International Journal for Ignited Minds (IJIMIINDS)

Design and Acoustic Analysis of Hybrid Muffler

Snehasis Pal

M.Tech, Department of Mechanical Engineering, Christ University, Bangalore, India.

ABSTRACT

In 21st century, automobile industries are booming at an unimaginable space. An inbred snag of IC engines is that it is a main root cause of noise pollution. That is the reason mufflers are used to muffle the noise produced. But mufflers need design and geometry considering the physics behind it which is very confounded. Established muffler design has been an iterative process by trial and error method. The present work involved the optimization of the mufflers design by designing a hybrid muffler. The 3D modeling was done using commercially available CAD software package such as CATIA. For acoustic analysis, the transmission loss of the present dissipative muffler and hybrid muffler was done using FEA software package ANSYS. To validate this method for acoustic analysis using ANSYS, comparison of Transmission loss was done for dissipative muffler models with experimentally measured values. It was found that Measured TL & predicted TL are matching well within +/-3dB, this validated that the FEA method holds good for this analysis. The hybrid muffler having three different iterations solely based on different air gap between absorptive layer (fibrous material) and perforated pipe was analyzed. Transmission loss analysis was compared with the TL of existing models which showed an increase of TL at higher frequency ranges.

Keywords – *Muffler, Acoustic, Dissipative, Hybrid Muffler and Transmission loss.*

1. INTRODUCTION

Mufflers [1] are a fundamental part of engine exhaust system and are used to minimize sound transmissions caused by exhaust gases. Design of mufflers is a complex function that affects noise characteristics, emission and fuel efficiency of engine. Mufflers presently used in the automotive industry are either reactive muffler or a dissipative muffler [2] which work at a certain target frequency spectrum. For example, the reactive muffler are good at a low frequency ranges whereas the dissipative mufflers work at high frequencies of 1500-2000Hz.To make a muffler model that can work at a wide range of frequency spectrum, it is necessary to design a muffler such that it can target this problem at the same time and its performance also is not compromised. The Finite element method (FEM) has already been used for dissipative silencers, for example, by Astley and Cummings [3], Craggs[4], Kagawa *et al.*[5], Cummings and Astley [6], and Peat and Pathi[7]. Craggs used FEM and a locally reacting model to predict the behaviour of a lined expansion chamber without experimental validation. Kagawa *et al.* compared their FEM results with the experiments for lined expansion chambers, including temperature gradient. Cummings and Astley, and Peat and Pathi illustrated the effect of mean flow in the main duct on the overall performance of dissipative silencers.

The objective of the current work is to design a hybrid muffler which is very good in performance and works well in the wide spectrum of frequency. For this purpose, we are going to perform acoustic analysis [8] which can show how the sound pressure is changing when it is passing through the muffler and what the difference in between inlet sound pressure is and outlet sound pressure. When we do acoustic analysis, we actually carry out transmission loss analysis. This can be achieved by doing a transmission loss analysis [9] which will be perfectly explained in the coming sections. We have to design a muffler that has reactive and dissipative properties and also show that it can perform in wide frequency ranges. To validate the FEA results, transmission loss analysis is done and compared with the conventional muffler designs which is taken from Lee's [10] thesis.

As a part of this study, below activities are performed.

- Study of literature of muffler is performed.
- Study of Reactive muffler principles
- Analyze a dissipative muffler using FEA & compare its results with experimental results from the thesis.
- Finally design a hybrid muffler & compare its performance with both reactive & dissipative mufflers.

First the acoustic performance of the dissipative mufflers is explored by doing a transmission loss analysis on quarter symmetry model and comparing it with theoretical values from Lee thesis. The analysis done on quarter symmetry model is well acceptable for doing further transmission loss analysis saving lot of computing power, time and also disk space. And +/-3 dB of variation was achieved which is acceptable.

Finally, the hybrid mufflers having both perforated reactive and dissipative muffler capabilities was designed with 3 different iterations for different air gaps between the absorptive material and perforated pipe. And transmission loss analysis was done using FEA and compared with perforated reactive and dissipative mufflers[11]. Results showed a proper +/-3dB variations with the experimental values. This work was then successfully concluded and design was feasible and goes with the industrial standards.

