Proceedings Paper

Design and modelling of MEMS Resonators for Artificial Basilar Membrane†

Basit Abdul [1]*, Mohammad Abul Hasan Shibly [2], Abdul Rab Asary [3] , Nusrat Jahan Ruma [2]

[1] Sabanci University, Nanotechnology Research, and Application Center Istanbul Turkey; abdul.basit@sabanciuniv.edu
[2] Department of Textile Engineering, National Institute of Textile Engineering and Research, Dhaka-1350, Bangladesh; hasan.niter@gmail.com
[3] University of Naples Parthenope, 80133 Napoli, Italy; abdulrabasary@hotmail.com
* Correspondence: abdul.basit@sabanciuniv.edu
† Presented at The 2nd International Electronic Conference on Chemical Sensors and Analytical Chemistry (CSAC 2023)— held online from 16 to 30 September 2023.

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 biomodel). 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 bridge beams with 450 µm thickness and varying lengths between 200 µm and 2000 µm. As the materials for bridge beam structures, Molybdenum (Mo), Platinum (Pt), Chromium (Cr) and Gold (Au) have been considered. For the cochlear biomodel, gold 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)

Citation: To be added by editorial staff during production.

Academic Editor: Firstname Lastname

Published: date

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 microelectromechanical system (MEMS) combines miniaturized mechanical and electro-mechanical 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 450 μm and a width of 150 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 Gold (Au). 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. The resonating structure represents a lumped mass, spring, spring, and damper within the model. 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 t_b and w_b are the bridge beam thickness and width respectively, E is Young's modulus for the material being used to construct the bridge beam structure $\boldsymbol{I = \frac{w_b t_b^3}{12}}$ is the moment of inertia, ρ indicates the material density, and l_b is the bridge beam length. Equation (1) can be simplified to equation (2), by which the resonant frequency f_0 can be observed to have an inverse proportional and direct proportional relationship with $\boldsymbol{l_b^2}$ and $\sqrt{\frac{E}{\rho}}$ respectively. In our work, we have used

t_b =450 μm and w_b =150 μm with l_b = 200 μm - 2000 μm.

$$\boldsymbol{fo = \frac{\gamma^2}{2\pi}\sqrt{\frac{EI}{\rho A_b l_b^2}}} \quad \text{……………………} \textit{ Eq. 1}$$

$$\boldsymbol{fo = 1.028\frac{t^b}{l_b^2}\sqrt{\frac{E}{\rho}}} \quad \text{………………} \textit{ Eq. 2}$$

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.

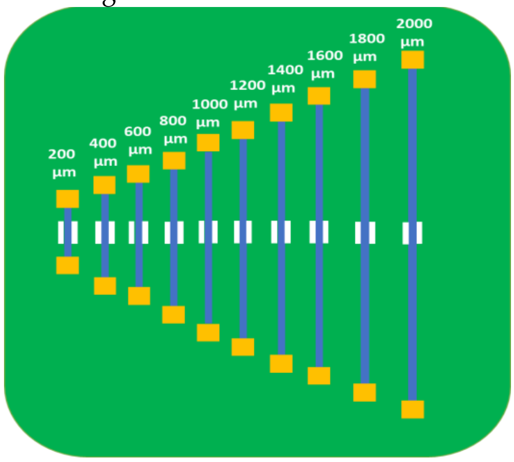

Figure 1. An array of designed bridge beam resonators.

The material structure for the MEMS bridge beams in this study includes Platinum (Pt), Molybdenum (Mo), Chromium (Cr) and Gold (Au). 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.

Beam	Size (µm)
Length	200-2000
Width	150
Thickness	450

Table 1. Geometrical dimensions of MEMS bridge beams

Material	Mass Density ($g\ cm^{-3}$)	Young's Modulus (GPa)
Platinum	21.45	168
Molybdenum	10.10	315
Chromium	7.20	140
Gold	19.3	79

Table 2. MEMS bridge beams' mechanical properties.

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 µm - 2000 µm, the simulated resonance frequencies for Platinum (Pt), Molybdenum (Mo), Chromium (Cr), and Gold (Au) are 32399.11 - 350.42 Hz, 64623.43 – 698.34 Hz, 51067.66 – 550.90 Hz, and 23434.89 – 251.90 Hz respectively. It has been observed that gold MEMS bridge beams offer the best performance due to proximity to audible frequencies.

