Design And Simulation of MEMS Helmholtz Resonator for Acoustic Energy Harvester

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***Abstract*—An acoustic energy harvester using Helmholtz resonator with piezoelectric circular diaphragm has been studied using COMSOL Multiphysics 5.1. In this paper, multiple designs considerations for MEMS Helmholtz resonator and piezoelectric circular diaphragm including the length and radius of the tube, the radius of the cavity and the thickness of the circular piezoelectric cantilever have been studied and investigated by varying it's size with 5 different values for each parts in order to find the best size for optimum output voltage. The input pressure have been set to 1 Pa as default. The simulation results demonstrated that under the same condition, a higher output pressure can be formed by having smaller tube radius and bigger cavity radius of the Helmholtz resonator. The resonance frequency of the Helmholtz resonator was found at 181 Hz. On the other hand, the interaction between air pressure's vibration and piezoelectric diaphragm plays an important role in determining the amount of harvested acoustic power and the position of piezoelectric circular diaphragm in the Helmholtz resonator is at the optimum when it is placed at the end of the resonator compared to at the beginning of the resonator's tube.**

Keywords— Helmholtz resonator, piezoelectric circular diaphragm, MEMS, energy harvesting.

INTRODUCTION

Today, there are so many studies that have been made on harvesting various types of energies presence in the atmosphere around us such as motion [1], heat [2] and light [3]. This paper on the other hand, focus and study on the acoustic energy harvesting which also a potential energy source.

Helmholtz resonance is a phenomenon of air resonance in a cavity [4]. Helmholtz resonator was introduced in order to deal with the noise, sound, and acoustic energy that existed in the air. It is a device which could compressed the scattered energy in the air and focus it at a point at the end of the device. Then, from that particular end, it could harvest the energy by joining the resonator with a system called piezoelectric. In this paper, the Helmholtz resonator was tested by varying its parameters in order to see the effects of the changes to the output air pressure produced.

A piezoelectric effect converts vibration (mechanical) energy into electrical energy. The mechanical vibration in the host will excite the cantilever beam which results in the induced strain in the piezoelectric material that cause an alternating voltage (AC) to be generated [5]. Circular piezoelectric diaphragm has been designed and used in this simulation in order to make it fit into the Helmholtz resonator's tube which is cylindrical in shape. It is placed at the end of the resonator's tube for an optimum output air pressure.

THEORY

Equation 1 shows the oscillating pressure of the air which is exposed to the Helmholtz resonator that flows from the tube of the resonator to the volume of its cavity [6].

Oscillating pressure: $$P_0(t) = P_0 e^{iwt} \quad (1)$$

As the air flows from the tube to the cavity, the pattern of the air current differs based on the size and volume of that particular space. Here, the tube consists of the resistance as well as the impedance.

Figure 1 illustrates the equivalent electric circuit of the Helmholtz resonator. This circuit is typically described using lumped-parameter (equivalent circuit) modeling as a serial coupling of an acoustic inertance L (equivalent to inductance in electric circuits and to mass in point-mass mechanics) caused by acceleration of the air in the tube, acoustic radiation resistance R caused by the dissipated energy out of the tube when the air in the tube moves into the volume, and an acoustic compliance C (equivalent to capacitance in electric circuits and a spring in point-mass mechanics) arising from compression of the volume. However, the value of the resistance does not affect the resonance frequency, only the absolute level of the impedance of the system, so we are well-justified in ignoring R.

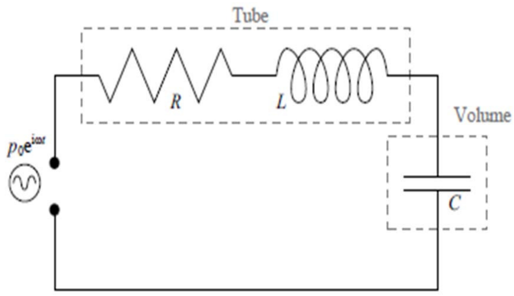

Figure 1: Illustration of equivalent electric circuit with the Helmholtz resonator.

