IOSR Journal of Electronics and Communication Engineering (IOSR-JECE)
e-ISSN: 2278-2834,p-ISSN: 2278-8735
PP 15-20
www.iosrjournals.org

Efficient Low Frequency, Low Power Electromagnetically Actuated Acoustic Microspeaker for Hearing Aid Applications

Gaurav Singh[1], Shadeeda Shahin[2], A.Vimala Juliet[3]
[a]*Instrumentation and Control Department, SRM University,Kattankulathur,Chennai-603203-India*

Abstract: *A Low-Power Electromagnetically Actuated microspeaker is a MEMS device that finds its use mostly in hearing aid applications. It is fabricated on a silicon base that holds the NdFeB hard magnet at the center that produces a strong vertical Magnetic Field and an Inductive copper coil just above it. A Lorentz force comes into play by the two vertical components namely: External Magnetic Field and Electric Current of the coil which will produce vertical actuation in the membrane placed above it. This movement will generate waves of damped vibrations that will finally produce sound and hit the eardrum. A Polydimethylsiloxane (PDMS) membrane is used in order to obtain a greater Sound Pressure Level (SPL) at low frequency as it exhibits the property of maximum flexibility and minimum Young's modulus. A NiFe soft magnet is used to focus the entire magnetic field which surrounds the structure within a desired arena. The coil position and copper feedthrough has a great effect on the flexibility of the membrane, as a result it affects the SPL and makes a huge shift to a higher frequency range which is not needed. Without taking feedthrough effect into account and on placing the coil right at the center of the membrane we will achieve a better response of SPL at low frequency, whereas placing the coil close to the border of the membrane we obtain better response at low frequency with feedthrough effect. Thus, on reviewing a number of microspeaker systems, based on different parameters , we can say that a system consuming 1.76mW and 3.3µm thick membrane, with an operational frequency of 1KHz and 106 dB of SPL designed on a silicon substrate along with a strong permanent magnet and a multi turned coil placed above it, held by a very soft 'PDMS' membrane and surrounded by circular soft magnet is observed to be most efficient one.*
Keywords: *MEMS device, Microspeaker, Coil placement, Copper feedthrough.*

I. Introduction

About 360 million people throughout the world are suffering from hearing loss. Hearing loss may result from genetic causes, complications at birth, certain infectious diseases, exposure to excessive noise and ageing.People with hearing loss can benefit from hearing aids, cochlear implants and other assistive devices, captioning and sign language, and other forms of educational and social support.Untreated hearing loss can cause embarrassment, social stress, tension, and fatigue. This is true not only for the person with hearing loss but also for family members, friends, and colleagues. They recognize what their face in the mirror is telling them. What prevents them from wearing a hearing aid is that it represents a change. It means learning and adapting to something different,in this case, how to use and insert a miniature but sophisticated electronic device. Change isthe keyword. Recently researchers have developed a miniaturised version of hearing aid which can be inserted completely into the ear cannel placed just near the eardrum called the 'completely in canal (CIC)' hearing aid. These hearing aids are a great option for those with mild to moderate-severe hearing loss who are looking for a discreet hearing aid solution. Depending on the size and shape of the ear, a 'CIC' hearing aid can fit deep inside the ear canal, making it almost invisible. This paper will focus on one of the element of the hearing aid called the speaker. A conventional speaker's function is fairly simple. It converts electrical signals into acoustic energy. By moving back and forth, the speaker increases and decreases the air pressure in front of it thus creating sound waves. In order to translate an electrical signal into an audible sound, speakers contain an electromagnet: a metal coil which creates a magnetic field when an electric current flows through it. This coil behaves much like a normal permanent magnet, with one particularly handy property: reversing the direction of the current in the coil which flips the poles of the magnet.Inside a speaker, an electromagnet is placed in front of a permanent magnet. The permanent magnet is fixed firmly into position whereas the electromagnet is mobile. As pulses of electricity pass through the coil of the electromagnet, the direction of its magnetic field rapidly changes. This means that it is in turn attracted to and repelled from the permanent magnet, vibrating back and forth. The electromagnet is attached to a flexible material such as a soft membrane or plastic which amplifies these vibrations, pumping sound waves towards our ears. But the conventional speaker operates at a high frequency level and consuming high amount of power. This paper will focus on the advancements made so far and coming up with a micro scale device for serving such an application which holds the most efficient, low frequency and power effective mode of operation thatinvolves the Micromachining Technology. There are different transduction principles for sound production such as piezoelectric, electrostatic, electrostrictive, electrodynamic, thermoacoustic and magnetic reluctance. As far as our work is concerned, neither piezoelectric actuation nor electrostatic actuation satisfies because of nonlinearities and need for high driving voltage. Whereas Magnetic Reluctance actuation requires least input power and shows an increased curve of performance butit has a very difficult manufacturing process and involves high cost. Thus, the electrodynamic actuation principle meets the objective as it possesses a linear response and a characteristic of sound reproduction thereby producing high 'sound pressure level (SPL)'. In this type of actuation the Lorentz force and the driving force are produced due to the interaction between inductive coil driven by the electrical current and the radical component of magnetic field felt by the coil which is best explained by (1):

