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Design of Gold based MEMS Acoustic Direction Finding Sensor for Small Arms Fire and its Analysis

Syed Osama Bin Islam
National University of Sciences and Technology, Islamabad, Pakistan

Abstract— **Acoustic sensors based on MEMS technology is an emerging area of research. Harmonic analysis of these devices is seen to be deliberated recently. The response of a microstructure when subjected to acoustic waves depends upon its geometric properties as well as its material properties; therefore it is important to understand these properties at this level, generally referred to as Meso scale properties. This paper presents the design and modeling of MEMS acoustic sensor optimized for detecting direction of sound at particular frequency range related to small arms fire. Design and FEM modeling is carried out using gold based process design rules. The sensor is modeled with a structural layer of gold with 4.8 µm thickness. The sensor plates' deflection amplitude varies when the applied pressure and angle of incidence is changed. Moreover, the stresses induced in the sensor, corresponding to the gunshot fire are analyzed to ascertain the fatigue effects.**

Keywords— Acoustic Sensor, MEMS, PTM, FEM, Yield Strength .

I. Introduction

Micro Electro Mechanical System (MEMS) devices are famous due to their reduced size and low power consumption. The applications include both sensors and actuators and a large facet of these devices are in military usage. Acoustic sensor for sound source detection is one particular area of application that can be used to detect large and small weapons fire [1]. Other applications of the MEMs acoustic sensors vary from medical applications to industrial and commercial applications [2]. An emerging area of research is the sensors imitating the hearing system of Ormia Ochracea. It is a fly commonly found in Mexico and southern parts of United States that has unique ability to locate the chirping sound of crickets. The parasitic fly has destroyed huge population of crickets in Hawaii while laying eggs on crickets [3]. The reproductive cycle of the fly relies on locating crickets which is essential for its existence [4]. This whole phenomenon took place at dawn or dusk when the visibility is low and fly particularly relies on its hearing system [5].

The fly has two ears which are called prosternal tympanic membranes (PTMs). These PTMs transfer the energy of sound incident on them to sensory organs called bulbae acusticae. There is a rod like growth that connects the pair of PTMs called apodeme, generally termed as intertympanal bridge. The behavior of the whole structure is like a see saw when the sound wave interacts at an angle to the normal from the PTMs surface. The PTM that first interacts with the sound wave is called (ipsilateral) and the one that interacts later is called (contralateral). However when the source is normal to both PTMs the behavior of both the ears is symmetric. In both the cases a bending motion is produced along the intertympanal bridge which is fixed at the center. The difference in amplitude of both ears stimulates different levels in sensory organs which enables the fly to locate the direction of cricket. The complete structure has two natural modes of vibration. The first mode in which the two ears because of minute pressure difference moves out of phase is called rocking mode. The second mode called the bending mode in which both the ears move in phase and a pure bending motion is produced among the inter-tympanal bridge. The amplitude of the ears has cosine angle dependence of the sound wave i.e. their amplitude varies as the incidence angle of sound wave is varied [6].

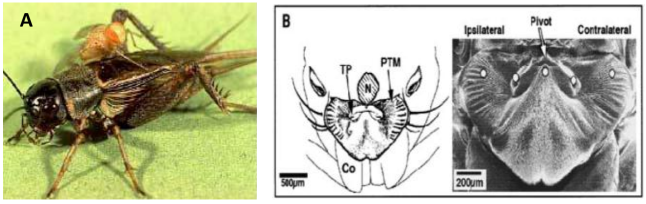

Fig. 1. A. Ormia Ochracea locating Cricket B. External Anatomy of Ears

Similar behavior is observed in pressure gradient microphones, which are also referred as "velocity microphones". This is due to variation in output displacement of two wings that in effect is proportional to the pressure produced by air particle velocity. A MEMs based pressure gradient microphone modeled in silicon was presented in [7]. The time delay between the two ears was investigated in [8] when the sound wave produced by gunshot was incident at certain angle, which causes the structure to rock. The time response was estimated for both ears by using a 2 DoF model and directional sensitivity was calculated by varying incident sound angle that came out to be 1.3µs/deg. The directional sensitivity was found comparatively larger than conventional microphone whose sensitivity is 0.06µs/deg. Also low deflection in the ears was observed in comparison to direct exposure to sound wave. In [9] it was found that coupling between the two ears increases the amplitude difference and the time response