METHODOLOGY

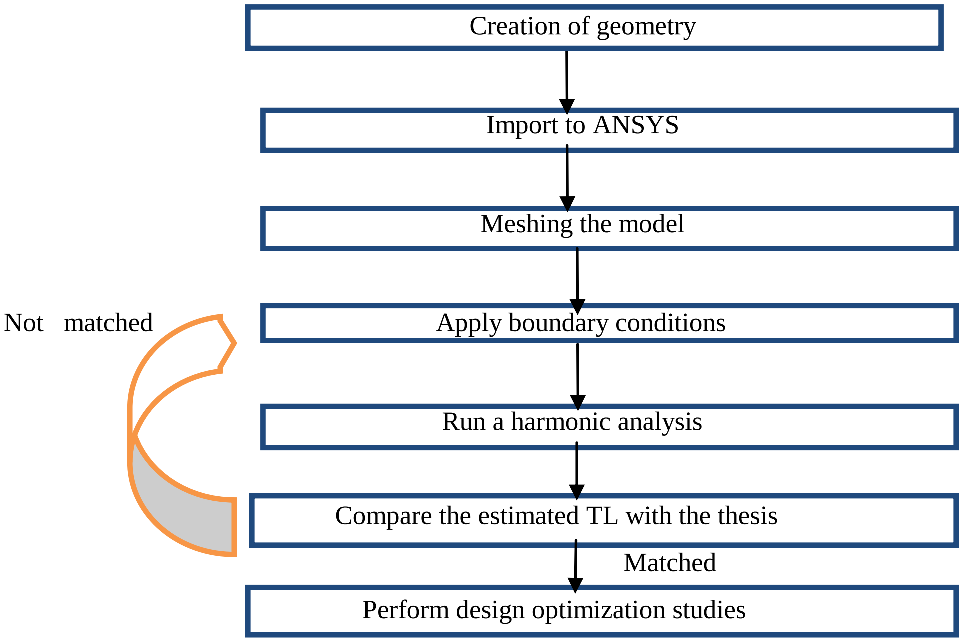

Fig 1: Shows work methodology

2. VALIDATION OF DISSIPATIVE MUFFLER USING ANSYS

2.1 Design

In dissipative mufflers, Outer Chamber is filled with fibrous material (here, Glass wool). Attenuation of acoustic waves in the absorbing material is mainly due to viscous and thermal dissipation. A Schematic diagram dissipative muffler is shown in the Fig 2.

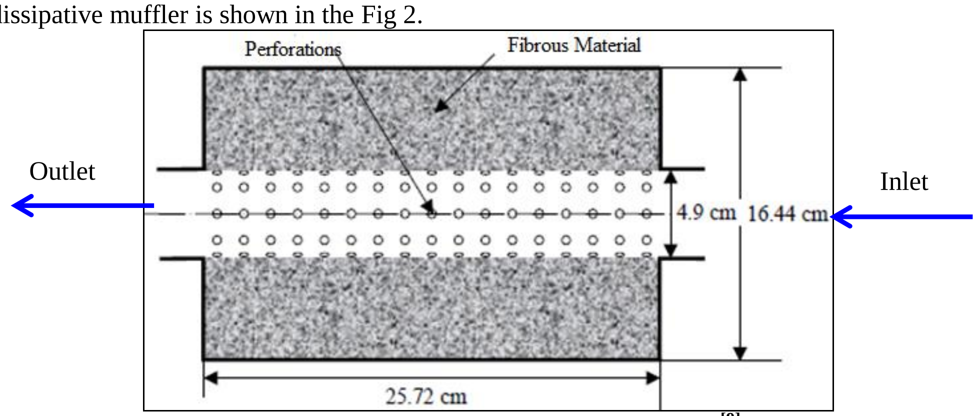

Fig 2: A schematic diagram of dissipative muffler [9]

2.2 Preprocessor

The CAD model can be then imported into ANSYS Mechanical APDL as a neutral file format. This model can be then imported into ANSYS which can be seen in fig. Apparently, ANSYS does have element that can suit for our type of applications.FLUID30 is used for modelling the fluid medium and the interface in fluid/structure interaction problems [12]. Typical applications include sound wave propagation and submerged structure dynamics. The below are the steps involved in ANSYS.

Preprocessor>element type>3d Fluid30>options>select K2=structure absent>select K4=1>ok

Preprocessor>real constants>edit>pref>20e-5>ok
Preprocessor>Material constants>select SONC=343>ok>select density=1.2041>ok>ok

Different dissipative fluid models

Dissipative material or fibrous material cannot be modeled directly in ANSYS. Equivalent fluid perforated material will be used for this purpose. Due to the complex structure of absorbing material, these acoustic properties are often determined experimentally (Delany and Bazley)[13]. There are five equivalent fluid models available in ANSYS. For designing the model using JCA, there are many inputs to be provided which will not be available in most of the times. And same goes for ZPRO and CDV method. This leaves us with Delany-Bazley and Miki Model which needs only one characteristics i.e., flow resistivity.

TBOPT	Model	Input Parameters
JCA	Johnson-Champoux-Allard	Fluid Resistivity σ, Porosity φ, Tortuosity α_{∞}, Viscous Characteristic Length Λ, Thermal Characteristic Length Λ′
DLB	Delany-Bazley	Fluid Resistivity σ (0.01 < f/σ <1.00)
MIKI	Miki	Fluid Resistivity σ (f/σ < 1.00)
ZPRO	Complex Impedance and Propagating Constant	Resistance R_s, Reactance X_s, Attenuation Constant α, Phase Constant β
CDV	Complex Density and Velocity	Complex Effective Density and Velocity

Table 1: Shows equivalent fluid models in ANSYS[12]

In general, the complex numbers of characteristic impedance and wavenumber are employed to account for the dissipation of wave through the absorbing material. Due to the complex structure of absorbing material, these acoustic properties are often determined experimentally which is available with us in literature. Hence, the TL estimation of dissipative muffler is preceded by using two models. One is based on Delany-Bazley model and other one is Miki model.

2.3 Boundary conditions

The following boundary conditions are defined:

- Definition of Ports i.e., inlet and outlet ports are defined using ANSYS Commands

  For defining ports using command in ANSYS, we can use these following commands

  For inlet port is defined as follows

  cmsel,,inletPortNodes ! select the inlet nodal components
  nplo ! plot nodes
  sf,all,port,1 ! inlet port definition

  For outlet port is defined as follows

  cmsel,,outletPortNodes ! select the outlet nodal components
  nplo ! plot nodes
  sf,all,port,2 ! outlet port definition

  This defines the inlet and outlet port for the model.

