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Course ID : ID2801
Title of the project : Design and development of an Acoustic energy harvester (AEH) array.

Introduction:

This report gives a brief glimpse of working and designing of acoustic energy harvester. The aim of this project is to design a model of Helmholtz resonator which could give maximum output(in terms of current output etc..) in real life scenario(roads, railways).

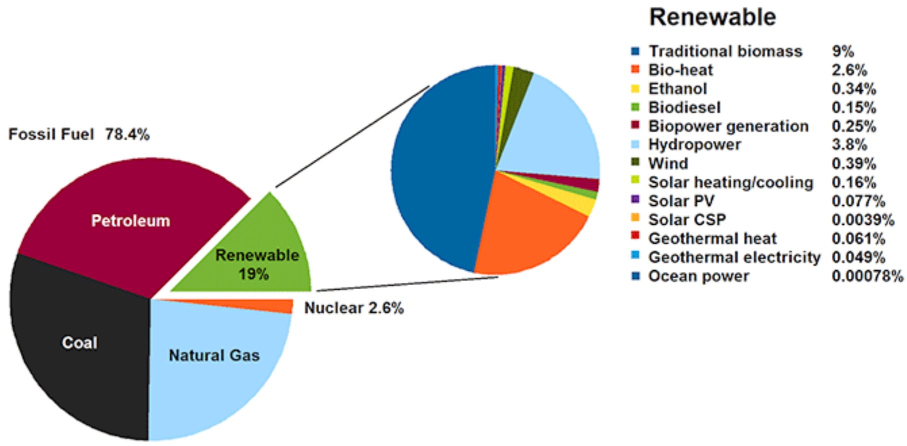
Acoustic energy is the energy concerning the mechanical vibrations from its components. The acoustics are mainly classified into environmental acoustics, musical acoustics, ultrasounds, infrasound etc.. based on the source and frequency of waves. Here, in this project the main concentration is on environmental acoustics. Noise caused by roadways, aircraft and activities that are related to the environment which releases sound into environment(unwanted noise) comes under environmental noise(environmental acoustics). Therefore, the AEH(acoustic energy harvester) is a model which absorbs this unwanted energy released into atmosphere(sound energy) and coverts into electrical energy which we humans almost use every moment in our lives. The importance and need of Acoustic energy harvester can be well understood by looking at the advantages of using solar panels, wind mills etc.

Why do we need AEH?

- *It absorbs the energy which is almost redundantly present in atmosphere and makes sense out of it!*
- *It helps in producing electric energy which can be either used instantly or stored for later use.*

*Statistics says that the contribution of fossil fuels in electric energy production is more than 70 percent. So, the use of acoustic energy harvester to produce electric energy '**efficiently**' can save large amounts of fossil fuels which are non-renewable and can thereby contribute its part to decreasing environmental pollution.*

contributions of various sources to electrical energy production.



A field survey is conducted to observe the frequencies of noise at nearby places of IIT Palakkad, like at the entrance of Nila campus IIT Palakkad, at railways, at traffic signal etc.. Based on the frequencies of noise observe at different places we can construct AEH model to get maximum output.

Observation of absorption, reflection and transmission of sound waves by the AEH model to get maximum output. This is done using with the help of COMSOL simulations. which we can get at maximum absorption frequency range.