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Syed Osama Bin Islam*(Author)*
National University of Sciences and Technology
Pakistan

amongst them. It was also found that coupling enhances the accuracy to estimate the direction of arrival of sound wave. A SOIMUMPs process based MEMS acoustic sensor was designed in [10] and was optimized for directional sensitivity. It was revealed that the coupling (intertympanal bridge) strength affect the directional sensitivity of the sensor. However the response is still not comparable with the one at 0 degree incident angle and bending mode. A SOIMUMPs process based sensor along with interdigitated comb fingers were designed in [11] still confirms the cosine dependence on incident sound. A PiezoMUMPs process based sensor was designed in [12] and sensitivity of the device was ascertained that came out to be 3.8nV/Pa. The modal, displacement and stress analysis were also performed. A SOIMUMPS based sensor with comb fingers was designed in [13] and the cosine angle dependence was verified. The sensor was primarily operated at its bending mode frequency to acquire maximum displacement amplitude. A pair of sensors is placed at canted angle to remove the direction ambiguity formed by cosine dependence through cumulative effects of both sensors. The sensitivity was found to be 25V/Pa.

When a bullet is fired from a muzzle the shock wave generated and the acoustic energy emanating are collectively called the muzzle blast. This blast energy travels in all directions and lasts for a maximum of 3 milliseconds; however the major portion propagates in the direction where the muzzle is pointing [14]. A simple microphone record this muzzle blast as a primary acoustic signal which spans over a range of frequencies emanated from explosion, shock wave, hissing and reflection. These frequency ranges can be segregated through the use of Fast Fourier Transform (FFT) techniques processed from high-speed computer systems. Larger caliber weapons are found to have higher magnitude at lower frequencies and smaller caliber weapons have higher magnitudes at higher frequencies. Acoustical characterization of five small arms was carried out in [15] to determine the most suitable as impulse sources. The 0.38 caliber was found most suitable and the peak frequency was found to be around 900 Hz. Acoustic characterization of gun fires was carried out in [16] to study the attenuation from hearing protectors. The study of the spectral content revealed that for small-calibers (rifles) the main part of acoustic energy lies between 150-2,500 Hz and peak (900-1,500 Hz) whereas for large-calibers it lies below 400 Hz and peak (16-100 Hz). Analysis of a 9mm gun through Force Fourier transform was carried out in [17]. The maximum amplitude was found for the frequencies ranging between 800 Hz to 1000 Hz. Lower magnitudes were observed at lower frequencies and higher magnitudes were observed at higher frequencies.

The main objectives of this work are:

- To design MEMS based sound direction finding sensor for detection of small arms fire.
- To optimize the design for a particular frequency range using design rules of gold based process.
- To ascertain the fatigue of the device by analyzing the stresses induced in device corresponding to the small arms fire.

II. Design of Proposed MEMS Acoustic Sensor

A MEMS based sensor is designed for small caliber weapons fire detection of frequency range (800-1000Hz). The structure is optimized for this particular frequency range through its structural dimensions following the design rules of FBK (gold based) process in SolidWorks software. The prototype is then imported to ANSYS for its modal analysis. Rocking and bending modes of the structure are ascertained. Subsequently modal superposition method is used in multiphysiscs to perform harmonic and stress analysis, wherein inputs of pressure and incident angle of acoustic waves were given. Pressure input was given for a maximum range of 200 mPa as evaluated from gunshots characterization from [14]. Damping parameters are considered by putting in values of damping ratio, alpha and beta coefficients of damping. Damping ratio is calculated through the structure dimensions as proposed in [18]. Alpha coefficient of damping is calculated as proposed in [19] and beta coefficient is calculated automatically through ANSYS by using “Frequency vs Damping” method. Validation of the results of SOIMUMPS based acoustic sensor from [13] are carried out and compared with ones obtained from the gold based design. The response of fabricated design is proposed to be sensed with parallel plate capacitance using MS3100 chip that will eliminate the requirement of additional mass of comb fingers.