- Inlet and outlet ports are assumed to have non-reflective boundary condition to achieve anechoic condition at inlet and outlet ports .To achieve non-reflective boundary at ports for getting anechoic conditions commands are used which are as follows:

  At inlet port

  cmsel,,inletPortNodes ! Select the inlet nodal components
  nplo ! Plot nodes
  sf,all,inf ! Radiation boundary or non-reflective condition

  At outlet port

  cmsel,,outletPortNodes ! Select the outlet nodal components
  nplo ! Plot nodes
  sf,all,inf ! Radiation boundary or non-reflective condition

- The dissipative muffler model can defined using commands.

  Below commands are used for the definition of Delany-Bazley and Miki model.

  Fluid resistivity is used as input for this which is default value of 4896 N.s/m^2.

  tb,perf,2,,model name ! Defining Delany-Bazley Model use DLB and for MIKI model use MIKI
  tbdata,1,4896 ! Fluid Resistivity

Meshing

For generating proper mesh, wavenumber and wavelength determination is important since we are doing analysis by FEA method. Normally, to have high accuracy in FEA analysis, it is necessary to maintain 4 elements per each wavelength.

For wavelength calculation,

$$\lambda = \frac{c}{f} \qquad \cdots\cdots\cdots (1)$$

Since the range of frequencies in muffler is from 0-3000Hz.

Maximum frequency, f=3000Hz

Sonic Velocity or sound velocity, c =343 m/sec

$$\lambda = \frac{343}{3000} = 0.114 \text{ m}$$

And there has to be 4 elements per wavelength,

then the Mesh density or Max element size = wavelength / 4

= 0.114/4= 0.0285 m = 28.5 mm

The above is the mesh density at frequency of 3000 Hz for max safety of the muffler. Then we will proceed with mesh tool of ANSYS. The Fig: 4b shows a good quality hexahedral mesh is generated with a mesh density of 10mm.

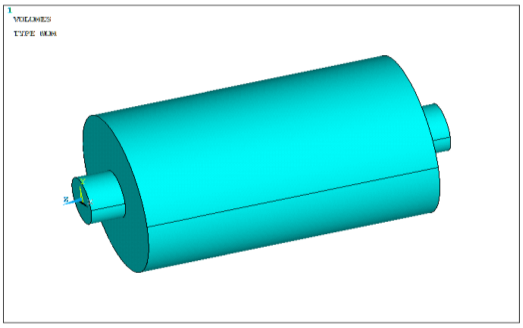

Fig 3: Shows a imported model of dissipative muffler

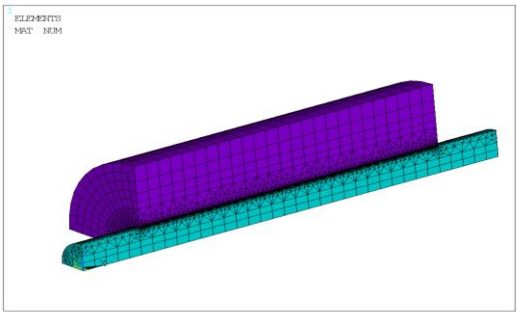

Fig 4 : Shows a meshed model of dissipative muffler

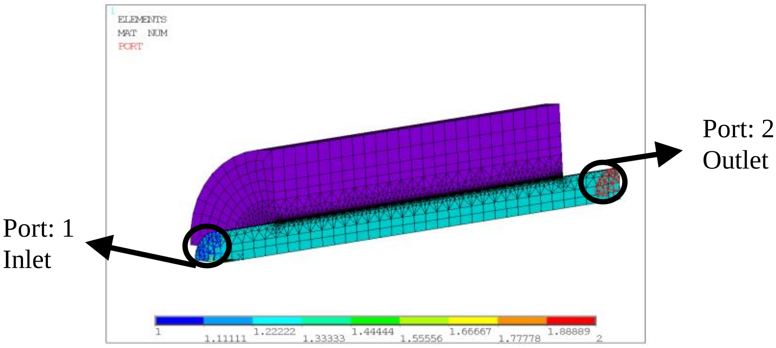

Fig 5: Shows a definition of ports in ANSYS

Solution

First we need to calculate impedance since without this thee TL cannot be calculated.To solve for the TL, a detailed harmonic analysis needs to be performed at several frequencies. The harmonic analysis is done in steps of 50 Hz each like 0, 50, 100,…, 3000 Hz. It can be obtained by giving GUI options or commands.

Impedance

The ANSYS commands for calculating impedance is given as

```
rho=1.2041              ! Air density
c0 =343.24              ! Sound Velocity
impedance=rho*c0        ! 1 Pa pressure wave
vn =-p / impedance      ! Estimated surface normal velocity
cmsel,,inletPortNodes   ! Select the inlet nodal components
nplo                    ! Plot nodes
```

sf,all,shld,v ! Uniform normal velocity at inlet port in harmonic analysis
sf,all,impd,impedance ! Apply impedance at inlet port

Harmonic analysis

Below is commands which can run the solution from 50Hz to 3000Hz in the step of 50hz each(means no of sub steps=60).

alls, ! Select everything
antype, harmic ! Analysis type-Harmonic
hropt,auto ! Full element formulation
harf,0,3000 ! Run from 0 to 3000 Hz
nsub,60 ! 50 Hz interval
solve
finish

