Modeling of Microelectromechanical Systems Diaphragm Based Acoustic Sensor

Vasudha Hegde, Narendra Chaulagain, H. M. Ravikumar, Sonu Mishra, Siva Yellampalli

Abstract—Acoustic sensors are extensively used in recent days not only for sensing and condition monitoring applications but also for small scale energy harvesting applications to power wireless sensor networks (WSN) due to their inherent advantages. The natural frequency of the structure plays a major role in energy harvesting applications since the sensor key element has to operate at resonant frequency. In this paper, circular diaphragm based MEMS acoustic sensor is modelled by Lumped Element Model (LEM) and the natural frequency is compared with the simulated model using Finite Element Method (FEM) tool COMSOL Multiphysics. The sensor has the circular diaphragm of 3000 μm radius and thickness of 30 μm to withstand the high SPL (Sound Pressure Level) and also to withstand the various fabrication steps. A Piezoelectric ZnO layer of thickness of 1 μm sandwiched between two aluminium electrodes of thickness 0.5 μm and is coated on the diaphragm. Further, a channel with radius 3000 μm and length 270 μm is connected at the bottom of the diaphragm. The natural frequency of the structure by LEM method is approximately 16.6 kHz which is closely matching with that of simulated structure with suitable approximations.

Keywords—Acoustic sensor, diaphragm based, lumped element modeling, natural frequency, piezoelectric.

I. INTRODUCTION

DUE to continuous advancement of the technology, the power consumed by WSN and electronic devices is dramatically reduced. For example, some of the WSN can be powered at less than 100 μW. Thus, small-scale energy sources which generate energy from ambient sources like vibration, acoustic signal, etc. are becoming popular. However acoustic energy harvesters are gaining importance since they can be integrated with the system making it autonomous and compact or they can be used to charge the batteries. The piezoelectric materials are commonly used in acoustic energy harvesters due to their advantages like ease of processing and scaling, robust design and no air gap like electrostatic acoustic sensors [1].

The main factors on which the energy harvested by piezoelectric acoustic sensors depend are, Young's modulus or modulus of elasticity of the material, Piezoelectric charge coefficient, applied strain, area of the electrodes and capacitance of the structure. Whereas some of the factors depend on the type of the material, the applied strain depends

on the deflection. When the acoustic source frequency matches with the natural frequency of the structure, maximum deflection occurs. Thus, knowledge of natural frequency which is the resonant frequency of the structure by mathematical model and equivalent circuit has been a point of concern for the acoustic sensors used for different acoustic applications. Hence, in this work, LEM of the diaphragm based piezoelectric acoustic sensor with the acoustic equivalent circuit is done to calculate the natural frequency of the structure, and the value obtained is compared with the structure being simulated using COMSOL Multiphysics.

The structure is designed in such a way that it has the key element as the silicon diaphragm upon which the piezoelectric material is sandwiched between two electrodes. The diaphragm has a back etched channel for pressure orientation [2]. The acoustic pressure is applied on the diaphragm coated with piezoelectric material from the top so that the deflection is aided by the gravitational pull. The whole structure has been designed to sustain high SPL and has the natural frequency 10 kHz to 20 kHz suited for industrial environment.

The following assumptions are made according to small deflection theory for the analysis of the diaphragm based structure [3], [4].

- The maximum deflection due to applied load is not more than 30% of the thickness of the diaphragm.
- The diaphragm is of uniform thickness and flat. The pressure applied is perpendicular to the plane of the diaphragm.
- The diaphragm is applied with pressure which caused deflection within the elastic limit and the deflection is due to bending.

II. ACOUSTIC SENSOR MODELING

A. Acoustic Sensor Structure

The approximate model (dimensions not to scale) of the acoustic sensor structure is as shown in Fig. 1. The acoustic sensor has circular diaphragm as key element. The circular diaphragm has been chosen over the other shapes because it gives maximum deflection, maximum strain and stress compared to any other shapes [5].

This structure with a circular diaphragm with radius 3000 μm has a thickness 30 μm and hinged across its periphery. The piezoelectric material ZnO of thickness 1 μm has been positioned on the diaphragm and sandwiched between two aluminium electrodes of thickness 0.5 μm. The piezoelectric material has been placed at the centre of the diaphragm where the compressive strain is more and the aluminium electrodes

Vasudha Hegde is with Department of Electrical and Electronics Engineering, Nitte Meenakshi Institute of Technology, Bangalore, India, (corresponding author, phone: +919880075377; e-mail: vasudha.hegde@nmit.ac.in).