<u>Theory:</u>

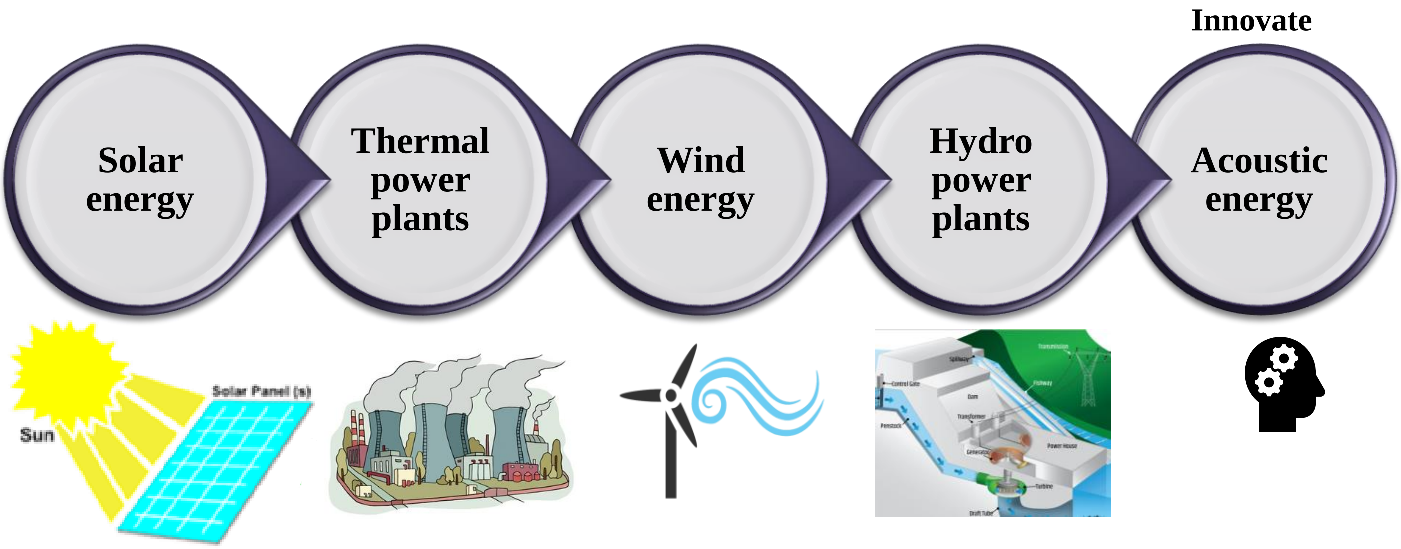
The idea of converting acoustic energy(sound) to electric energy looks so simple but actually it is not. It is so simple to convert electrical to sound using speakers but the other way round is not all and that can be understood by the end if this report. The main agenda that is converting renewable energy to electric energy is similar to that of windmills and solar panels. It is rather complex than converting solar energy or wind energy to electrical energy.

The two main reasons which are making difficult to convert sound energy to electrical when compared to solar and wind are:

1) *Low energy density*
2) *Less abundant*

'Low energy density' : The energy density of sound is very less compared to solar and wind energy. Due to which energy extracted from it on gross scale will be much lower than electrical energy obtained from solar, wind, hydro energy(dams). The technique used here to overcome the limiting factor of efficiency of AEH (low energy density) is 'pressure amplification' which can be done by Helmholtz resonator.

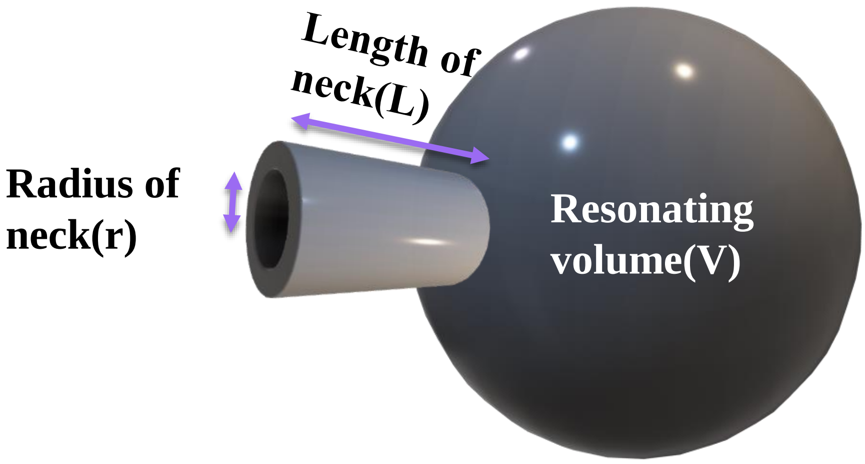
'Less abundant' : Though sound energy is available in abundant, but it is not as abundant as solar and wind. Even though sound energy is abundantly present in atmosphere due to noise pollution, in industries etc.., most of the sound cannot be harvested to get electric energy either due to high frequency or low frequency of sound which is difficult to harvest.



Pressure amplification by 'Helmholtz Resonator':

Helmholtz resonator consists of an acoustical cavity contained by rigid walls and connected to the exterior by a small opening called the neck. It is a special type of air-spring oscillator. The name comes from a device created in the 1850s by *Hermann von Helmholtz, the Helmholtz resonator, which he used to identify the various frequencies or musical pitches present in music and other complex sounds. The acoustical cavity could be any shape like sphere, cylinder, cuboid etc.. The size that is volume of cavity and length, radius of neck defines the frequency at which the resonator resonates.*

3-D model of Helmholtz resonator:



Condition of Helmholtz resonator: $V <<< \lambda^3$

That is resonating volume should be much less than cube of target wavelength.

