminium (Al) materials used for the structure of MEMS bridge beams. The sold mechanics interface was mainly applied for the simulations. In COMSOL, the calculation part starts with the study setup, where a parameter sweep can be configured that allows the variation of the values for the structure geometries and, of course, the displacement. The next step is the so-called stationary, where the equilibrium state's deformation, stress and strain are calculated. This is followed by eigenfrequency, which is only needed for the resonance frequency calculation. An appropriate mesh has to be created since a wider mesh saves simulation time but causes larger errors. Due to the high aspect ratio of the beams, they are thin and long; about 150000 domain elements are required. The simulated resonant frequency decreases with respect to the beam length, showing the inverse proportional relationship between f_o and l_b^2 as in equation 1. This simulates the tonotopic organization behaviour of the basilar membrane within the human cochlea. The shortest beam length represents the apex, while the longest indicates the base region.

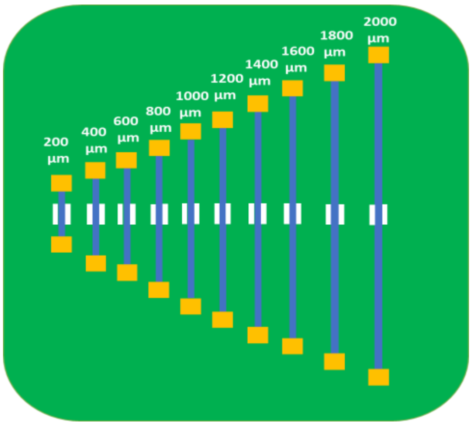

Figure 2. An array of designed bridge beam resonators.

The material structure for the MEMS bridge beams in this study includes Platinum (Pt), Molybdenum (Mo), Chromium (Cr) and Aluminium (Al). Each material has different mechanical/material properties [15] and must be considered. MEMS bridge beams might be able to operate at desired audible frequencies with these proposed materials, given their small E/ϱ ratios. Table 1 summarizes the geometrical dimensions of the designed MEMS bridge beams, while Table 2 shows the mass density and Young's modulus of the materials considered. Finite and lumped element models have been developed based on these data.

Table 1. Geometrical dimensions of MEMS bridge beams.

Beam	Size (µm)
Length	200–2000
Width	50
Thickness	0.65

Table 2. MEMS bridge beams' mechanical properties.

Materials	Density ($g\ cm^{-3}$)	Young's Modulus (GPa)
Molybdenum	10.10	315
Chromium	7.20	140
Aluminum	2.70	70
Platinum	21.45	168

4. Results and Discussion

MEMS bridge beam resonance frequencies for all four materials are shown in Figure 2, with bridge length as a function of the resonance frequency. The design of the MEMS bridge beams resonates close to the audible frequency range, as shown by the simulation. Based on their design, MEMS bridge beam resonators mimic the apex-to-base characteristics of basilar membranes.

For bridge length lb = 200–2000 μm, the simulated resonance frequencies for Platinum (Pt), Molybdenum (Mo), Chromium (Cr), and Aluminium (Al) are 46,801.83–492.01 Hz, 93,330.19 Hz–978.61 Hz, 73,696.19 Hz–780.51 Hz, and 85,110.19 Hz–896.29 Hz respectively. It has been observed that platinum MEMS bridge beams offer the best performance due to proximity to audible frequencies.

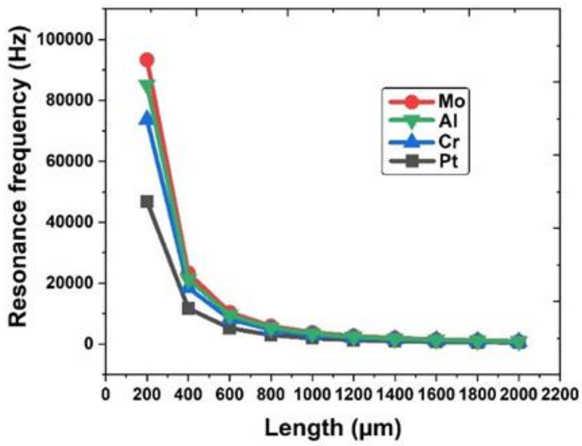

Figure 2. MEMS bridge beam resonance frequency Finite element model for all materials.

A comparison is then made between the simulation results from FE modelling and those from lumped element modelling. Materials have been analyzed based on their dimensions and mechanical properties.

Material 1: Platinum (Pt)

Due to the smallest E/ϱ ratio, platinum is one of the top materials that can fabricate MEMS bridges because of its unique properties of beams. The finite element model of platinum MEMS bridge beams with resonance frequencies between 46,801.83–492.01 Hz is shown in Table 3. A comparison of FE and LE models for platinum MEMS bridge beam resonance frequencies is shown in Figure 3a. A comparison of the resonance frequencies of platinum MEMS bridge beams using FE and LE models is shown in Figure 3.

Material 2: Molybdenum (Mo)

As shown in Table 3 and Figure 3b, the resonance frequency of MEMS bridge beams made of Molybdenum ranges from 93,330.19 Hz to 978.61 Hz (FE Model). FE and LE models have acceptable error percentages as the highest percentage error is 4.66%.