Narendra Chaulagain is Undergraduate Department of Electrical and Electronics Engineering, Nitte Meenakshi Institute of Technology, Bangalore, India (e-mail: naren.chaulagain@gmail.com).

collect the charge generated by piezoelectric material. ZnO has been chosen over the other piezoelectric materials because of scaling and fabrication compatibility. The channel of radius 3000 μm and length 270 μm has been attached at the bottom of the diaphragm.
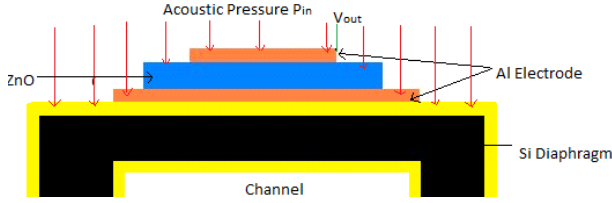

Fig. 1 Structure of the acoustic sensor

B. Lumped Element Modelling

The LEM method gives efficient prediction of the acoustic transducers because the basic requirement of LEM is to have the dimensions of the structure much less than the incident acoustic signal wavelength. The variation of the distributed energy in this case is very less as function of space. Mathematically, for this condition, the spatial and temporal components can be decoupled, allowing the use of ordinary differential equations to solve the problem. Physically, it means that each stored energy or dissipation mechanism can be equated to energy stored or dissipated in an equivalent element that is lumped to a chosen spatial location [6].

The analogy between the acoustic domain and electric domain has been used to represent the system in the form of equivalent RLC model. Table I gives the equivalent lumped models in acoustic and electrical domains. Once the equivalent circuit representation is done the standard analysis techniques like Kirchhoff's laws can be applied to analyze the circuit [7].

TABLE I
EQUIVALENT LUMPED PARAMETERS IN ACOUSTIC AND ELECTRICAL DOMAINS

	Kinetic energy storage	Potential energy storage	Energy dissipation
Acoustical	Acoustic Mass [kg/m^4]	Acoustic Compliance [m^3/Pa]	Acoustic Resistor [m^{4}S]
Electrical	Inductance [H]	Capacitance [F]	Resistance [Ω]

The lumped element equivalent circuit is as shown in Fig. 2. The total acoustic pressure applied on the diaphragm is represented by P_{in}, and the pressure across the other end of the diaphragm is represented by P_d. Since the input pressure is shared between the parameters M_{ad} and C_{ad} (in the form of kinetic energy in mass(M_{ad}) of the diaphragm and in the form of potential energy in acoustic compliance C_{ad}) [6], they are connected in series across the source. For the designed structure, the applied acoustic pressure is assumed to be equal to the pressure applied by the diaphragm in the downward direction since the acoustic resistance (R_{ad}) of the channel is assumed to be negligible. The energy is stored in the acoustic mass (M_{ad}) and the acoustic compliance (C_{ad}) of the diaphragm. The transduction from acoustic energy to electrical energy is majorly due to the energy stored in acoustic mass and acoustic compliance of the diaphragm which converts it

into the deflection. The stress and strain due to the deflection when acting on the piezoelectric material convert it into electric charge. Hence, this transduction is represented in the form of a transduction transformer (n:1 ratio) in the LEM equivalent circuit. The primary side of the transduction transformer has acoustic energy parameters, and secondary side has electrical energy parameters. Further the charge which is stored in the capacitance of the sandwiched piezoelectric material between two electrodes is represented by the capacitance Cp.
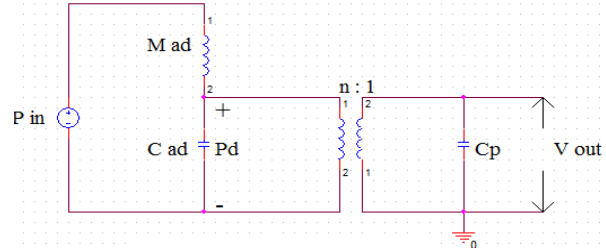

Fig. 2 LEM of acoustic sensor

To get the lumped element representation of the diaphragm, the diaphragm is assumed to be circular plate attached to a piston of mass M_{ad} and acoustic compliance of C_{ad}. Assuming that the acoustic pressure on piston is uniform and the deflection is equal to maximum deflection at the centre, mass of the diaphragm (M_{ad}) and acoustic compliance (C_{ad}) are calculated.