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Acoustic lumped-parameter elements are given by [6]:

$$L = \frac{P_0(\ell + \gamma a)}{S} \quad (2)$$

$$C = \frac{V}{P_0 C_0^2} \quad (3)$$

where:

P_0 = Background quiescent density of fluid/air

C_0 = Background quiescent of sound

ℓ = Tube length

a = Tube radius

S = Cross-sectional area of the tube transverse to the direction of the flow

γ = End correction factor

V = Closed volume

Then, in obtaining the resonance frequency, the following formula has been used [6]:

$$W_e = C_0 \sqrt{\frac{S}{V(\ell + \gamma a)}} = C_0 \sqrt{\frac{a^2}{\frac{4}{3} R^3 (\ell + \gamma a)}} \quad (4)$$

where the following formula are used as the references for the resonance frequency formula [6]:

Volume of sphere; $V = \frac{4}{3} \Pi R^3$, and (5)

The tube is cylindrical, hence, $S = \Pi a^2$ (6)

When the air exits the tube and enters the cavity, the acoustic waves disperse and the acoustic pressure drops. However, the waves initially continue along the axis of the tube when they just leave it. Consequently, as the waves leave the tube, they do not completely disperse immediately and the immediate region at the end of the tube before entering the cavity is therefore still felt by the air in the tube where it imposes an acoustic load [6]. The acoustic load is the load that are required to make vibrations to the cantilever.

SIMULATION OF HELMHOLTZ RESONATOR

Device Structure

A Helmholtz resonator consists of a tube and also the cavity of the device which until now, the typical Helmholtz resonator consist both of these parts despite the changes made on the design [7]. In this study, a 3-dimensional geometry is considered for this simulation. The Helmholtz resonator's neck is constructed in cylinder shape while the cavity is in circular shape as shown in Figure 2. The ideal shape for a Helmholtz resonator is a circular as compares to square or oval tubes because these shapes amplify the non-harmonic pitches. The circular tube is typically chosen because it is good at amplifying the desired harmonic waves that are very important in having a consistent sound wave in the resonator [8]. The tube radius and tube length of the resonator are 10 mm and 50 mm respectively while the volume radius for the cavity is set to 50 mm. The device is filled of air.

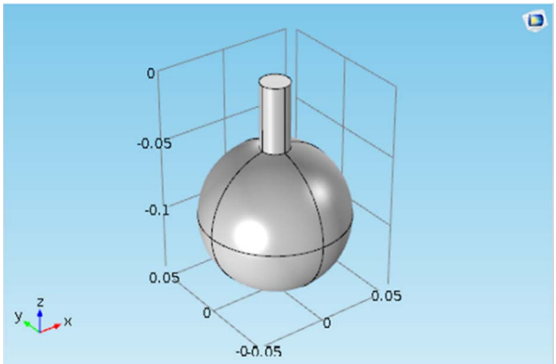


Figure 2: Helmholtz resonator's model design in 3-D axisymmetric.

Meshing Size

In this simulation, the Helmholtz resonator's pressure is meshed using the physics-controlled mesh, finalized geometry has 1 domain, 13 boundaries, 24 edges, and 13 vertices. Complete mesh consists of 7058 domain elements, 1116 boundary elements, and 160 edge elements.

SIMULATION RESULTS

Eigenfrequency Analysis

Eigenfrequency analysis is done in order to determine the first 6 modes of frequency of the Helmholtz resonator beam and their corresponding deformation shape. Eigenfrequency is one of the natural resonant frequencies of a system which it has the largest amount of vibration in a volume.

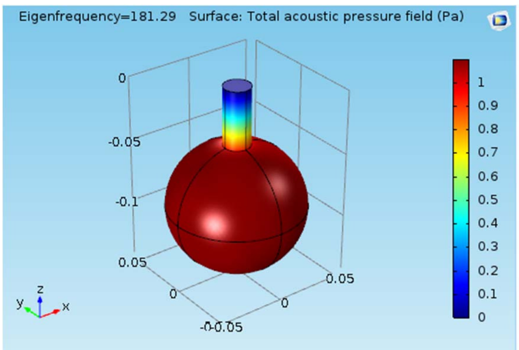


Figure 3: Eigenfrequency for Helmholtz resonator.