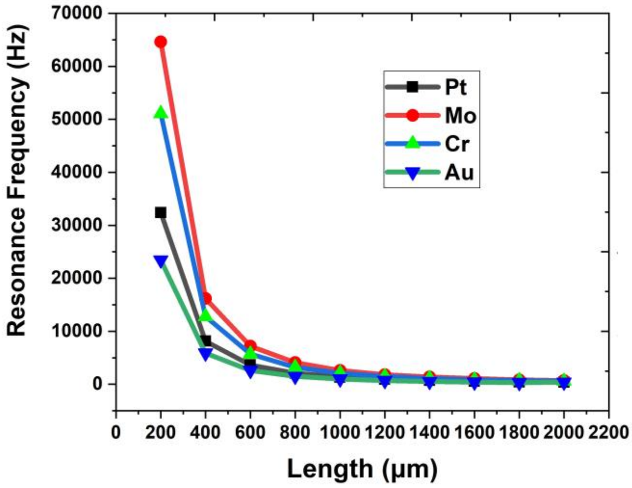

Figure 2. MEMS bridge beam resonance frequency Finite element model for all materials

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 small 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 32399.11 - 350.42 Hz is shown in Table 3. A comparison of FE and LE models for platinum MEMS bridge beam resonance frequencies is shown in Figure 3(a). This figure shows the difference between FE and LE models for the resonance frequency of platinum MEMS bridge beams.

Material 2: Molybdenum (Mo)

As shown in Table 3 and Figure 3(b), the resonance frequency of MEMS bridge beams made of Molybdenum ranges from 64623.43 – 698.34 Hz (finite element model). The percentage of errors between the FE and LE models are also acceptable as the highest percentage error is 7.50%.

Material 3: Chromium (Cr)

As shown in Table 3 and Figure 3(c), the resonance frequency of MEMS bridge beams made of copper ranges from 51067.66 – 550.90 Hz (finite element model). The percentage of errors between the FE and LE models are also acceptable as the highest percentage error is 7.47%. Having smaller E/ϱ ratio, chromium is better than molybdenum as it operates closer to the audible frequency range [16, 17].

Material 4: Gold (Au)

In Table 3, the lumped element model of MEMS bridge beams for gold has a a resonance frequency ranges from 23434.89 – 251.90 Hz. The highest error is 7.15% at lb = 2000 µm, and the lowest is 0.15% at lb = 200 µm. Figure 3(d) shows the comparison of both the simulated (FE model) and calculated (LE model) values for the resonance frequencies.

Length (µm)	Platinum (Pt)			Molybdenum (Mo)			Chromium (Cr)			Gold (Au)		
	FE	LE	Error (%)	FE	LE	Error (%)	FE	LE	Error (%)	FE	LE	Error (%)
200	32399.11	32365.80	0.10	64623.43	64586.24	0.05	51067.66	50996.79	0.13	23434.89	23398	0.15
400	8140.32	8091.45	0.60	16188.32	16139.58	0.30	12793.34	12743.68	0.38	5887.33	5846.99	0.68
600	3634.28	3596.20	1.04	7208.90	7176.24	0.45	5699.98	5666.20	0.59	2623.87	2599.78	0.91
800	2092.87	2022.86	3.34	4098.87	4036.57	1.15	3218.87	3184.90	1.05	1501.45	1462.35	2.60
1000	1333.99	1294.63	2.95	2612.12	2583.44	1.09	2089.98	2039.87	2.39	998.34	935.92	6.25
1200	945.78	899.05	4.94	1819.81	1794.06	1.41	1479.47	1416.56	4.25	699.56	649.94	7.09
1400	700.46	660.46	5.71	1384.65	1317.97	4.81	1092.56	1040.66	4.75	500.76	477.47	4.65
1600	533.87	505.70	5.27	1078.46	1009.14	6.42	845.76	796.81	5.78	393.43	365.58	7.07
1800	419.89	399.36	4.88	837.67	796.92	4.86	679.78	629.68	7.37	310.44	288.91	6.93
2000	350.42	323.51	7.67	698.34	645.58	7.50	550.90	509.74	7.47	251.90	233.87	7.15

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 Gold (Au) and the error percentage of each entry.