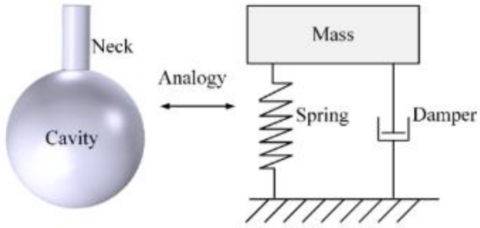
If it is a sphere then radius of sphere should be less than wavelength. And similarly so on…

The Helmholtz resonator resonates at certain frequencies and one of such frequencies is fundamental frequency. This frequency is generally referred to as natural frequency of resonator. Whenever the natural frequency of the Helmholtz resonator system is equal to the driving frequency that is incident frequency(from surroundings) acoustic coupling takes place. This acoustic coupling will drive air molecules back and forth inside neck. The oscillations are maximum at resonant frequency.

Incident sound waves causes air molecules in the neck to vibrate back and forth, while air inside the cavity provides the restoring spring force. Helmholtz resonator behaves like an acoustical mass-spring system, where

- *Mass of air in neck ~ Mass in spring-mass system.*
- *Bulk modulus of air in the cavity ~ spring constant. (provides restoring force)*

Resemblance of Helmholtz resonator with spring-mass system:

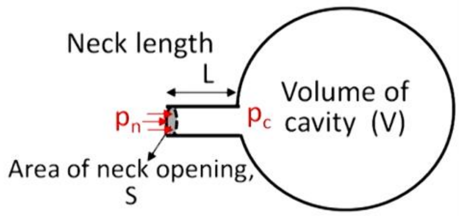


The damping forces are like viscosity of air, very minute cohesive and adhesive forces between air and wall molecules.

Natural frequency of a Helmholtz resonator:

- *In steady state P(pressure) and V(volume) inside the cavity remains spatially uniform and varies only with time.(this assumes that cavity is big enough compared to neck which ensures that the change in volume of the cavity due to oscillations of air molecules in neck is negligible).*
- *As air oscillates in and out in along the neck, the acoustic pressure causes air in the cavity to compress and expand.*
- *Acoustic pressure inside the neck is* $p_n(x,t)$
- *Acoustic pressure inside the cavity is* $p_C(t)$.
- *Surface area of neck is S*
- *Angular frequency is* ω.
- *Length of the neck is L.*
- *Volume of the cavity is V.*
- *The overall density is* ρ. *(*$\rho = \rho_c$ *is the overall density inside the cavity)*
- *Mean density at equilibrium position is* ρ_0.
- *Speed of sound in atmosphere is* c_0.
- *Bulk modulus of air inside cavity is B.*
- *All these acoustic expansions and compressions are adiabatic.(no heat transfer, work id done due to the change in its internal energy)*

  This assumption of adiabatic processes in cavity:



$$p_C(t) = B\left(\frac{\rho-\rho_0}{\rho_0}\right)$$

$$c^2 = \frac{B}{\rho_0}$$

Then by above two formulae due to adiabatic conditions we get

$$\Rightarrow p_c(t) = c^2\,(\rho - \rho_0)$$

As adiabatic expansion are very small we can approximate to:

$$\Rightarrow p_c\ (t) = c^2\,\rho_c$$

density is mass per unit volume.

$$\rho_c = \frac{m}{V}$$

$$\frac{d\rho_c}{dt} = \frac{1}{V}\frac{dm}{dt}$$

$$\rho_c = \frac{1}{V}\int \dot{m}\,dt$$

($\dot{m}$ *is the rate of flow of mass entering or leaving the cavity)*

$$p_C(t) = \frac{c^2}{V}\int \dot{m}\, dt$$

Newton's second law of air movement in the neck:

$$\rho_0 \frac{dv}{dt} = -\frac{\partial p_n}{\partial x} - F$$

Where F = viscous and resistive forces, v = velocity of air molecule or layer

Based on viscous theory: viscous force is directly proportional to velocity and inversely proportional to length in which flow takes place. Then we can write F as

$$F = \frac{Rv}{L}$$

Where R is proportionality constant.