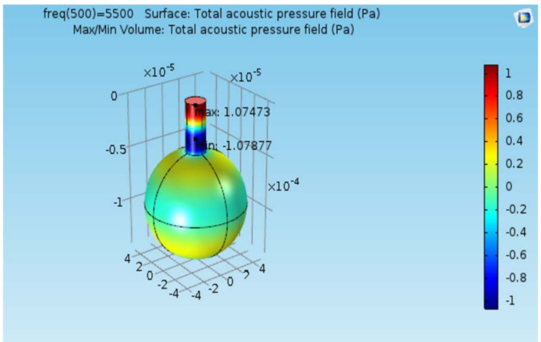
Figure 3 shows the eigenfrequency for Helmholtz resonator that has been designed. The first 6 eigenfrequencies for Helmholtz resonator beam found are 181.29, 2251.9, 2274.4, 2274.4, 3160.5, and 3649.2. It was found out that the natural frequency for this resonator is 181.29 Hz as it suits well the mechanical behavior of the resonator. The value is then used as the reference value for this experiment.

VARYING PARAMETERS

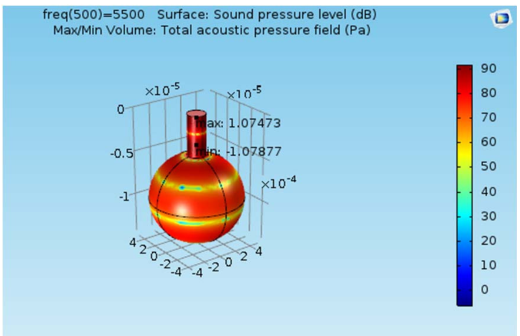
Some parameters are varied in order to see the effects of those parameters to the output air pressure produced. The parameters that have been investigated are the input pressure, the length of the tube, the radius of the tube, and the radius of the cavity.

Table 1: Default parameters for Helmholtz resonator.

Input Power	1 Pa
Tube Radius	10 mm
Tube Length	50 mm
Cavity Radius	50 mm



(a)



(b)

Figure 4: (a) Acoustic pressure for the default parameters. (b) Sound pressure level for default parameters.

Each parameter was varied at five different values and the results were presented in a form of graphs. The optimum size for each parameters is obtained from the graphs accordingly. The default parameters that have been used are shown in Table 1. Figure 4 shows the results of simulations for acoustic pressure and sound pressure level from the default parameters that have been set. The results obtained and all the values generated from the simulation have been set as the reference values throughout the experiments.

VARYING INPUT PRESSURE

Input pressure is the air pressure that will enter the Helmholtz resonator through its tube to the cavity. The air pressure will then be focused inside the chamber and vibrates the piezoelectric circular diaphragm. This study investigates the input pressure that flows into the Helmholtz resonator by varying its value. The source of pressure is placed at the tip of the tube and the value is varied from 0 Pa to 4 Pa.

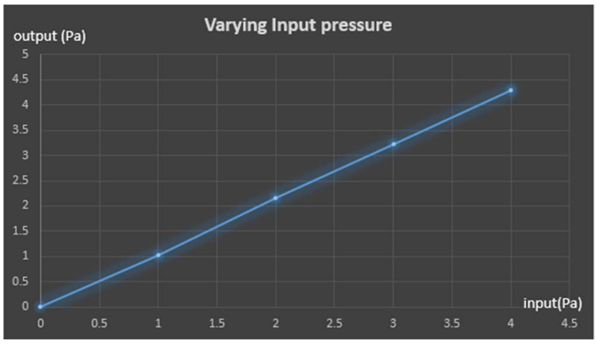


Figure 5: Input pressure versus output pressure in the Helmholtz resonator

Figure 5 illustrates the graph of input pressure varied versus the output pressure resulted in the Helmholtz resonator. It can be observed that as the input pressure increased from 0 Pa to 4 Pa, the output pressure also increased from 0 Pa to 4.3 Pa respectively. Hence, it can be concluded that the input pressure significantly affects the output pressure.