A. *Prototype Design*

Designed MEMS acoustic sensor following gold based process rules is shown in figure 2. The plates mimicking the PTMs of fly are clamped by an interlinked bridge similar to inter-tympanal bridge, which in turn clamped from the center by a small torsional bridge. The bridges can be considered as four beams two under torsion and two under bending, when pressure is applied on plates. The deflection of the plates will be in accordance to sound pressure basing on particular incident angle falling on them.

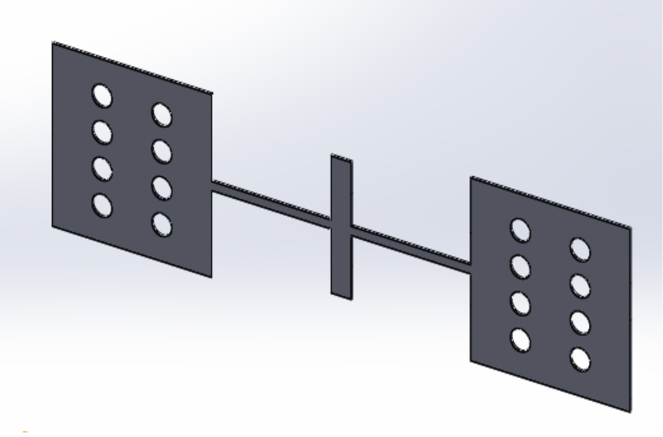

Fig. 2. Prototype designed in solid works

The pair of plates are symmetric in shape both having dimensions of 400 × 400 μm^2. Each plate is incorporated with eight etch holes of 50 µm diameter. The beams under bending attached with each plate have a length of 300 µm and width of 20 µm. Thickness of the complete structure is 4.8 µm as per the design rules of gold based process, whereas minimum feature size is kept 8µm. Fixed-free beam configuration can be seen for these two beams. The central two beams which are in torsion are of length 140 µm and width 50 µm. Young's modulus for the structure is kept 98.5×10^3 MPa, Poison ratio 0.42 and density is kept 19.32×10^{-15} kg/μm^3 (19320 kg/m^3).

B. *Mathematical Formulation*

The displacement in beam is related to the force acting at some point and the spring constant of the beam. The bending stiffness *K* of a flexible pivot with a constant rectangular section without tensile load is expressed as:

$$K = \frac{CEI}{L^3} \tag{1}$$

where *I* is moment of inertia,

$$I = \frac{wt^3}{12} \tag{2}$$

The resonant frequency of the structure can be found from the equation.

$$w = \sqrt{\frac{K}{m}} \tag{3}$$

where,
w = Width of the flexible pivot
t = Thickness of the beam
E = Young's Modulus of Nickel
I = Moment of Inertia
L= Length of beam
C is a constant determined by the end to end configuration
m = Mass of the wings

III. FEM Analysis of the MEMS Acoustic Sensor

Modal analysis of the structure was carried out followed by structural and harmonic analysis. Details are covered as under:

A. *Modal Analysis*

Modal analysis of the designed structure is carried out for six frequency responses as shown in Table I.

TABLE I
MODAL ANALYSIS IN ANSYS

Serial	Mode	Frequency
1	1	779.09
2	2	851.92
3	3	2978.4
4	4	3018.3
5	5	3447.8
6	6	3477.8

Deformation of the structure at first mode of resonant frequency appears as reflected in Fig. 3. This type of response is also referred as rocking mode.