Acoustic contour plots

For getting SPL contours plots , we can type the commands which is given as
spower,1,2 ! sound pressure between port 1 & 2

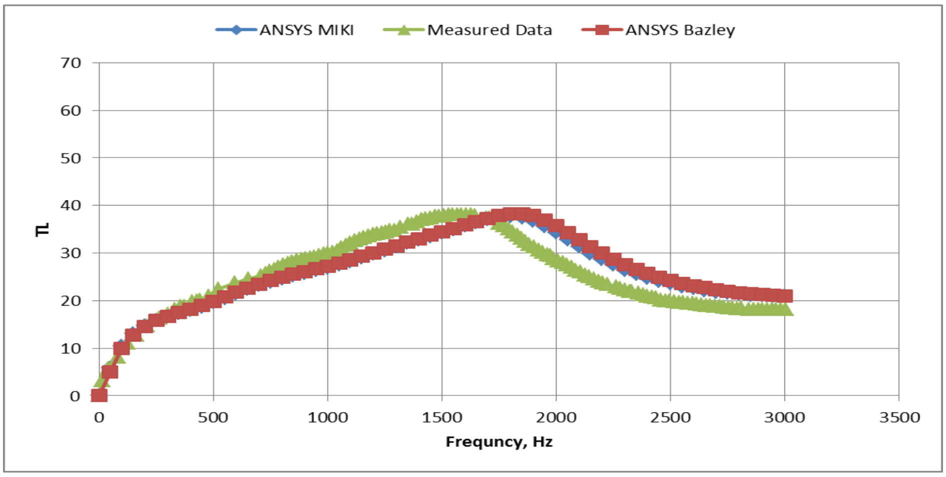

Fig 6: Shows comparison of TL with literature data, ANSYS miki and ANSYS delany-bazley dissipative muffler model

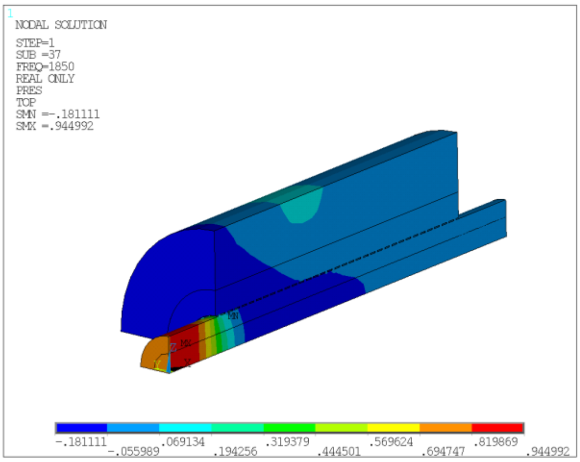

Fig 7: Shows pressure contour at frequency, f=1850 Hz

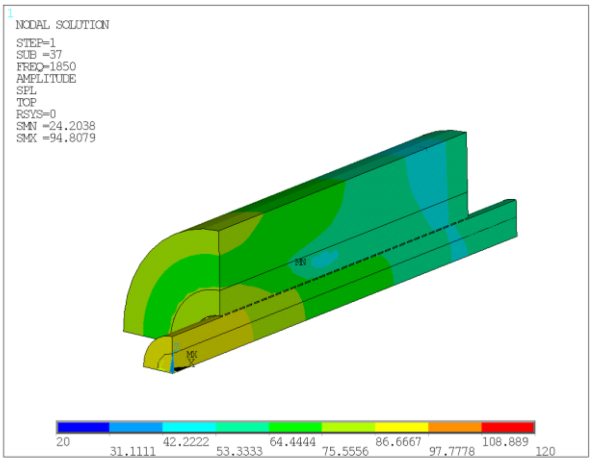

Fig 8 : Shows SPL contour at frequency, f= 1850 Hz

The graph in fig 6 shows the TL comparison of ANSYS MIKI and ANSYS Delany-Bazley with literature data. If we have a good observation of this graph, we can see that Miki and Delany-bazley model curves coincide with eachother i.e., they have almost same values. This tells us that the values of model is more than enough for this TL comparison with hybrid muffler TL analysis. In the fig 7, we can see that TL difference between both Miki and Delany-Bazley models is +/-2dB only. The delany bazley and miki models shows similarities hence we can proceed for pressure contour and SPL contour at a frequency of 1850 Hz where TL observed is maximum. The fig 8 shows the SPL contours at frequency where TL is high. In this figure we can see that sound pressure at inlet is 88 dB and the sound pressure at outlet is 52 db.This makes the TL of about 36 dB which we can also see in the TL graph at f= 1850 Hz.

The following inference can be taken from this analysis which are

- The trend of literature data & ANSYS results are almost similar.
- Even though max TL is same in both the cases, there is shift of 150Hz in case of ANSYS. This is due to the material properties. Capturing porous media is always challenging with the present formulations.
- Both Miki & Bazley results are quite comparable & are similar in trend.
- Miki model will be used for the next hybrid analysis.

3. DESIGN OF HYBRID MUFFLER

3.1 Design

In this design, we will design a hybrid muffler having same design specification that we have used previously for dissipative. The silencer length L= 25.72 cm, d_1 = 4.90 cm, d_2 = 16.44 cm, hole dia. = 2.49 mm, porosity =8.4 %, fibrous material density ρ_f=100kg/m^3 and no .of holes = 680 holes [9]. This model can be designed using CAD software packages such as CATIA.