VARYING TUBE RADIUS

Helmholtz resonator's tube is a part of Helmholtz resonator where the air will flow into before it reaches the cavity. The tube plays an important role in determining the volume and concentration of the air flows through the resonator. The Helmholtz resonator's tube radius has been varied and tested. The radius of the tube has been varied from 2.5 mm to 17.5 mm.

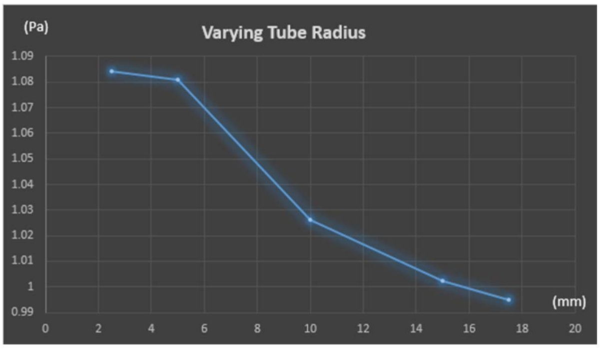


Figure 6: Tube radius versus output pressure in the Helmholtz resonator.

Figure 6 illustrates the graph of varied tube radius versus the resulting output pressure in the Helmholtz resonator. Based on the results obtained, it can be observed that as the tube radius increased from 2.5 mm to 17.5 mm, the output pressure decreased from 1.08414 Pa to 0.00488 Pa respectively. This is because when the area of the tube is bigger, the concentration of air pressure in the tube is lower. Therefore, once the pressure reached the cavity of the resonator, the value of the pressure is already decreased.

VARYING TUBE LENGTH

The Helmholtz resonator's tube length has been varied and tested. The length of the tube has been varied from 12.5 mm to 87.5 mm. Figure 7 illustrates the graph of tube length varied versus the output pressure resulted in the Helmholtz resonator. It can be observed that as the input length increased from 0.0125 m to 050 mm, the output pressure also increased occasionally. However, it starts to drop to its original point once the length of tube is increased to 75 mm. Then, it can also be seen that the pattern started to increase again at 87.5 mm length of tube. This results shows that the harmonic wave phenomenon is happening in that tube. This phenomenon has already reported in an experiment where there are peaks for maximum and minimum value of pressure and it keeps repeating for every waves produced [9].

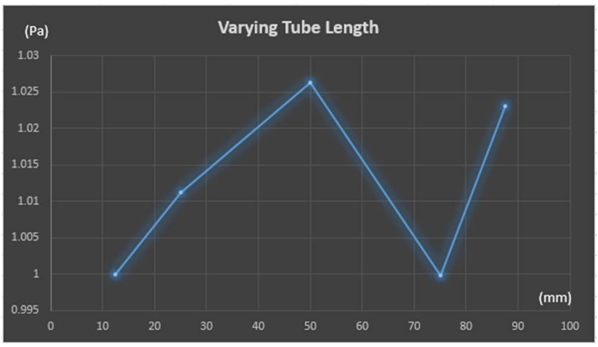


Figure 7: Tube length versus output pressure in the Helmholtz resonator.

VARYING CAVITY RADIUS

Helmholtz resonator's cavity is a part where the air is collected and focused to one focal point in order to have the highest concentration of air that can produce vibrations inside it. Helmholtz resonator's cavity is very important because when air is forced into a cavity, the pressure inside increases. The Helmholtz resonator's cavity radius has been varied in the range of 12.5 mm to 87.5 mm.

Figure 8 illustrates the graph of cavity radius varied versus the output pressure resulted in the Helmholtz resonator. It can be observed that as the cavity radius increased, the output pressure also increased from 0.10094 Pa to 1.06033 Pa occasionally. This is due to the capability of the Helmholtz resonator to produce harmonic waves has become better as the increasing room of the cavity. By having larger cavity, the waves can move more smoothly thus resulting in better harmonic waves flow which then cause the vibrations inside the resonator become higher. Hence, it can be concluded that the value of cavity radius significantly affects the output pressure.