$$F = \sum_{i=1}^{N} I \cdot 2\pi \cdot R_i \cdot B_r(R_i) \quad (1)$$

Where F is the Lorentz force, I is current flowing through the coil, R_i the radius of each turn and B_r is the radial component of magnetic field in the coil plane [1].

II. Different designs and configuration

A microspeaker is designed on a silicon base which holds a hard magnet that produces a strong vertical magnetic field and coil above it. A vertical actuation is produced in a flexible membrane due to the effect of Lorentz force. A soft magnet is used to confine the fields to the structure so that it doesn't deflect or escape. Thus air vibrations are created to produce sound. But based on the efficient, reliable, low power and low frequency operations we consider different designs of the microspeaker to pick out the best of it. One of the most important features that help in the generation of high 'SPL' is the membrane elasticity. More the rigidity of the membrane lesser is the 'SPL' produced. A characteristic manner in which a system does not dissipate energy and whose motions are restricted by boundary conditions can oscillate by having a characteristic pattern of motion and one of a discrete set of frequencies. This is known as mode of vibration. Here we are concerned with two major modes of vibration, namely: Drum mode and Piston mode. When vibrating in drum mode the membrane acts much like a monopole source, which radiates sound very effectively. Since it radiates sound so well when vibrating in this manner, the membrane quickly transfers its vibrational energy into radiated sound energy and the vibration dies away. The short duration of the mode means that this mode does not contribute greatly to the tone quality of the sound whereas in piston mode of vibration the decay of amplitude occurs exponentially. Thus lower frequency will not damp out quickly unlike higher frequency. In this particular design we use a stiff and a light membrane instead of deformable diaphragm to produce acoustic wave. This is due to the fact that on using deformable membranes the principle vibration mode will be drum mode which will ultimately affect the efficiency of the system, rather we use a rigid membrane supported by low stiffness suspension beam which will contribute to the production of piston vibration mode thus increasing the quality and sound reproduction. Moreover, for the same membrane surface and displacement, if the displaced air volume is bigger than the other structure then we can infer that high 'SPL' is obtained.

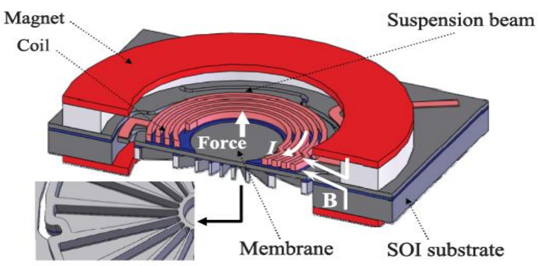

Fig.1. Cross sectional view of the microspeaker

Fig.1 explains the structure of the microspeaker wherethe planar coil is placed above the membrane and in order to feed it tothe conductor, tracks are kept on the suspension beams. To prevent the coil from short circuit, an electrically insulator layer is providedwith two viabetween the coil and the conductor tracks. Two magnet rings are located on the back and the front side of the substrate to induce maximum of radial magnetic field.To maximize the radical component of magnetic field by the coil, the distance between the magnet and the coil should be as small as possible. Nevertheless it is important to keep in mind that it is necessary to have a rigid membrane which can resist undesirable deformations and also a light membrane to keep the efficiency. The suspension beams are held to the substrate on one end and to the membrane on the other end and so the maximum stress takes place at both the ends. On taking the stress and displacement relations for this kind of beam and on applying the Hooke’s law, the following equation is formulated:

$$x = \frac{\epsilon \cdot l^2}{3 \cdot h} \quad (2)$$

Where x is the displacement, is the strain, l and h are the respective length and thickness of the beam.
The following equation reveals that the membrane peak displacement for a given diameter is defined by the minimum working frequency.

$$P_{Acoustic} = 0.27\, d^4 f^4 x_{peak}^2 \quad (3)$$

Here PAcoustic is the acoustic pressure, d is the membrane diameter, f is the working frequency and x is the peak displacement of the membrane.
The equation below defines the piston mode frequency of the membrane:

$$2\pi f = \sqrt{\frac{4Eb\left(\frac{h}{l}\right)^3}{M_{membrane}}} \quad (4)$$

Here *E* is silicon Young’s modulus, *M* membrane is weight of the membrane and *b* isthe beam width. The piston mode frequency should be out of the microspeaker bandwidth, below the lower working frequency. Dimensions of the beams were calculated using (3) and (4) with maximum strain lower than 0.1%. After calculating the membrane and the beam dimensions, the coil was designed. Because of this purpose, the following efficiency relation was taken into account:

$$n = \frac{(3.5 \cdot 10^{-4} \cdot d^4 \cdot B^2)}{(\rho^* \cdot \rho^2)} \cdot \frac{M_{coil}}{(M_{membrane} + M_{coil})^2} \quad (5)$$

Here*n* is the efficiency, ρ and ρ* are the coil metal density and resistivity (ρ.ρ* $=1.6\text{x}10^{-4}$ $(\text{kg/m}^3)(\Omega\text{.m})$ for copper) and B is the radial component of magnetic field. According to this relation, the efficiency is maximum for an equal weight of the membrane and coil. Thus, on assuming 0.9T magnetic field, the efficiency becomes 0.04%, which is approximately ten times more than that of conventional microspeaker [2].

Now, considering a microspeaker device as shown in Fig. 2 that has a multi-layered copper-coil, a NiFe soft magnet on polyimide membrane and anNdFeB permanent magnet placed on its perimeter.This speaker operates at low power where, at 88mA a peak displacement of 7µm is created thereby producing 110 dB ‘SPL’. On the other hand, by adjusting and manipulating the diameter of membrane, different ranges of ‘SPL’ are achieved while consuming power at different levels. This will find and edge over the other in terms of efficiency and the closeness to serving the purpose of application.

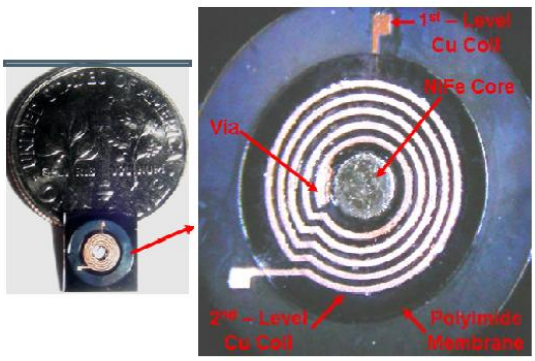

Fig.2. A Micromachined Loudspeaker

From Fig.3 we can observe that the membrane having 3 mm diameter (marked X) vibrates 1.35µmwhich corresponds to slightly more than 90 dB 'SPL' and the membrane having 4 mm diameter (marked square) vibrates 7µm which corresponds to 107 dB 'SPL' at applied current of 88 mA. These are much enough to use in 'CIC' type hearing aids applications to treat the profound hearing impaired [3].