Assuming hormonic oscillations of air molecules in the neck

$p_n(t) = p_{n\max} e^{i\omega t}$, $v(t) = v_{\max} e^{i\omega t}$

$$\frac{\partial p_n}{\partial t} = i\omega p_n$$

$$\frac{\partial v}{\partial t} = i\omega v$$

Putting the above three equations in newtons second law equation

$$\rho_0(i\omega v) + \frac{Rv}{L} = -\frac{\partial p_n}{\partial x}$$

integrating wit respect to 'x' along neck 0 to L.

$$[\rho_n]_0^L = i\omega\rho_0 vL + Rv$$

$$p_n - p_c = i\omega\rho_0 vL + Rv$$

Differentiating with respect to 't':

$$\frac{\partial p_n}{\partial t} - \frac{\partial^p c}{\partial t} = i\omega\rho_0 L\frac{\partial v}{\partial t} + R\frac{\partial v}{\partial t}$$

$$i\omega p_n = \frac{dp_c}{dt} + i\omega\rho_0 L(i\omega v) + R(i\omega v)$$

$$i\omega p_n = \frac{c^2\dot{m}}{v} - \omega^2\rho_0 vL + i\omega Rv$$

Where $\dot{m} = \rho_0 vs$

$$p_n = Rv - i\rho_0 c[\frac{cSv}{\omega V} - \frac{\omega vL}{c}]$$

Acoustic Impedance $z = \frac{p_n}{v} = Rv - i\rho_0 c[\frac{cS}{\omega V} - \frac{\omega L}{c}]$

At resonance Impedance is minimum so $\rho_0 c[\frac{cS}{\omega V} - \frac{\omega L}{c}] = 0$

$$\omega = c\sqrt{\frac{S}{vL}}$$

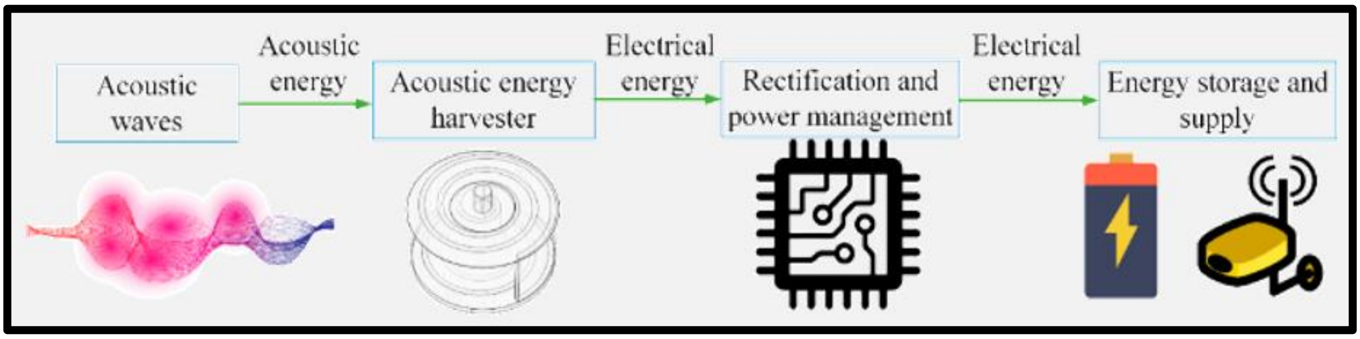
at resonance frequency is $f = \frac{c}{2\pi}\sqrt{\frac{S}{vL}}$

including end correction factor: $f = \frac{c}{2\pi}\sqrt{\frac{S}{v(L+1.7r)}}$

The absorption is maximum at fundamental frequency of Helmholtz resonator. The idea of constructing acoustic energy harvester is that by placing a piezoelectric plate at the bottom, there will be uncontrollable vibrations (oscillations) of piezo plate due to resonance effect. Piezoelectric materials are widely referred to as "smart" materials because they can transduce mechanical pressure acting on them to electrical signals and vice versa. They are extensively utilized in harvesting mechanical energy from vibrations, human motion, mechanical loads, etc., and converting them into electrical energy for low power devices.

Circuitry:

Simple circuitry of Acoustic Energy Harvester:



Acoustic waves trapped by resonator, and due to maximum absorption at natural frequency of resonator which leads to maximum vibrations in piezo plate and thereby maximum current derived.

Analysis using COMSOL Multiphysics:

Engineers and scientists use the COMSOL Multiphysics software to simulate designs, devices, and processes in all fields of engineering, manufacturing, and scientific research. COMSOL Multiphysics is a simulation platform that provides fully coupled multi-physics and single-physics modeling capabilities. The Pressure Acoustics, Frequency Domain (acpr) interface, found under the Pressure Acoustics branch when adding a physics interface, is used to compute the pressure variations for the propagation of acoustic waves in fluids at quiescent background conditions. It is suited for all frequency-domain simulations with harmonic variations of the pressure field.