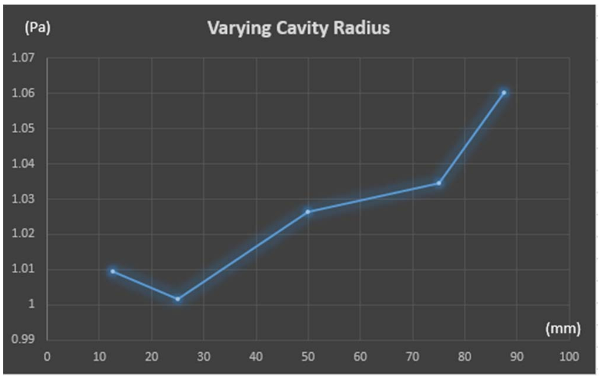


Figure 8: Cavity radius versus output pressure in the Helmholtz resonator.

SIMULATION OF HELMHOLTZ RESONATOR WITH PIEZOELECTRIC CIRCULAR DIAPHRAGM

3-D Device Structure

A 3-dimensional geometry is also considered for this simulation. Figure 9 shows the real view of how the piezoelectric cantilever will be constructed and combined with the Helmholtz resonator structure. The piezoelectric circular diaphragm is constructed in round shape structure as shown in Figure 10. The circular diaphragm structure is composed of 0.012 mm thickness and the piezoelectric layer's material is Zinc oxide (ZnO). The radius of the circular diaphragm is 10 mm. The main reason on why the shape of the diaphragm set to be round is because it has to be fit in a round-shaped Helmholtz resonator. This is not the first time a piezoelectric cantilever has been set to be round despite of its normal shape; rectangular. For example, [10] has reported this round shape piezoelectric circular diaphragm in his experiment as well.

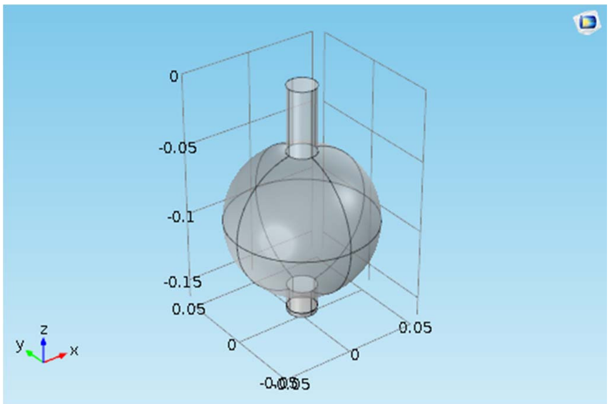


Figure 9: Combination of Helmholtz resonator with piezoelectric circular diaphragm.

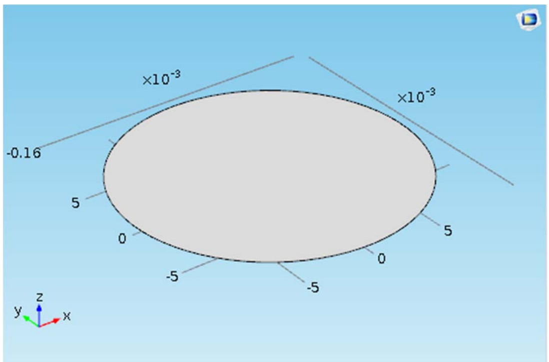


Figure 10: Circular Diaphragm Structure.

Boundary Conditions

The cantilever's fixed end is set to be fixed all around the wall of the Helmholtz resonator. The boundary load is actually the load that come from the neck of Helmholtz resonator in the (-z) direction. However, as in this section we are just testing the piezoelectric circular diaphragm alone, the boundary load is set as 10 μN/m². This value is generally chosen since MEMS structure is only capable to tolerate to a small amount of force [11].

Static Analysis: Electric Potential

The strain that occurs within the piezoelectric layer ZnO results in the generation of the potential. As shown in Figure 11, the maximum potential occurs at the center of the circular diaphragm with a value of 4.32×10^{4} V when 0.5 Pa of input pressure was supplied.