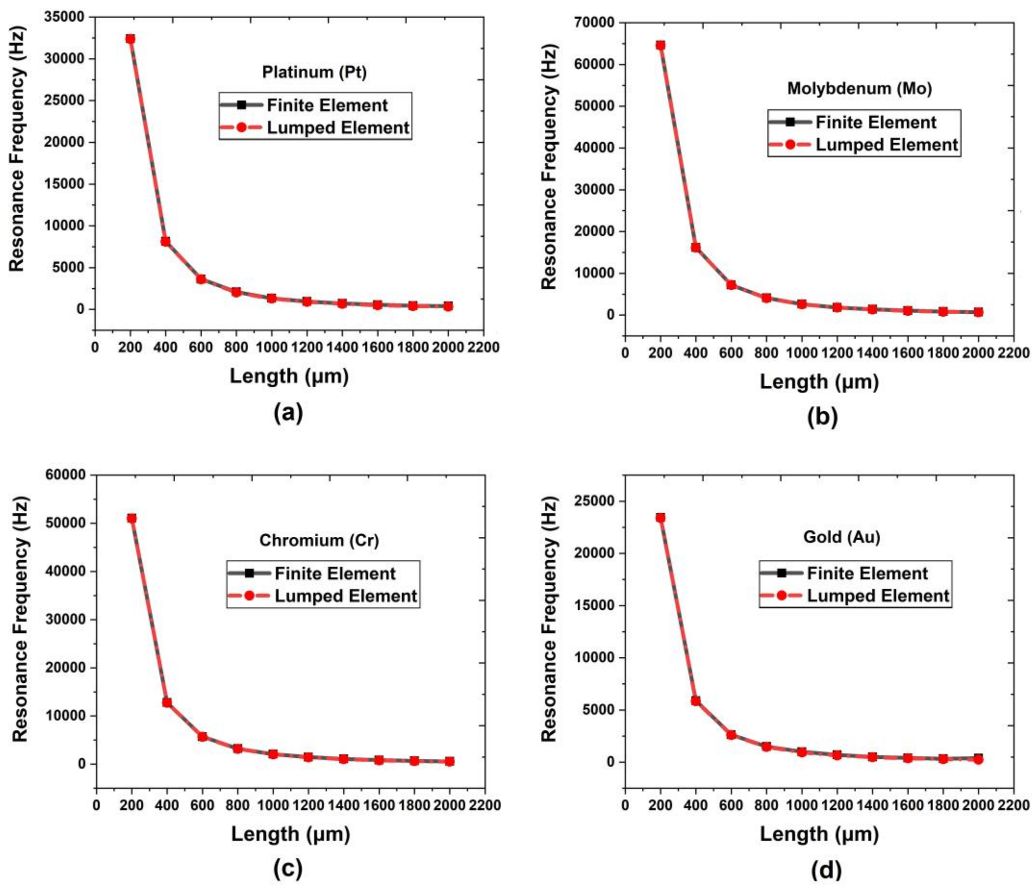

Figure 3. An illustration of the resonance frequency simulated and calculated for MEMS bridge beams made of Platinum (Pt), Molybdenum (Mo), Chromium (Cr), and Gold (Au)

5. Conclusion

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 450 µm thickness, 150 µm width, and 200 µm to 2000 µm length has been designed using Platinum (Pt), Molybdenum (Mo), Chromium (Cr), and Gold (Au) 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. Gold provides resonance frequency closest to the desired audible range, making it the ideal material for the artificial basilar membrane. A MEMS bridge beam resonator can be accurately designed with both FE and LE models with very small percentage differences.

Author Contributions: Conceptualization, B.A. and A.H.S.; methodology, B.A.; software, B.A, AH.S; validation, B.A., A.H.S. and AR.S; formal analysis, AR.S.; investigation, B.A.; resources, B.A; data curation, B.A. and A.R.S; writing—original draft preparation, B.A.; writing—review and editing, B.A., A.H.S and A.R.S; visualization, A.H.S.; supervision, B.A.; project administration, B.A.; All authors have read and agreed to the published version of the manuscript.

Funding: "This research received no external funding."

Institutional Review Board Statement: "Not applicable".

Informed Consent Statement: "Not applicable."