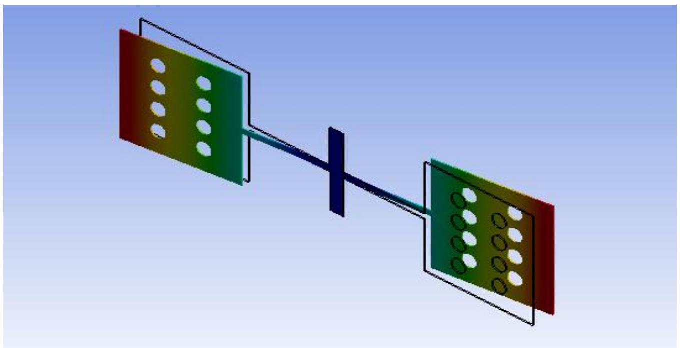

Fig. 3. 1st mode Frequency response (Rocking mode – 779.09 Hz)

Deformation of the structure at second mode of frequency appears to be as shown in Fig. 4. This type of response is referred as bending mode.

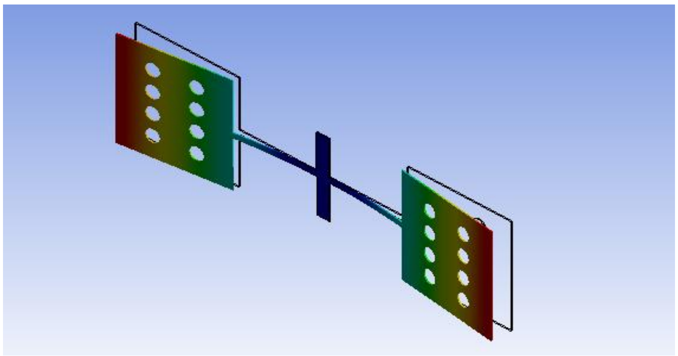

Fig. 4. 2nd mode Frequency response (Bending mode – 851.92 Hz)

B. *Structural Analysis*

By varying the sound pressure on the plates the response of a sensor is calculated as shown in Fig. 5. To draw maximum output incident sound angle is considered normal to the sensor wings (θ = 0°). The data in the figure shows that the sound pressure has linear relationship with response. Damping and resonant frequency of sound are not considered during the analysis. The slope of the line gives sensitivity of about 527.14 nm /Pa.

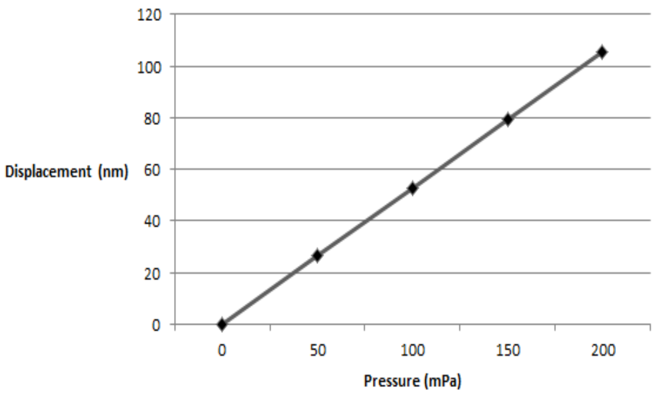

Fig. 5. Displacement against applied Pressure without Resonant Frequency and Damping

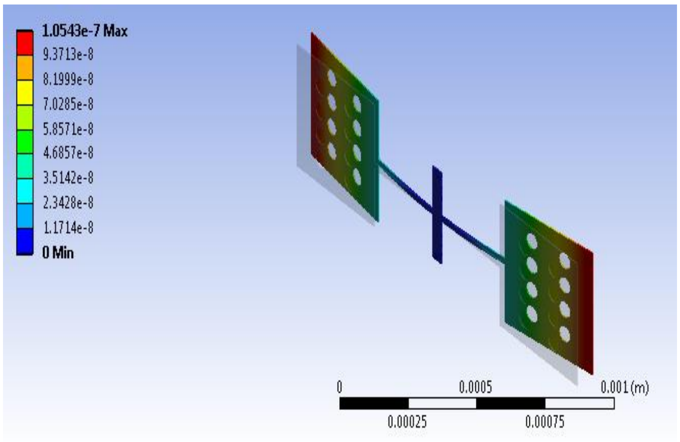

Fig. 6. Sensor Response corresponding to Pressure without Resonant Frequency and Damping