1. Mass of the Diaphragm (M_{ad})

$$M_{ad} = \text{Density x volume } = \rho \times A \times h \qquad (1)$$

where, A-Area of the diaphragm = πr^2 m^2, ρ-Density of the diaphragm=2320 kg/m^3.

$$M_{ad} = 1.967893 \ \mu kg$$

2. Acoustic Compliance of Diaphragm (C_{ad})

The calculation of Acoustic Compliance of Diaphragm (C_{ad}) has the following steps.

a. Effective Diameter

The diaphragm is hinged at the periphery and for a distributed load, the effective diameter is calculated as shown in Fig. 3 and is given by (2).
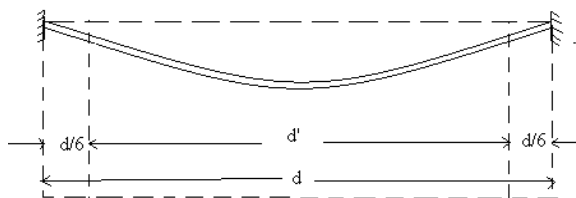

Fig. 3 Effective diameter calculation

From Fig. 3,

$$d' = d - \frac{d}{3} \qquad (2)$$

where, d' - the effective diameter in m, d- the actual diameter of the diaphragm in m, Effective diameter (d')=4000 μm.

b. Moment of Inertia (I)

Moment of inertia of the diaphragm is calculated using (3)

$$I = \frac{1}{2} M_{ad}(r')^2 \qquad (3)$$

where, M_{ad}- Mass of the diaphragm in Kg, r'- Effective radius in m.

$$I = 3.957 \text{ kg.m}^2$$

c. Flexural Rigidity (D)

The flexural rigidity is calculated using (4)

$$D = E \times I \qquad (4)$$

where, E-Young's modulus of elasticity for silicon=160x 10^9 Pa. I-Moment of inertia in kg.m^2.

$$D = 0.6297 \text{ Nkg}$$

Thus, acoustic compliance of the diaphragm, C_{ad} is given by (5)

$$C_{ad} = \frac{A}{D} \qquad (5)$$

where, A- Area of the diaphragm in m^2, D-Flexural rigidity in Nkg.

3. Natural Frequency of the Structure

The natural frequency at which the structure resonates is given by the expression (6).

$$f_o = \frac{1}{2\pi\sqrt{M_{ad}C_{ad}}} \qquad (6)$$

$$f_o = 16.93 \text{ kHz}$$

From Fig. 2, it is clear that the diaphragm with piezoelectric coating is acting like a mode of converting acoustic energy in to electrical energy. The equivalent circuit representation depicts this transduction between two domains, i.e. acoustic and electric as a transformer having turns ratio 'n'.

4. Voltage Generated(Vout)

In order to calculate the voltage generated in the piezoelectric material, the following steps are carried out.

a. Capacitance of the Piezoelectric and Electrodes Structure(C_p)

The capacitance of the sandwitched piezoelectric layer, ZnO of 1 μm with aluminum electrodes of thickness 0.5 μm. The capacitance of the sandwitched piezoelectric layer is represented by C_p and is given by (7)

$$C_p = \frac{\varepsilon_o \varepsilon_{ZnO} A_e}{t_{ZnO}} \qquad (7)$$

where, A_e-Area of electrodes (both electrodes are assumed to be equal=πr^2 m^2), ε_{ZnO}-Dielectric constant of ZnO layer=

8.5446, t_{ZnO}-Thickness of ZnO layer.

Assuming the radius of electrode 1800 μm and thickness of the electrode as 0.5μm

$$C_p = 86.973 \text{ farads}$$

b. Turns Ratio of the Transduction Transformer (n)

The number of turns in the transduction transformer refers to the part of the acoustic energy getting converted in to electrical energy as in (8)

$$n = \frac{d_a}{C_{ad}} \qquad (8)$$

where, d_a -effective piezoelectric coefficient (d_{33}) (Assume d_a =0.81 cm^{-2}), C_{ad}-Acoustic compliance of the diaphragm.

$$n = 18040$$

Thus, the voltage generated (V_{out})is calculated by (9)

$$V_{out} = \frac{P_d}{n} \qquad (9)$$

where, P_d-Input acoustic pressure on the diaphragm Assume P_d=1Nm^{-2}.

$$V_{out} = 55.43 \mu V$$

C. Simulation

The simulation of the proposed structure is done using COMSOL Multiphysics tool. The physics considered for the acoustic sensor structure analysis is Solid Mechanics subpart of Structural Mechanics and the study used for deflection and natural frequency calculations are stationary study and eigenfrequency, respectively. The results are approximately matching with that of LEM model.