In this there will be three iterations, Iter-1 will have only one difference i.e., thickness of the absorptive material will not be 57 mm but 40 mm. This is because we will keep 17 mm gap between absorptive material and perforated pipe to provide resonance inside the muffler giving it a reactive effect as in fig 10. The Iter-2 will have air gap of 23mm between absorptive material and perforated pipe which is greater than the 17mm air gap as shown in fig 11.The Iter-3 will have air gap of 31mm between absorptive material and perforated pipe, this is greater than the absorptive material thickness as shown in fig 12.

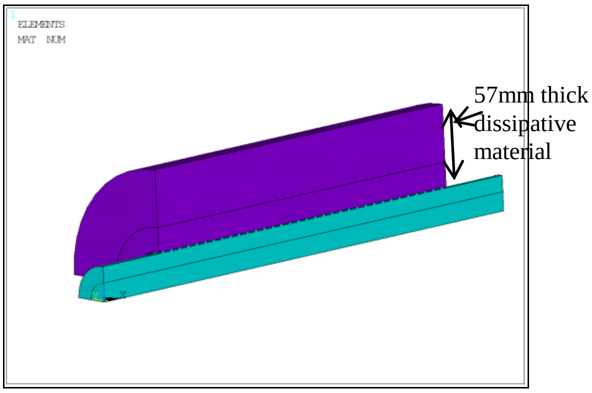

Fig 9: Shows the dissipative material thickness in dissipative muffler model

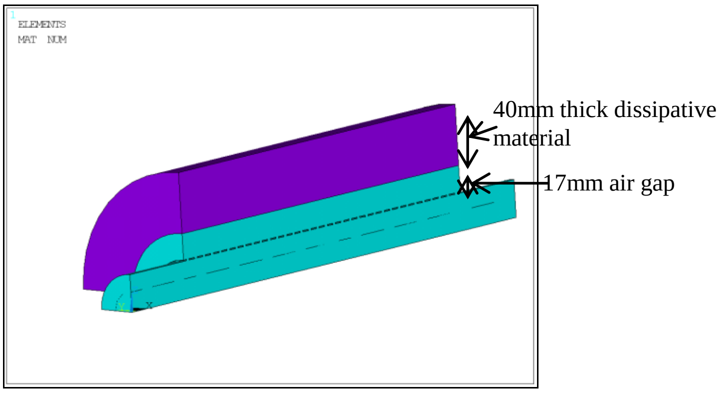

Fig 10: Shows the hybrid muffler iter-1 model

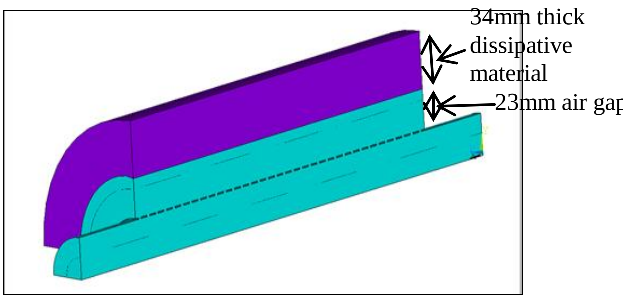

Fig 11 : Shows the hybrid muffler iter-2 model

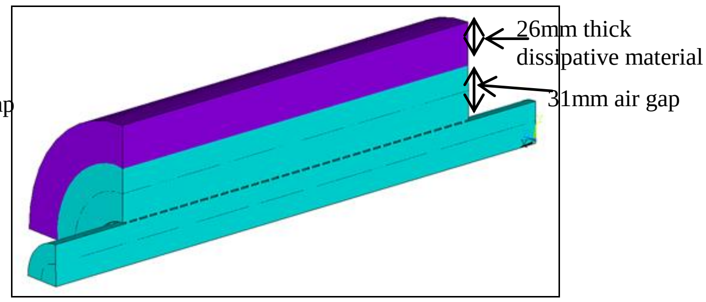

Fig 12: Shows the hybrid muffler iter-3 model

3.2 Meshing and Definition of Ports

The meshing can be done on the basis of principle of wavelengths i.e., only maximum of 4 elements per each wavelength. The previous calculated values of Mesh density or maximum element size of 28.5 mm is good enough for this analysis as well. Hence we will design a good quality hybrid mesh which is generated with a mesh density of 10mm more than the calculated mesh density of 28.5mm and tetrahedral mesh is used at the corners. The definition of ports is next important step that we should never forget. In this step, ports are defined using commands we previously used in case of dissipative muffler.

The commands for this can be taken from the previous dissipative model. Since we already know that we got to have non-reflective boundary condition at the inlet and outlet for having anechoic conditions. This condition is necessary to create reactive muffler property. The present hybrid muffler is based on the miki model for dissipative muffler. This makes it easy to do analysis for hybrid muffler. The next figure 13a, 13b & 13c shows the definition of ports for iter-1, iter-2 and iter-3 respectively. After defining the boundary conditions we will proceed with the solution generation. The Command for which is already been defined for dissipative muffler. The same commands will be used here as well. Then result for this solution is generated for harmonic analysis in next section.