C. *Harmonic Analysis*

Input of sound frequency was given during the analysis i.e. 851.92 Hz (bending resonant frequency of the structure) which in actual is dependent on the mass of the wings and dimensions of the bridge in the middle. Without damping at bending resonant frequency huge deformation in comparison to deformation without resonant frequency is observed and the sensitivity came out to be 172.19 mm/Pa. Input of damping parametrs were given; Damping ratio calculated from the mathematical formulae as 14.991 and alpha coefficient as 2.381×10^{-3}, whereas beta coefficient is calculated automatically by ANSYS through “Damping vs Frequency” option. Again the response of a sensor is calculated by varying sound pressure using sound incident angle normal to the sensor wings ($\theta = 0°$) for the maximum output, as shown in Fig. 7. The response of the sensor has reduced due to incorporation of damping parameters. The data in the figure again shows that the sound pressure has linear relationship with the response. The slope of the line gives sensitivity of about 16.76 nm /Pa. Considering the same damping technique, the displacement sensitivity for the SOIMUMPs based design [13] was calculated which came out to be 0.158 nm/Pa at the structure’s bending mode.

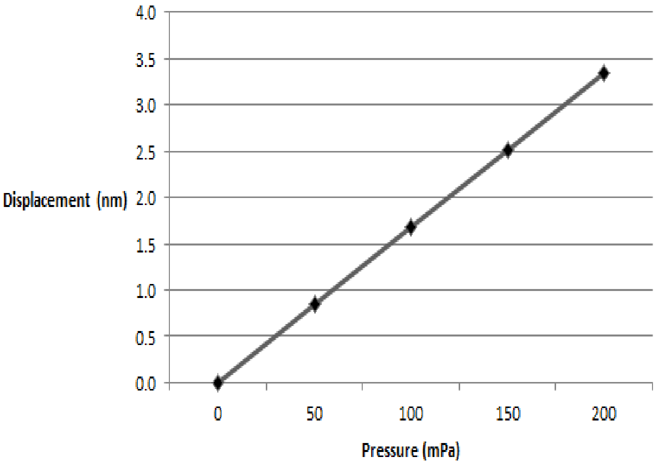

Fig. 7. Displacement against Pressure with Bending Resonant Frequency and Damping

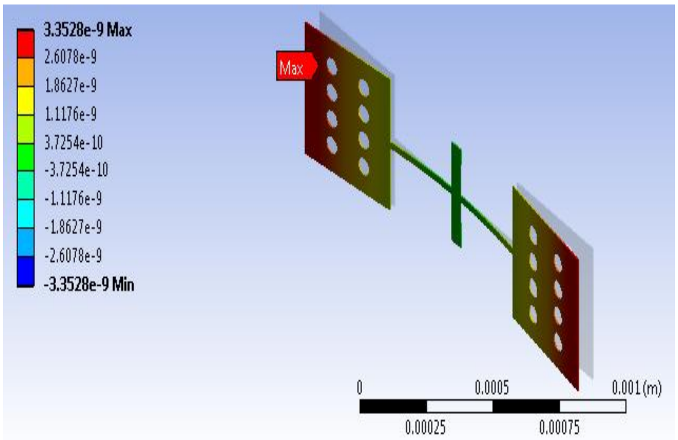

Fig. 8. Sensor Response corresponding to Pressure with Resonant Frequency and Damping

D. *Response against Incident Angle*

The angle of incident sound was varied for 200 mPa and an angle ambiguity can be seen mirrored about incident angle 0. This angle ambiguity is proposed to be removed by placing two sensors at canted angle as was suggested in [13].