Data Availability Statement: "The data presented in this study are available within the article and there is presented in every graph. There is no more data apart from the presented."

Conflicts of Interest: "The authors declare no conflict of interest."

References

1. Kaskel, A., Hummer, P. J., Daniel, L., & Glencoe/McGraw-Hill. (1999).Biology: An everyday experience. New York, N.Y: Glencoe/McGraw-Hill.
2. Abdul, B.; Mastronardi, V.M.; Qualtieri, A.; Guido, F.; Algieri, L.; Rizzi, F.; De Vittorio, M. Design, Fabrication and Characterization of Piezoelectric Cantilever MEMS for Underwater Application. Micro Nano Eng. 2020, 7, https://doi.org/10.1016/j.mne.2020.100050
3. Abdul, B.; Mastronardi, V. M.; Qualtieri, A.; Algieri, L.; Guido, F.; Rizzi, F.; De Vittorio, M. Sensitivity and Directivity Analysis of Piezoelectric Ultrasonic Cantilever-Based Mems Hydrophone for Underwater Applications. J. Mar. Sci. Eng. 2020, 8 (10), 1–15. https://doi.org/10.3390/jmse8100784
4. B. Abdul, S. Abdul, A. R. Asary; Biomimetic Cilia-based MEMS Sensors for Underwater Applications - A Review; North American Academic Research, 4(12) 11-21 December 2021, https://doi.org/10.5281/ zenodo.5768208
5. Berenice Goelzer, Colin H. Hansen, & Gustav A. Sehrndt (1995). THE ANATOMY AND PHYSIOLOGY OF THE EAR AND HEARING. In Occupational exposure to noise evaluation, prevention and control. Geneva: The World Health Organization.
6. Ellen A. Rhoades (2001). Advantages & Disadvantages: Hearing Aids vs. Cochlear Implants forThose with Severe Hearing Loss. Retrieved April 11, 2023, from http://www.auditoryverbaltraining.com/ha-ci.htm
7. Mahalik, N. P. (2007). MEMS. New Delhi: Tata McGraw-Hill Pub.
8. Li Y, Grosh K. Direction of wave propagation in the cochlea for internally excited basilar membrane. J Acoust Soc Am. 2012 Jun;131(6):4710-21. doi: 10.1121/1.4707505.
9. S. Liu, D.A. Gauthier, E. Mandelup, R.D. White, Experimental investigation of a hydromechanical scale model of the gerbil cochlea, ASME International Mechanical Engineering Congress and Exposition. 11 (2009) 277.
10. Michael J. Wittbrodt, Charles R. Steele, Sunil Puria; Developing a Physical Model of the Human Cochlea Using Microfabrication Methods. Audiol Neurotol 1 January 2006; 11 (2): 104–112. https://doi.org/10.1159/000090683
11. R.D. White, K. Grosh, Proceedings of the National Academy of Sciences of the United States of America", pp.1296-1301, 2005.
12. Bachman M, Zeng FG, Xu T, Li GP. Micromechanical resonator array for an implantable bionic ear. Audiology and Neurotology. 2006;11(2):95-103. https://doi.org/10.1159/000090682
13. N.S. Lawand, W. Ngamkham, G. Nazarian, P.J. French, W.A. Serdijn, G.N. Gaydadjiev, J.J. Briaire, J. H. M. Frijns, 35th Annual International Conference of the IEEE EMBS, pp.5163-5166, Jul 2013
14. Guy Rebillard (n.d.). Voyage au centre de l'audition - Spécialites | Cochlea. Retrieved march 28, 2023, from http://www.cochlea.eu
15. Lyshevski, S. E. (2007). Mems and Nems: Systems, devices and structures. Boca Raton: CRC press.

16. B. Choubey, S. Collins and M. Ward, "On Characterizing Microelectromechanical Processes Using Coupled Resonators," in Journal of Microelectromechanical Systems, vol. 21, no. 4, pp. 791-800, Aug. 2012, doi: 10.1109/JMEMS.2012.2190821 .
17. M. J. Kobrinsky, E. R. Deutsch and S. D. Senturia, "Effect of support compliance and residual stress on the shape of doubly supported surface-micromachined beams," in Journal of Microelectromechanical Systems, vol. 9, no. 3, pp. 361-369, Sept. 2000, doi: 10.1109/84.870062.