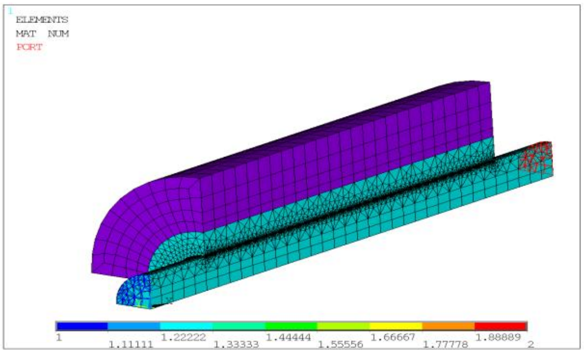

Fig 13a: Shows definition of ports in iter-1 hybrid muffler model

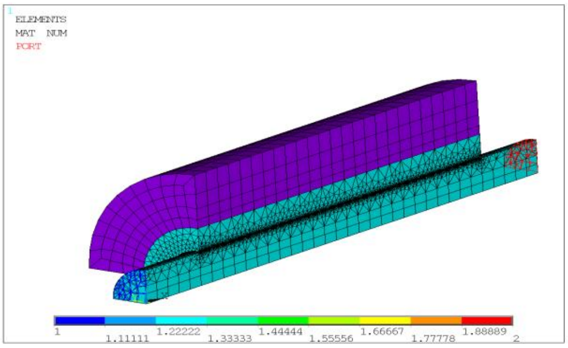

Fig 13b: Shows definition of ports in Iter-2 hybrid muffler model

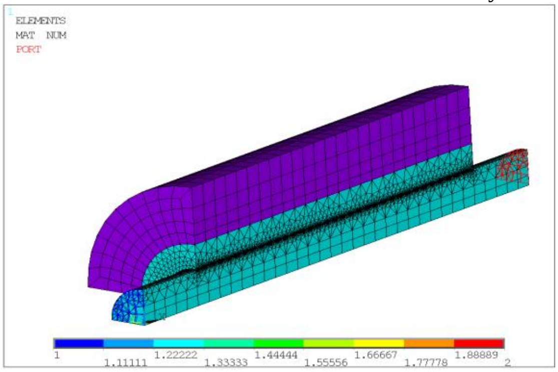

Fig 13c: Shows definition of ports in iter-3 hybrid muffler model.

4. RESULTS AND DISSCUSSION

The solution for the harmonic analysis is done at a frequency interval of 50 Hz is based on the commands given in the previous section for dissipative muffler. The frequency ranges for this analysis is from 0-3000Hz.

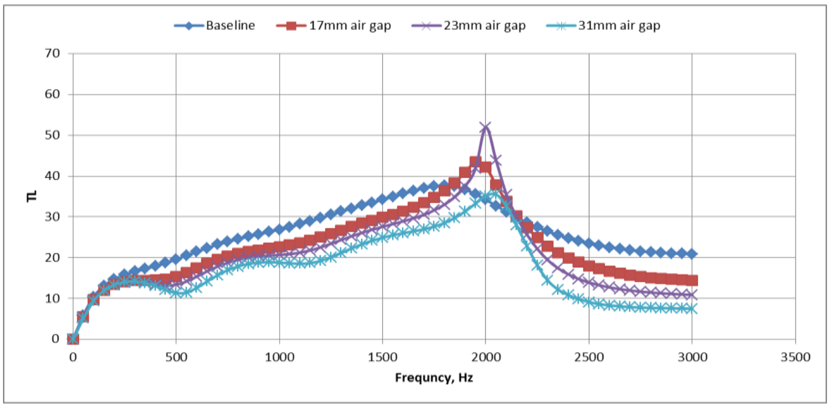

Fig 14: Shows the comparison of TL between baseline data, iter-1,iter-2 and iter-3 muffler model.

The comparison of TL b/w experiment & current ANSYS values for 17 mm, 23 mm & 31 mm hybrid models is shown in fig 14. The baseline values are the MIKI model values for dissipative mufflers. The frequency at which the highest TL is observed is 1950 Hz is around 43.7 dB for the case of iter-1 hybrid muffler model which is 5dB higher than the baseline values. In case of iter-2 model, the maximum TL is observed is 52dB which is 14dB greater than the baseline value at a frequency of 2000Hz. Now for iter-3 model, the maximum TL is observed is 35dB which is 3dB less than the baseline value at a frequency of 2050 Hz. This can be seen in fig 16 as the graph takes a peak in the range of 1500-2500 Hz. This means that the muffler performs well in the high range where conventional mufflers do not perform.

To understand the TL shown in the graph, we can have a look into the pressure contour and SPL contour at a frequency of 1950 Hz which is shown in fig 15a and fig 15b shows the pressure contour for iter-1 at frequency where TL is high. In this figure, we can see that SPL at inlet is around 97 dB and the SPL at outlet is around 53 dB. This makes the TL of about 44 dB which is the difference between the inlet and outlet SPL. We can also see this in the TL graph at f= 1950 Hz.