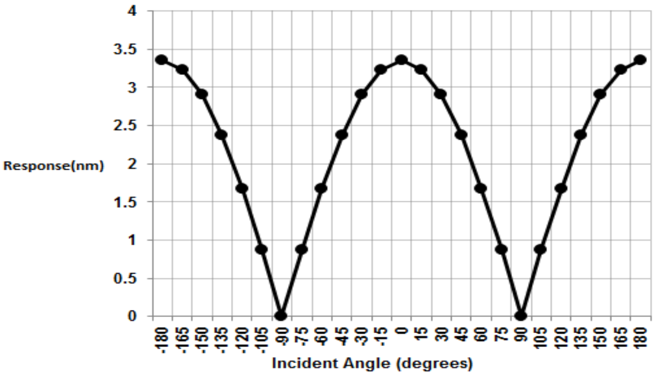

Fig. 9. Displacement with respect to change in Incident Angle

E. *Stress Analysis*

The stress analysis is carried out for peak pressure at the bending frequency. The maximum stresses are concentrated at the center of the structure where there is a junction of torsional and bending beams. The stresses are well below the yield stress of gold structure (70-220 MPa) as indicated in [20]. The maximum von-Mises stress value came out to be 5953.7 Pa as seen in Fig. 10. It is to mention that inclusion of damping greatly reduce the stress levels in device which otherwise have crossed the yield stress.

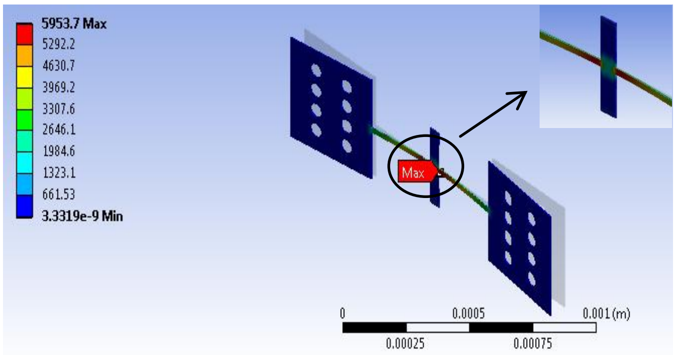

Fig. 10. Stress Analysis for Harmonic Response

F. Comparison

The designed structure is compared with the design presented in [13] made from SOIMUMPs process along with comb fingers for sensing. The comparison includes design specifications, resonant frequencies, sensitivity and damping ratio as shown in Table II. Additional mass of comb fingers for SOIMUMPs design is considered during calculations. The sensitivity of the proposed sensor can be seen to have improved when modeled using design specifications of the gold based process, even though the dimensions of the structure has reduced. As parallel plate capacitance is recommended the additional mass required for comb fingers is also reduced. Damping ratio of SOIMUMPs design is greater than proposed design due to larger plate size.

TABLE II
COMPARISON OF DESIGNED STRUCTURE WITH SOIMUMPS DESIGN

	SOIMUMPs Design	Gold Design
Bridge length (μm)	800	650
Bridge width (μm)	30	20
Bridge thickness (μm)	25	4.8
Plate length (μm)	1200	400
Plate width (μm)	1200	400
Plate thickness (μm)	25	4.8
Support length (μm)	880	300
Support width (μm)	30	50
Support thickness (μm)	20	4.8
Sensitivity (nm/Pa)	0.158	16.76
Rocking mode Frequency(Hz)	1019.5	779.09
Bending mode Frequency(Hz)	1690	851.92
Damping Ratio	370.6	14.991
Overall Size (μm)	3200	1450

IV. Conclusion

MEMS based direction finding acoustic sensor is popular area of research due to its reduced size, accuracy and low power consumption. Choosing best material and geometric properties is essential for reliability and optimized output. Continuous exposure to vibrations subject the material to fatigue effects, hence stress analysis of the device is also essential. A micro sensor was designed for direction finding of small arms fire. The sensor was designed using gold based process and compared with the output of sensor made from SOIMUMPs fabrication process. The designed sensor has more displacement sensitivity i.e. 16.76 nm/Pa than the SOIMUMPs sensor i.e. 0.158 nm/Pa. Damping ratio of the structure is less due to reduced dimension. Stress analysis revealed that stress level is quite below the yield stress. It was also revealed that the sensitivity increases when structure is subjected to bending mode and when the strength of coupling is reduced.