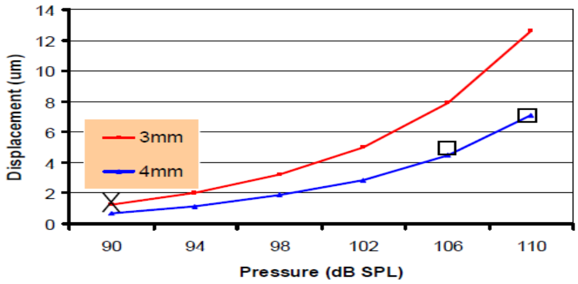

Fig.3. Conversion chart between displacement and sound pressure levelwith two different sizes of membrane i.e. 3 mm membraneand 4 mm membrane.

For low power applications in hearing aid, there should be a large membrane displacement which can produce high 'SPL' in ear canal. The following equation is formulated to find the 'SPL' with pressure and volume inputs:

$$SPL = 20\,log_{10}\left(-\frac{1.4P_o}{P_{rate}} * \frac{\Delta v}{V_o}\right) \quad (6)$$

Where P_o is the air pressure, P_{rate} is the rated air pressure= 20µPa,V_o is volume of ear canal =2cc.

On analysis, we inferred that 'Polydimethylsiloxane (PDMS)' membrane gives the largest displacement in comparison to Si and Si_3N_4 due to its low elastic modulus i.e.6.3 MPa leading to production of high 'SPL'. One of the major drawbacks of the system is that the peak resonance shifts to a higher frequency i.e. from 600Hz to 1.36 KHz as shown in Fig. 4because of the membrane rigidity as well as the 100µm wide and 600µm long copper feedthrough [4].

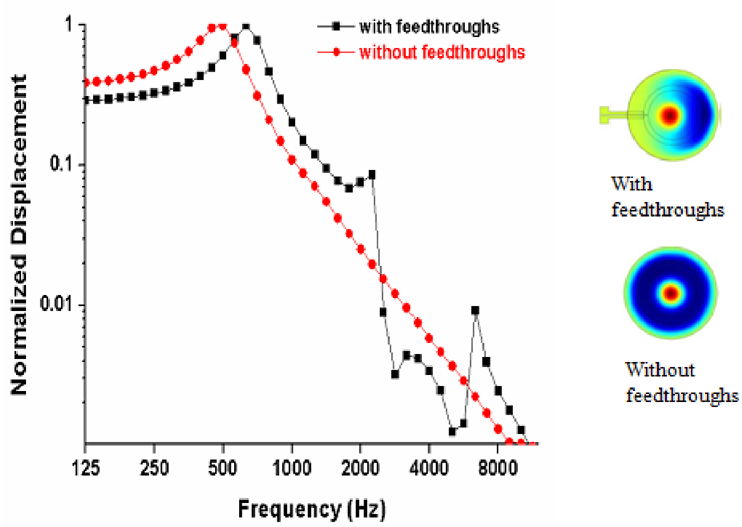

Fig.4. Displacement of membrane at differentfrequencies with and without feedthrough.

(Figs. 5 and 6) shows another possible configuration for the reduction in size of the microspeaker which is done by using micromachined permanent magnet. This uses NdFeBmicroparticlein a wax binder that is photolithogaphically embedded on the back which can provide asource of magnetic field to the system.

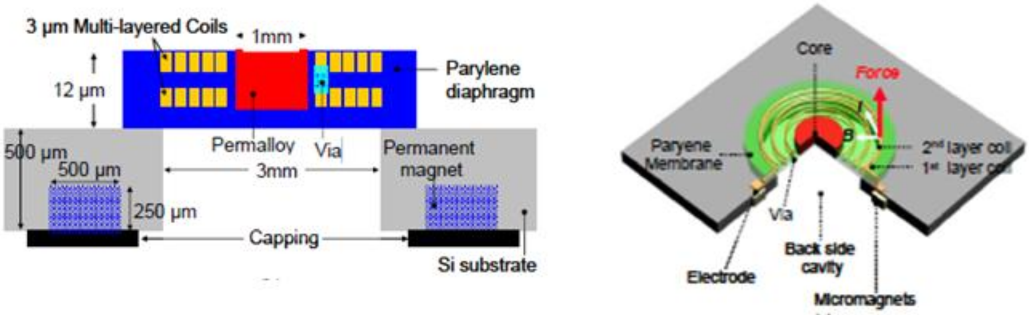

Fig.5. (a) Fully integrated microspeakerwith magnet powder, **(b)** Cross sectional view of microspeaker.