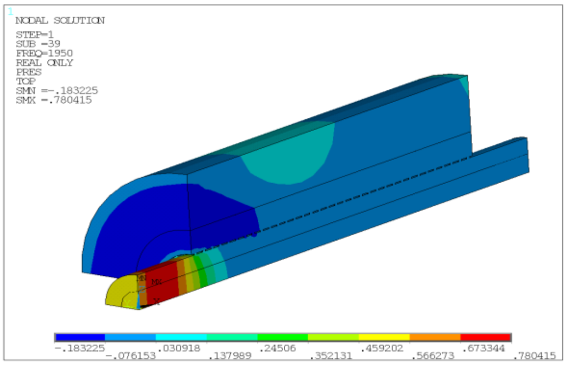

Fig 15a: Shows SPL contour plot for iter-1 at frequency, f =1950 Hz

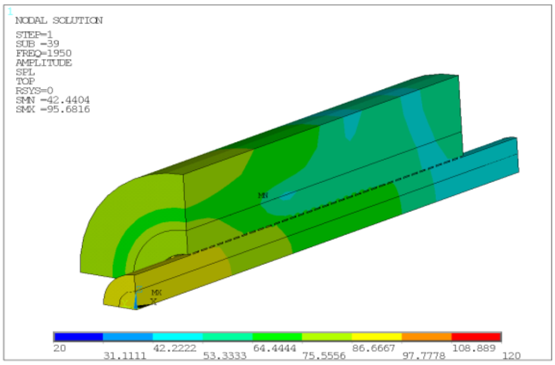

Fig 15b: Shows pressure contour plot for iter-1 at frequency, f =1950 Hz

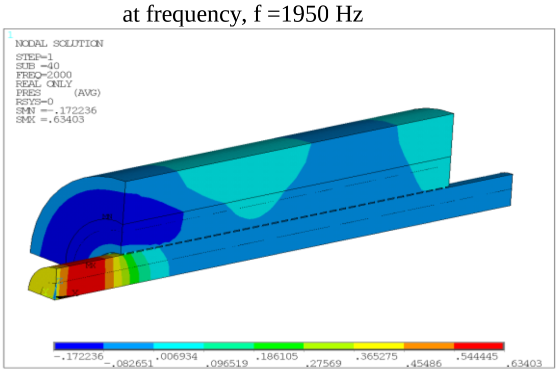

Fig 16a: Shows SPL contour plot for iter-2 at frequency, f=2000 Hz

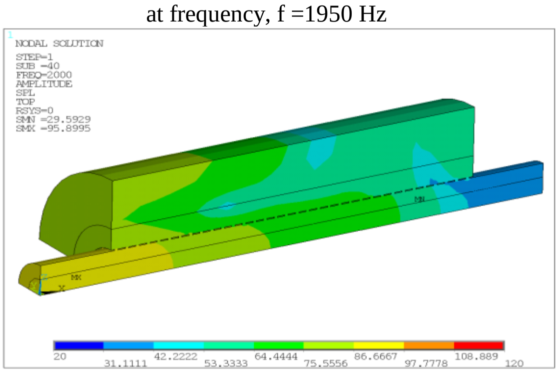

Fig 16b:Shows pressure contour plot for iter-2 at frequency, f=2000Hz

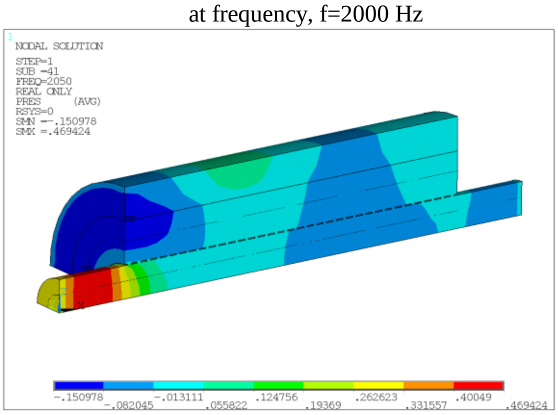

Fig 17a: Shows pressure contour plot for iter-3 at frequency, f = 2050 Hz

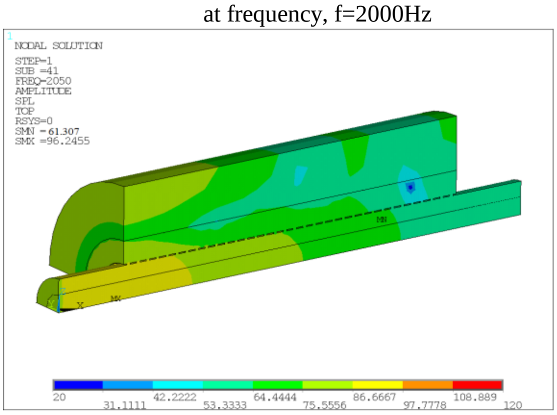

Fig 17b: Shows SPL contour plot for iter-3 at frequency, f = 2050 Hz

Similarly, the fig 16a shows the SPL contour of iter-2 model at a frequency of 2000Hz. Now for iter-2 model having 23mm air gap at frequency of 2000Hz is around 51.9 dB which is 8.2 dB higher than the TL of 43.7 dB observed for 17 mm gap muffler. This can be seen as the graph takes a peak in the range of 1500-2500 Hz. This means that the muffler performs well in the high range where conventional mufflers do not perform.

The fig 17b shows the SPL contours for iter-3 model having 31mm gap at frequency of 2050Hz. In this figure, we can see that sound pressure at inlet is 97 dB. The highest TL observed is around 35 dB which is 8.7 dB less than the 17mm gap hybrid muffler. This iter-3 muffler follows closely with the baseline curve at lower frequencies. This means that the muffler performs well in the range in the low range i.e., its reactive muffler capabilities are intact whereas same cannot be said for the case of higher frequencies. This results shows that the absorptive capabilities of dissipative muffler are over performed by resonant chamber due to increase in the air gap between the dissipative and reactive pipe. From the above statement we understand that if the air gap is more than the absorptive glass wool material thickness then the dissipative property of hybrid muffler is undermined and hybrid muffler performance decreases as the TL decreases.