Eigenfrequency=13786.317167
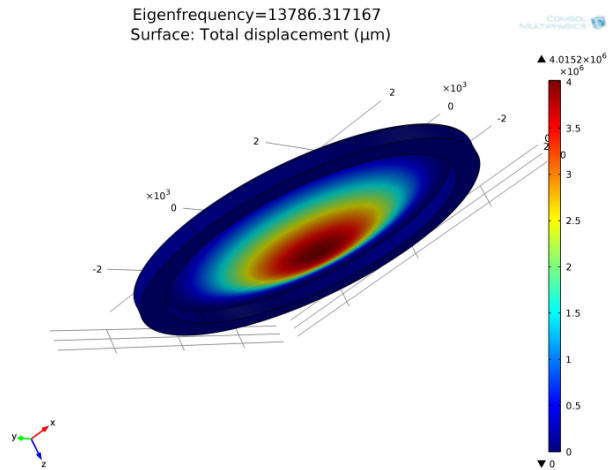Surface: Total displacement (μm)

Fig. 4 Simulated model of the acoustic sensor

The FEM techniques in tools like COMSOL, ANSYS predict the system behavior through a numerical approach. The results produced can precisely follow the physical system. However, the physical insight is limited. The results depend on

the numerical mesh and convergence of the iterative calculations. The scaling behavior of the structure is difficult to estimate which puts a critical design issue in fabrication using micromachining technology [6].

The proposed model which is simulated is as shown in Fig. 4 and the natural frequency by FEM technique is 13.78 kHz. The voltage generated during this is also in close approximations with the simulated structure [5] using piezoelectric devices (pzd) and is of the order 85 μV.

While simulating the structure design, the aluminum electrodes of very small thickness (0.5 μm) are not considered due to meshing and convergence limitation and also the thickness of the piezoelectric material is restricted to 1 μm due to limitations in fabrication.

III. CONCLUSION

The proposed acoustic sensor with circular diaphragm as key element and the ZnO piezoelectric material for voltage generation is simple and the fabrication requirements are met. The design is suited for acoustic applications from the point of view of natural frequency and SPL of the acoustic signal. The results obtained by the LEM method and FEM are in good agreement. The slight disparity in natural frequency and voltage is justified from the approximations considered in the calculations and simulation.

ACKNOWLEDGMENT

REFERENCES

[1] Liew Hui Fang et.al, ''A Review of Techniques Design Acoustic Energy Harvesting'', 2015 IEEE Student Conference on Research and Development (SCOReD); DOI: 978-1-4673-9572-4/15, 2015 IEEE.

[2] Sherif Saleh Ahmad et.al, Electronics Research Institute, Cairo, Egypt, CEERI, Pilani, India, "Design and Fabrication of Piezoelectric Acoustic Sensor", Proceedings of the 5th WSEAS Int. Conf. on Microelectronics, Nanoelectronics, Optoelectronics, Prague, Czech Republic, 2006 (pp92-96).

[3] K. Y. Madhavi, et.al., "Diaphragm Design for MEMS Pressure Sensors using a Data Mining Tool", Proceedings of the World Congress on Engineering 2011 Vol II, WCE 2011, July 6 - 8, 2011, London, U.K.

[4] Design Considerations for Diaphragm Pressure Transducers, Strain gauges and instruments, Tech Note TN-510-1, Micro –Measurements.

[5] Vasudha Hegde et.al "Piezoelectric acoustic pressure sensor diaphragm design for energy harvesting", International Conference on Advances in Energy Conversion Technologies (ICAECT), 2014, 23-25 Jan. 2014, Manipal, DOI:10.1109/ICAECT.2014.6757055.

[6] Stephen Brian Horowitz, 'Development Of A Mems-Based Acoustic Energy Harvester' Doctoral Thesis, graduate school of the University of Florida. (2005).

[7] D.S Arya et.al, 'Design And Modeling Of A Zno –Based MEMS Acoustic Sensor For Aero Acoustic And Audio Applications' ,Second international symposium on Physics and Technology of Sensors, Pune 2015.