For analysis of Helmholtz resonator in COMSOL, Pressure acoustics frequency domain is needed.

Geometry in COMSOL:

A cylindrical Helmholtz resonator is constructed in COMSOL to observe pressure variations at different frequency values. The resonator is placed inside a sphere of large radius(atmosphere). The walls of resonator are plastic(PVC) and volume inside the hemisphere and resonator is air.

The entire structure can be cut into two halves by a plane which reduces simulation time and symmetry bound condition is applied to the plane which is being cut.

__Getting the values from formulae by using python code:__

Length of neck = 16 mm

Radius of neck = 10 mm

Radius of resonating volume = 25 mm

Height of resonating volume = 60 mm

Designed frequency = 500 Hz

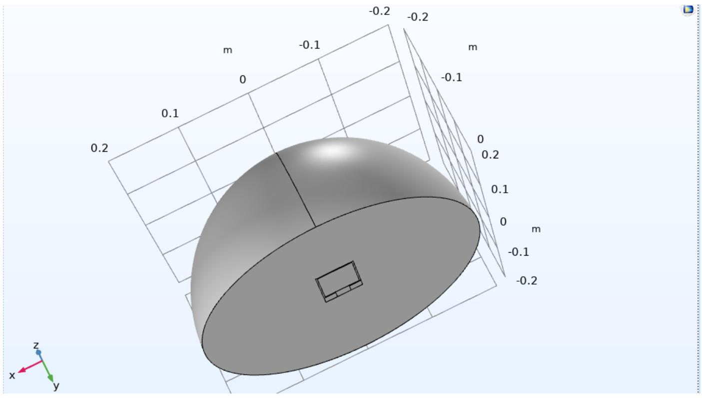
In [4]:
```python
# To get resonating volume
F = float(input("Enter Frequency:"))
r = float(input("Enter radius of neck:"))
L = float(input("Length of neck:"))
Co = float(input("Speed of sound:"))
V = (((Co * r) ** 2) * 7) / ((4 * 22 * (F ** 2)) * (L + 1.7 * r))
print(V)
```

```
Enter Frequency:500
Enter radius of neck:0.010
Length of neck:0.016
Speed of sound:343
0.00011343567493112949
```

In [6]:
```python
# to get radius of resonating culinder from volume and height
# R = sqrt(v / (H * pi))
V = float(input("Enter volume of resonating volume: "))
H = float(input("Enter height of resonating volume: "))
R = ((V * 7) / (H * 22)) ** (1/2)
print("Radius R = ", R)
```

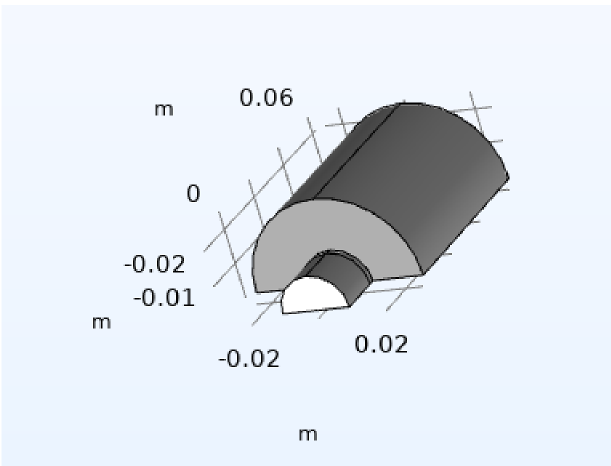
```
Enter volume of resonating volume: 0.000113435674931129
Enter height of resonating volume: 0.06
Radius R =  0.024526573784458196
```