References

[1] Nance D., Ahuja K. K. Kaushik B., "A Review of the Role of Acoustic Sensors in the Modern Battlefield," in 11th AIAA/CEAS Aeroacoustics Conference , Monterey, CA, USA, 23–25 May 2005.

[2] N. Islam and A. N. Nordin I. Voiculescu, *Acoustic Wave Based MEMS Devices, Development and Applications in Microelectromechanical Systems and Devices*., 2012.

[3] Understanding Evolution. [Online]. http://evolution.berkeley.edu/evolibrary/news/061201_quietcrickets

[4] W. Cade, "Acoustically orienting parasitoids: fly phontaxis to cricket song," in Science, vol. 190., 1975, pp. 1313–1313.

[5] Cornell Chronicle. [Online]. http://www.news.cornell.edu/chronicle/01/4.19.01/fly-hearing.html.

[6] R.N. Miles, D. Robert, and R.R. Hoy. “Mechanically coupled ears for directional hearing in the parasitoid fly Ormia Ochracea.” The Journal of the Acoustical Society of America vol. 98 pp. 3059–3070, December 1995.

[7] M. L. & Hall, N. A. Kuntzman, "Sound source localization inspired by the ears of the Ormia ochracea," Appl. Phys. Lett. 105, 033701, 2014

[8] Luke Currano, Danny Gee, Benjamin Yang, and Miao Yu Haijun Liu, "Fly-ear inspired acoustic sensors for gunshot localization," Proc. of SPIE, vol. 7321,73210A-1, 2009.

[9] Murat Akcakaya and Arye Nehorai, "Performance analysis of the Ormia ochracea’s coupled ears," Acoustical Society of America, pp. 2100–2105, 2008.

[10] Deepak Uttamchandani and Andrew Reid James F.C. Windmill, "James F.C. Windmill, Deepak UttaBio-inspired sound localization sensor with high directional," EUROSENSORS, 2015.

[11] M. Touse, J. Sinibaldi, K. Simsek, J. Catterlin, S. Harrison, and G. Karunasiri, “Fabrication of a microelectro mechanical directional sound sensor with electronic readout using comb fingers,” Appl. Phys. Lett. 96, 173701, 2010.

[12] Rudresh. KJ, Veda Sandeep Nagaraja and Dr. SL Pinjare Nithya. G., "Design And Simulation of a Novel MEMS Acoustic Sensor," in COMSOL Conference in Bangalore, 2016.

[13] Fabio Alves & Gamani Karunasiri Daniel Wilmott, "Bio-Inspired Miniature Direction Finding Acoustic Sensor," Nature, Scientific Reports, 2016.

[14] Maher, R.C., “Acoustical characterization of gunshots” IEEE Workshop on Signal Processing Applications for Public Security and Forensics, Washington D.C., 109-113, 2007.

[15] M. J. R. Lamothe and J. S. Bradley, "Acoustical characteristics of guns as impulse sources," in *Can. Acoust. 13*, 1985, pp. 16-24.

[16] Ylikoski M, Pekkarinen JO, Strack JP, Paakkinen RJ and Ylikoski JS. “Physical characteristics of gunfire impulse noise and its attenuation by hearing protectors” in Scand Audiol 24, 1995, pp. 3-11.

[17] Gun sound -- frequency analysis. [Online]. https://www.physicsforums.com/threads/gun-sound-frequency-analysis.898882/

[18] Adi Minikes, Izhak Bucher and Gal Avivi, “Damping of a micro-resonator torsion mirror in rarefied gas ambient”, Journal of Micromechanics and Microengineering, 2005.

[19] Giorgio De Pasquale, Timo Veijola and Aurelio Som`a, “Modelling and validation of air damping in perforated gold and silicon MEMS plates”, Journal of Micromechanics and Microengineering, 2009.

[20] Timpano, Katherine. "Mechanical characterization of gold thin films for RF-MEMS." Proc. Virginia Space Grant Consortium Student Research Conf. 2005.

About Author :

The author is from faculty of Mechatronics Engineering, National University of Sciences and Technology, Pakistan.