This results in the out of plane magnetisation that is due to the packing of magnet powder in 250µm deep groove which is sealed by a thin parylene film. Thus, the device produces 0.64µm peak displacement at 1 KHz for 88mA current which consumes 46mW power [5].

Moreover optimizing the coil properties or its placement in the device affects the output and efficiency to a great extent. Using electroplated Cu-Ni nanocomposite where Ni particles are intruded into the copper matrix,can modify the magnetic field from diamagnetic to ferromagnetic. Consequently, Lorentz force increases due to subsequent increase in the magnetic flux density. From the following equation we can draw that power saving is possible by measuring the electric and magnetic properties.

$$\frac{P_{composite}}{P_{Cu}} = \left(\frac{\mu_{r,Cu}}{\mu_{r,comp}}\right)^2 * \frac{K_{Cu}}{K_{comp}} \qquad (7)$$

Here $P_{Composite}$,$\mu_{r,Composite}$, $k_{Composite}$,P_{Cu}, $\mu_{r,Cu}$, k_{Cu}*are* the power consumption, relative permeability, and conductivity of the coil made by Cu-Ni nanocomposite and pure Cu, respectively.

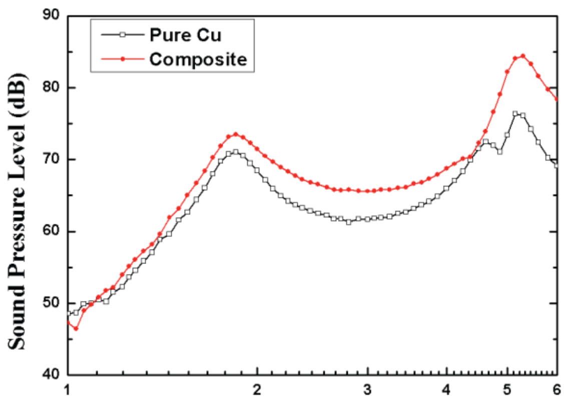

Fig.7. Measured 'SPL' response versus frequency at the same power input.

From Fig.7 we can say that composite coil can help power saving upto 40% than copper coil for same 'SPL' at 70dB.The Cu-Ni composite coil helps to generate higher 'SPL' than pure copper under same power input [6].

The electrical interconnects to the coil is the copper feedthrough because of which the rigidity of the membrane increases thus reducing the production of 'SPL'. Without taking feedthrough effect in account and on placing the coil at the centre of the membrane we will achieve a better response of 'SPL' at low frequency, whereas placing the coil close to the border of the membrane we obtain better response at low frequency with feedthrough effect. Theoretically larger the speaker, smaller is the output frequency with large 'SPL'. When coil is close to the centre active membrane becomes small and we get a better response of 'SPL' for high frequency, whereas when coil is far from the centre we get better response for low frequency.

From (Figs. 8 and 9) we can say that closer the coil is to the center, the membrane can move more which results in having a good response at low frequency. Thus coil placement on the membrane has a strong effect on the 'SPL' which can help us get rid of the feedthrough effect. So, by placing the coil close to the center can give a good response at low frequency [7].