__Total structure in COMSOL:__

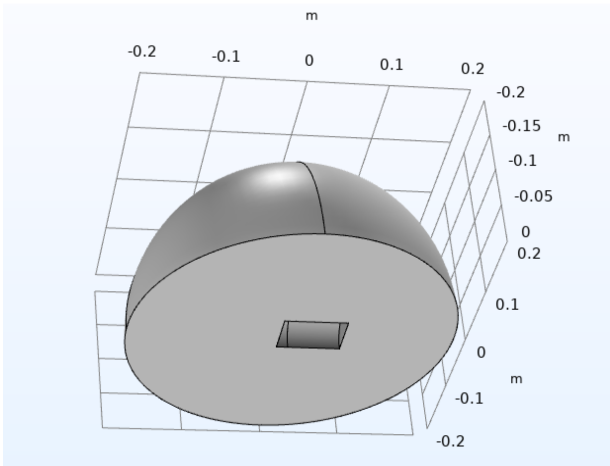


__Total air:__

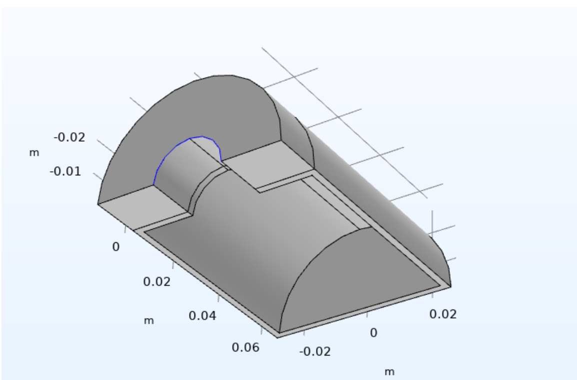
Air inside resonator



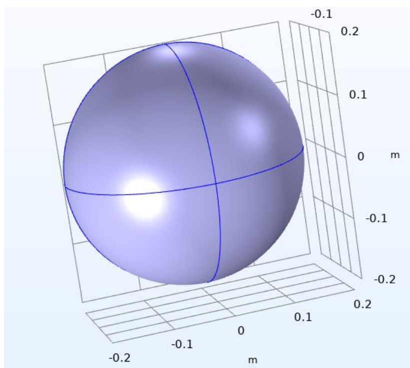
air in atmosphere



__Walls of resonator:__



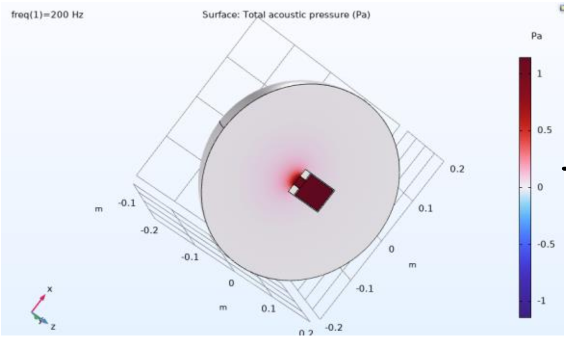
__Spherical wave radiation(boundary condition) of sphere:__

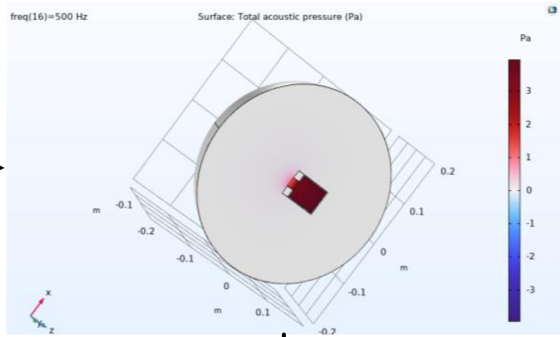


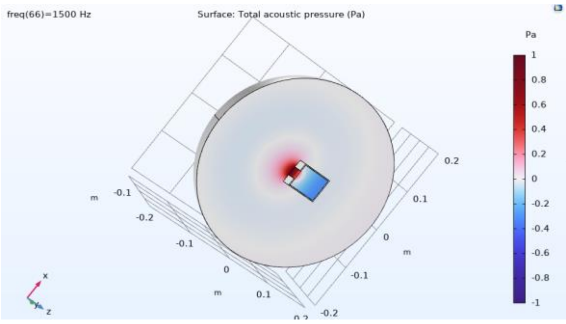
Results:

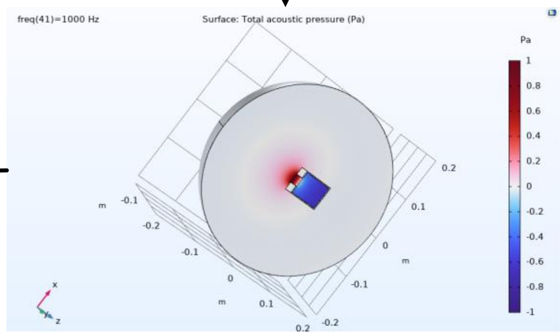
Pressures variations at different frequencies:

Acoustic pressure:

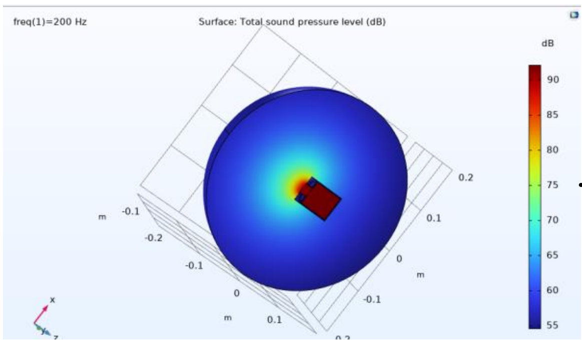


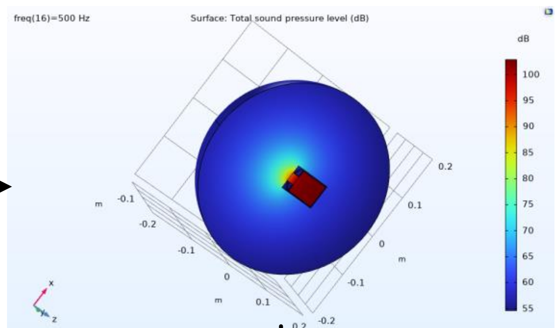


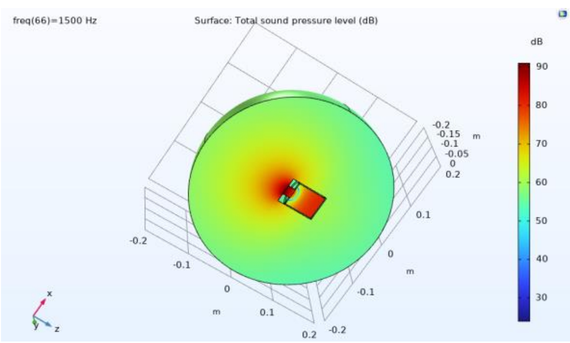


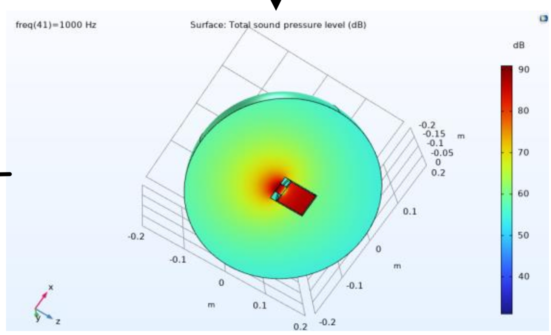


Sound Pressure Level(SPL):