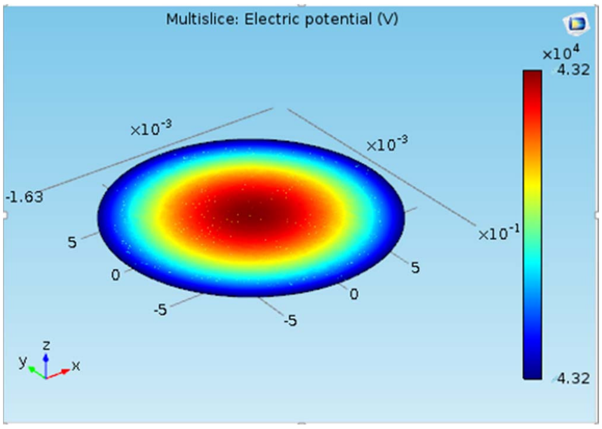


Figure 11: Electric potential for ZnO.

Figure 12 shows the results of electric potential gained when varying the input pressure from 0.5 Pa to 1.0 Pa. Based on Figure 12, it can be seen that as the input pressure increases, the electric potential also will be increased.

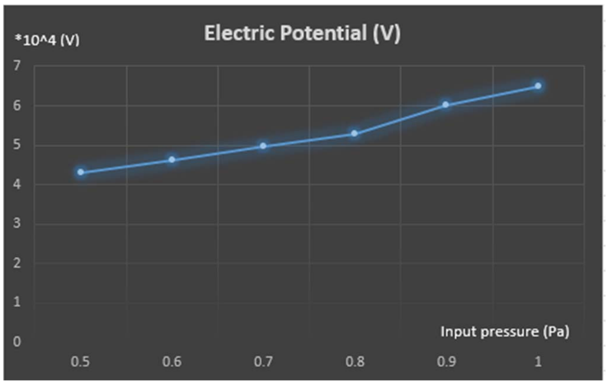


Figure 12: Input pressure (Pa) versus electric potential (V).

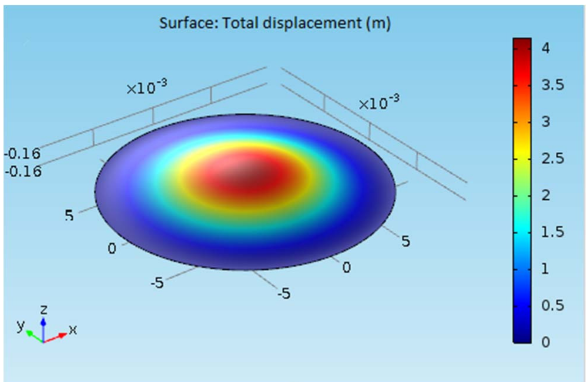


Figure 13: Mode shape corresponding to the first eigenfrequency value for ZnO.

Eigenfrequency Analysis

In this study, there were numbers of eigenfrequencies that have been gained from the test of ZnO circular diaphragm beam. The first Eigenfrequency which is about 189.57 Hz is used in setting the excitation frequency for the transient analysis so that the beam vibrates near its resonance end and thus gives a maximum potential. The mode shape of the first Eigenfrequency is shown in Figure 13.

CONCLUSIONS

It can be stated that the MEMS Helmholtz resonator with piezoelectric circular diaphragm energy harvester has been successfully designed and simulated. The results of this experiment and investigation indicates that each design parameters give significant changes to the output voltage performance of both the Helmholtz resonator and piezoelectric circular diaphragm. On top of that, we can also see that the changes of the tube length, tube radius and cavity radius really affect the output voltage from the resonator. Moreover, in case of piezoelectric circular diaphragm, in terms of device shape, we have chosen to use a round shape diaphragm because we want to adapt it to the circular shape of the Helmholtz resonator. It can be seen that even though it is quite different from the normal piezoelectric cantilever which is usually rectangular in shape, it still gives a good results of output voltage.

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