Material 3: Chromium (Cr)

As shown in Table 3 and Figure 3c, the resonance frequency of MEMS bridge beams made of copper ranges from 73,696.19 Hz to 780.51 Hz (FE Model). FE and LE models have acceptable error percentages as the highest percentage error is 5.62%. Having smaller E/ϱ ratio, chromium is better than molybdenum as it operates closer to the audible frequency range [16,17].

Material 4: Aluminum (Al)

An aluminium MEMS bridge beam LE model has a resonance frequency range from 85,110.19 Hz to 896.29 Hz, shown in Table 3. The highest error is 5.10% at lb = 2000 μm. The resonance frequency values of the FE and LE models are compared in Figure 3d.

Table 3. Comparison of the value for the simulated and calculated resonance frequency of MEMS bridge beams built from Platinum (Pt), Molybdenum (Mo), Chromium (Cr), and Aluminum (Al) and the error percentage of each entry.

Length (μm)	RF (Hz)		Error (%)
	FE	LE	
Material 1. Pt			
200	46,801.83	46,750.63	0.10
400	11,710.19	11,687.65	0.19
600	5224.10	5194.20	0.57
800	3001.44	2921.91	2.64
1000	1923.62	1870.02	2.78
1200	1329.70	1298.55	2.34
1400	980.92	954.09	2.73
1600	757.02	730.47	3.50
1800	600.29	577.15	3.85
2000	492.01	467.50	4.91
Material 2. Mo			
200	93,330.19	93,291.28	0.04
400	23,389.22	23,321.41	0.28
600	10,402.67	10,365.07	0.36
800	5896.09	5830.35	0.01
1000	3769.80	3731.64	1.01
1200	2620.49	2591.26	1.11
1400	1964.92	1903.85	3.10
1600	1503.66	1457.64	3.06
1800	1203.37	1151.15	4.33
2000	978.61	932.91	4.66
Material 3. Cr			
200	73,696.19	73,662.12	0.04
400	18,490.21	18,414.40	0.41
600	8222.67	8184.18	0.46
800	4679.10	4603.60	1.61
1000	2992.54	2946.48	1.53
1200	2109.71	2046.04	3.01
1400	1589.62	1503.26	5.32
1600	1199.81	1150.94	4.07
1800	953.33	909.38	4.61
2000	780.51	736.62	5.62
Material 4. Al			
200	85,110.19	85,057.69	0.06
400	21,291.31	21,263.14	0.13
600	9510.40	9450.28	0.63
800	5391.61	5315.78	1.41
1000	3481.57	3402.00	2.28
1200	2399.09	2364.60	1.43
1400	1791.11	1735.82	3.03
1600	1390.23	1328.99	4.40
1800	1103.44	1050.07	4.83
2000	896.29	850.57	5.10

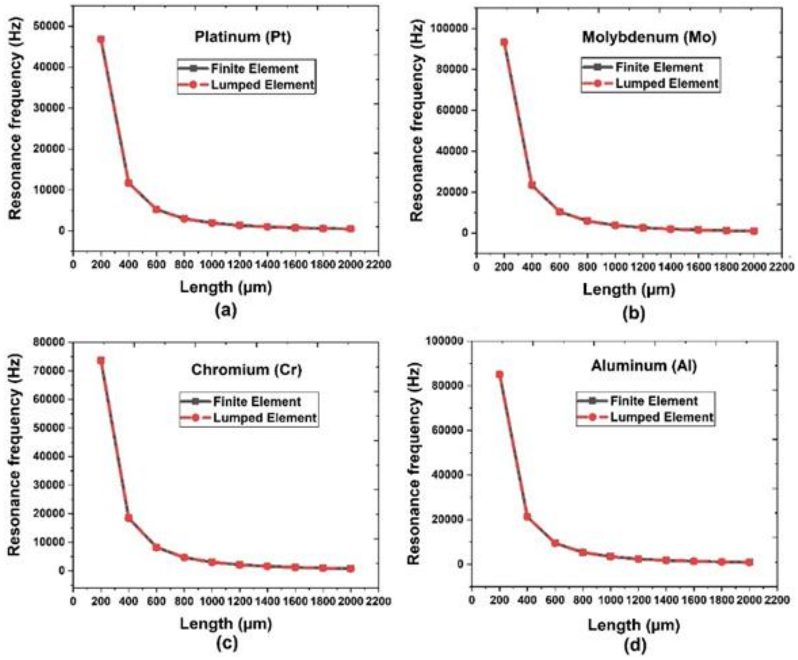

Figure 2. An illustration of the resonance frequency simulated and calculated for MEMS bridge beams made of Platinum (Pt), Molybdenum (Mo), Chromium (Cr), and Aluminium (Al).

5. Conclusions

In this work, MEMS bridge beam resonators have been designed to mimic the cochlear basilar membrane to operate in the audible frequency range. An important consideration has to be taken into account when designing the MEMS bridge beams of the future, and these factors include the geometry of the beam and the material used in the beam structure. Based on FE and LE models, a beam array of MEMS bridge beams with dimensions of 650 μm, 50 μm, and 200 μm to 2000 μm thickness, width, length respectively, has been designed using Platinum (Pt), Molybdenum (Mo), Chromium (Cr), and Aluminium (Al) as the materials. According to the functions of the base and apex in the basilar membrane, the resonant frequencies have been shown to decrease with increasing bridge lengths. The artificial basilar membrane is ideal for platinum, since its resonance frequency is closest to that of the intended audible range. A MEMS bridge beam resonator can be accurately designed with both FE and LE models with very small percentage differences.

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