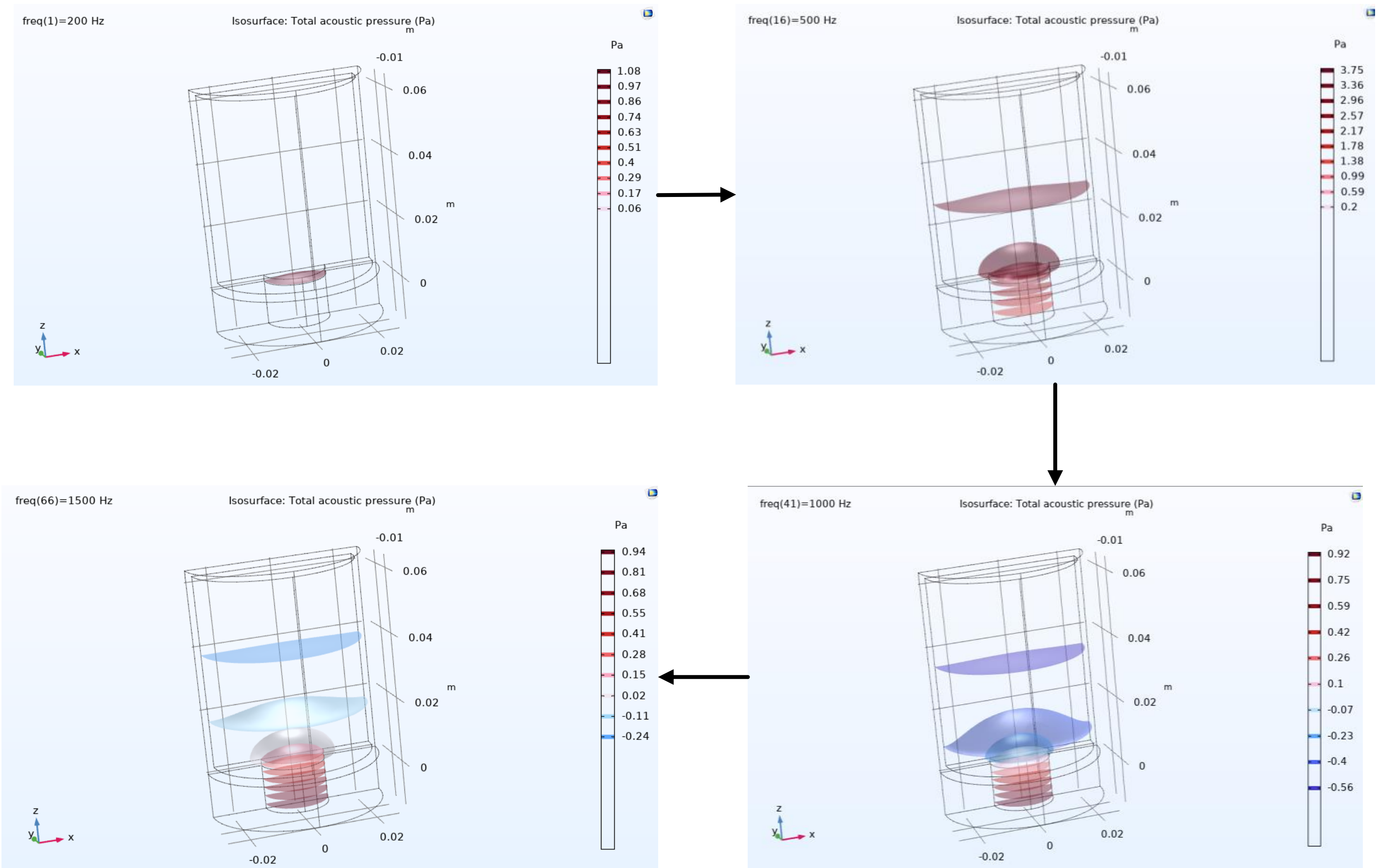








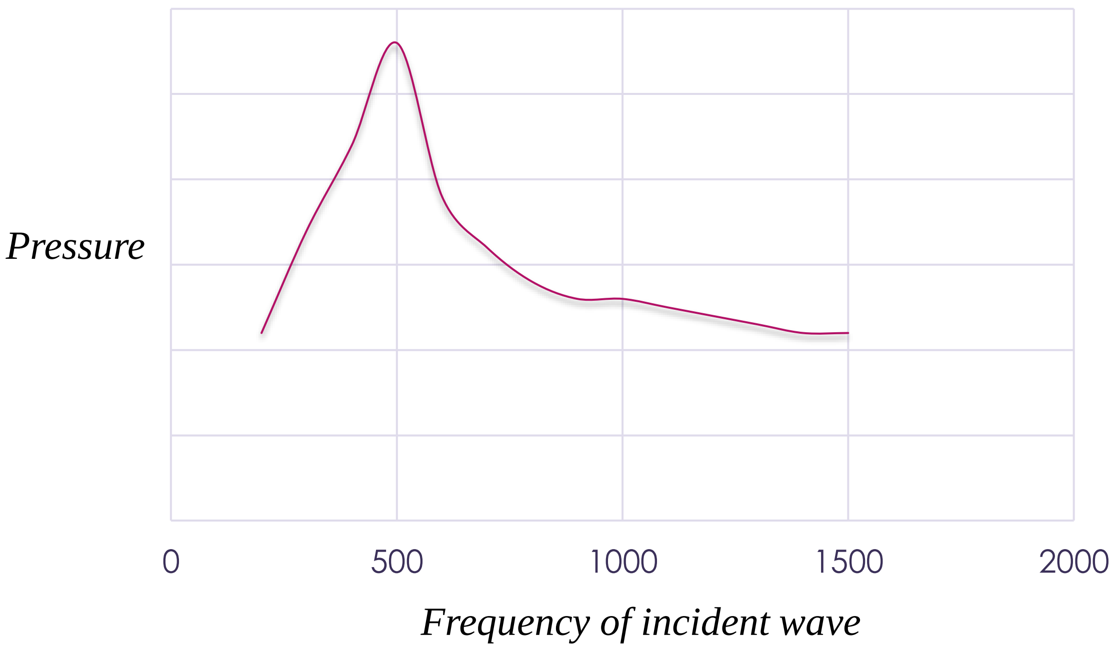
Isosurfaces:



<u>Observations:</u>

By observing results from COMSOL it can be inferred that at resonance the pressure inside the resonator is maximum and at remaining frequencies the pressure decreases as we go away from the resonant frequency. The approximate graph of pressure vs frequency is:

Acoustic Pressure in resonator:



Field survey
Conclusion
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