Comparison of results

To understand the above result more accurately we will compare the TL for iter-1, 2 &3 as well as miki and delany bazley model. The following table shows the comparison of all muffler models discussed in terms of Maximum TL.

Muffler Models	**Maximum Transmission Loss (dB)**
Iter-1	44
Iter-2	52
Iter-3	35
Miki	38
Bazley	38

Table 2: Shows transmission loss comparison of muffler models.

The comparison shows that the Iter-2 hybrid muffler model is giving more TL than the rest of muffler models. The conclusions to the above results will be given in the next section.

5. CONCLUSION

In this present work there can be numerous conclusion can be taken which can improve the study for future work in this area of research. When the TL analysis of dissipative muffler with porous media using bazely & miki models was carried out then we observed that the trend of TL of these two models are quite comparable with experimental results. This showed that the either of the model can be used as the basis for carrying out the analysis on the hybrid muffler. Analysis of a hybrid muffler designed from dissipative muffler by creating an air gap before glass wool was executed. An increase in TL was observed. This was due to combination of reactive, dissipative & resonant behaviour of muffler. This hybrid muffler was analysed in 3 different iterations based on different air gap between perforated pipe and absorptive layer.

In iter-1, at 1950Hz, max TL of 43.7dB was observed which 5dB higher than baseline analysis curve was. Also, the TL curve of current analysis is bit lower by 3dB (approx.) to baseline TL curve.

In iter-2, at 2000 Hz, max TL of 51.9 dB was observed which 14 dB higher than baseline analysis curve. This TL curve of current analysis is bit lower by 4dB (approx.) to baseline TL curve.

In iter-3, unlike the previous iterations, at 2050Hz, max TL of 35dB was observed which was 3dB lesser than baseline analysis. It was explicitly visible from these analysis, that the effect of porous & air media was well affecting the TL for these three iterations. In iter-3, the air gap was more than the thickness of absorptive media which decreases the TL.

From iter-1, 2& 3 TL analyses, we can conclude that the thickness of air media cannot be less than the thickness of porous media. Else, there will be an adverse effect of TL. After carrying out this work the iter-2 hybrid muffler was found to be more feasible to work with. This work will significantly give hybrid muffler design a new way of analysis using ANSYS.

SCOPE FOR FUTURE WORK

There is still room for improvement in this area as we all know that research is a never stopping thing. The following are the areas where future work can be done:

- TL of dissipative muffler can be estimated using JCA method which requires more material properties.
- In iter-1&2, the trend of TL can be changed further by fine tuning the air & muffler interaction or introducing a perforated sheet b/w them.
- Studying the complex interaction of impedance b/w air gap & porous media, a correlation can be derived for predication of TL in case of hybrid muffler.
- We can further do analysis check for the optimal air gap between the perforated pipe and porous media.

ACKNOWLEDGEMENTS

The author would like to thank Mr. Aravind Kumar who helped me in conducting this work. Also the author would like to thank the support of the Department of Mechanical Engineering, Christ University, Bangalore, in particular to Prof. Hadiya Pritesh the Asst. Professor of Mechanical Engineering for the computing and other facilities he has offered me to conduct this paper.

REFERENCES

1. Peik, P. G., "Muffler", United States Patent, 2014666, 1935.
2. Munjal, M. L., "*Acoustics of Ducts and Mufflers*", John Wiley and Sons, Inc., New York, 1987.Craggs, A., "*A finite element method for modeling dissipative mufflers with a locally reactive lining*", *Journal of Sound and Vibration* 54, 1977, pp.285-296.
3. Astley, R. J. and Cummings, A., "*A finite element scheme for attenuation in ducts lined with porous material comparison with experiment*", *Journal of Sound and Vibration* 116, 1996, pp.239-263.
4. Kagawa, Y., Yamabuchi, T., and Mori, A., "*Finite element simulation of an axisymmetric acoustic transmission system with a sound absorbing wall*", *Journal of Sound and Vibration* 53, 1977, pp.357-374.
5. Cummings, A. and Astley, R. J., "*Finite element computation of attenuation in bar silencers and comparison with measured data*", *Journal of Sound and Vibration* 196, 1996, pp.351-369.
6. Peat, K. S. and Pathi, K. L., "*A finite element analysis of the convected acoustic wave motion in dissipative Silencers*", *Journal of Sound and Vibration* 184, 1995, pp.529-545.
7. Crocker, M. J., "*Handbook of Acoustics*", John Wiley & Sons, Inc., 1998, New York.
8. Israel Jorge Cardenas Nuñez, *et al*., "*Investigating the Transmission Loss of Compressor Suction Mufflers Applying Experimental and Numerical Methods*", *International Compressor Engineering Conference*, 1172, 2008, pp.1-8.
9. Iljae Lee, M.S., "*Acoustic characteristics of perforated dissipative and hybrid silencers*", Ph.D. Thesis, Ohio State University, 2012.
11. Potente, Daniel, "*General Design principles for an automotive muffler*", *Proceedings of Acoustics*, Western Australia, 2005.
12. ANSYS Mechanical APDL acoustic analysis guide release 15, 2013.
13. Delany, M. E. and Bazley, E. N., "*Acoustical properties of fibrous absorbent materials*", *Applied Acoustics 3*, 1970, pp.105-116.