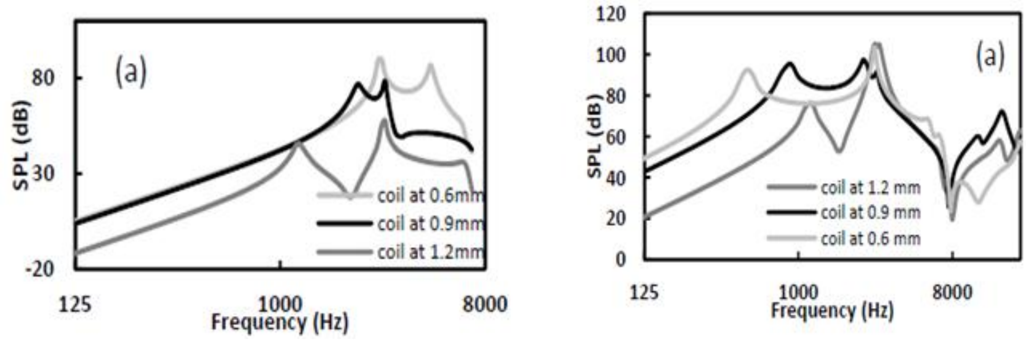

Fig.8. (a) 'SPL' at different coil placement with feedthrougheffect **(b)** without feedthrough effect.

III. Conclusion and Future work

A system consuming 1.76mW and 3.3μm thick membrane, 106dB 'SPL' can be generated at an operational frequency of 1KHz by designing a microspeaker that is placed on a silicon substrate along with a strong permanent magnet and a multi turned coil placed above it, held by a very soft 'PDMS' membrane and surrounded by circular soft magnet can be observed to be most efficient one. Our major concern was on the rigidity of the membrane which directly affected the required 'SPL'. So the future work will comprise of completely nullifying the feedthrough effect and working more on the rigidity or a better flexible material which can result in production of more 'SPL' at a very low frequency. Using graphene membrane will make a revolutionary change to the concept of rigidity and 'SPL' production in the device which shall prove to be a boon in the applications of hearing aids.

Acknowledgement

The authors would like to thank the staff of Electrical Engineering and Computer Sciences department, National Chiao Tung University (NCTU), Taiwan and Instrumentation and Control Engineering department, Sri Ramaswamy Memorial (SRM) University, Chennai, India for their help and technical support.

References

[1]. S. Je et al., "A compact and low-cost MEMS loudspeaker for digital hearing aids," IEEE Transactions on Biomedical Circuits and Systems,2009, Vol. 3, No. 5, pp. 348-358.

[2]. I. Shahosseini, E. Lefeuvre, M. Woytasik, J. Moulin, X,G. Lemarquand, V. Lemarquand, "Towards High Fidelity highe efficiency MEMS Microspeakers",IEEE SENSORS 2010 Conference; 978-1-4244-8168-2/10/$26.00 ©2010 IEEE

[3]. Sang-SooJe,JunseokChae, "An Electromagnetically actuated micromachined loudspeaker for hearing aids application",IEEE SENSORS 2007 Conference, 1-4244-1262-5/07/$25.00 ©2007 IEEE

[4]. Sang-Soo Je and JunseokChae, Member IEEE, "A Compact, Low-Power, and Electromagnetically Actuated Microspeaker for Hearing Aids",IEEE ELECTRON DEVICE LETTERS, VOL. 29, NO. 8, AUGUST 2008

[5]. Sang-Soo Je1, Naigang Wang2, Henry C. Brown1, David P. Arnold2, and Junseok Chae1, "AN ELECTROMAGNETICALLY ACTUATED MICROSPEAKER WITH FULLY-INTEGRATED WAX-BONDED ND–FE–B MICROMAGNETS FOR HEARING AID APPLICATIONS",Transducers 2009, Denver, CO, USA, June 21-25, 2009,978-1-4244-4193-8/09/$25.00 ©2009 IEEE.

[6]. Y. C. Chen, Wei-Ting Liu, Tzu-Yuan Chao, and Y. T. Cheng*,"AN OPTIMIZED CU-NI NANOCOMPOSITE COIL FOR LOW-POWER ELECTROMAGNETIC MICROSPEAKER FABRICATION",Transducers 2009, Denver, CO, USA, June 21-25, 2009,978-1-4244-4193-8/09/$25.00 ©2009 IEEE.

[7]. C. Webera, Y. C. Chenb, Y. T. Cheng,"The Study of the Inductive Coil to the Acoustic Performance of Electromagnetic Driven Microspeaker",EUROSENSORS 2014, the XXVIII edition of the conference series.