INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

RESEARCH ARTICLE

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OPEN ACCESS

Received: 09-08-2022

Accepted: 19-12-2022

Published: 19-05-2023

Citation: Kale A, Surve F (2023) Role of End-Correction in Enhancing Transmission Loss Estimates in Case of Extended Inlet-Outlet Expansion Chamber Mufflers Using Simulation. Indian Journal of Science and Technology 16(19): 1453-1460. https://doi.org/10.17485/IJST/v16i19.1645

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Funding: None

Competing Interests: None

Published By Indian Society for Education and Environment (iSee)

ISSN
Print: 0974-6846
Electronic: 0974-5645

Role of End-Correction in Enhancing Transmission Loss Estimates in Case of Extended Inlet-Outlet Expansion Chamber Mufflers Using Simulation

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Abstract

Objectives: Measuring transmission loss of a muffler in a lab setting ideally requires an anechoic termination at one end, and hence turns out to be tedious. Simulation gives the freedom of changing the geometry of object without destructing it. **Methods:** Lab grade expansion chamber mufflers are remodelled into extended tube expansion chamber mufflers using simulation. Furthermore, applying end correction helps in optimizing their geometry. The same technique is extended to concentric tube resonators by varying the porosity handle. **Findings:** With simulation, number of parameters can be changed multiple times by keeping other handles constant. **Novelty:** Lab grade mufflers are to be modified with non-destructive method for getting improved performance. Hence, to check and optimise the parameters, the present dimensions of lab grade mufflers are kept constant and the results are checked using simulation technique.

Keywords: Concentric tube resonator; Endcorrection in mufflers; Extended tube expansion chamber muffler; Simulation; Transmission loss

1 Introduction

The muffler is inevitable part of automobiles. Reactive muffler is one of the passive noise control devices used to control unavoidable noise; using destructive interference as a principle [1]. Wherever there is either sudden contraction or sudden expansion, the phase of the reflected wave changes causing destructive interference [2]. The reactive muffler is prone to generate backpressure, decreasing efficiency at times, and increasing fuel consumption [3]; however, the reactive muffler is the perfect option for studying Transmission Loss at low frequency range [4].

A Simple expansion chamber muffler (SECM) is the type of reactive muffler having two tubes of different cross sections joined together creating an expansion chamber. Figure 1 shows schematic diagram and actual view of lab grade mufflers. Muffler performance or attenuating capability is evaluated mainly by determining transmission loss. Transmission loss (TL) is the acoustic power level difference between the incident and transmitted wave through a muffler [5]. It is due to sudden expansion of acoustic wave at inlet and contraction at outlet of expansion chamber which causes sound waves to reflect and interfere destructively with each other [6]. The result of this destructive interference is studied with the help of three mufflers as: M-1 with ratio of cross section of expansion chamber to that of inlet/outlet pipe m=4.78, M-2 with m=7.27 and M-3 with m=12.14 [7].

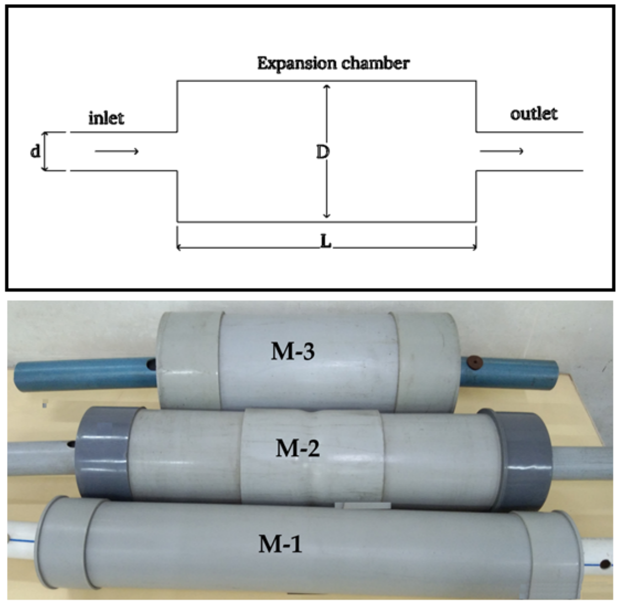

Fig 1. Simple Expansion Chamber Muffler schematic diagram and actual lab mufflers

For Simple Expansion Chamber, Transmission Loss in dB is calculated using standard formula [6].

$$TL = 10log_{10}\left(1+\frac{1}{4}\left(m-\frac{1}{m}\right)^2 sin^2 kL\right\} \tag{1}$$

where,

TL is Transmission Loss due to the muffler

$m = \frac{D^2}{d^2}$ where, D = Diameter of central chamber&d= Diameter of inlet or outlet pipe

L= length of central chamber, (parameters are as shown in Figure 1)

and k is wave number that can be given by $\frac{2\pi f}{c_0}$

The predictable transmission loss curve has a maximum at sin kL=1 hence, frequency at which TL is maximum is given by

$$f = \frac{(2n+1)\,c_0}{4L} \tag{2}$$

where, n = 0, 1, 2, …. and c0 is speed of sound at 20°C

The minima i.e., TL=0 is at sin kL=0 (ref. Eqn.1) and hence,

$$\text{kL} = \text{n}\pi \text{ or } \frac{2\pi f}{c_0}L = n\pi \text{ hence, } f = \frac{nc_0}{2L} \tag{3}$$

Hence, troughs will occur at the frequency values $\frac{c_0}{2L}, \frac{c_0}{L}, \frac{3c_0}{2L}, \ldots\ldots\ldots$ [6] proving inefficiency of muffler at those frequencies. Troughs cannot be avoided but can be uplifted to some extent, which can be achieved using an "extended tube expansion chamber muffler" (ETECM); in which the inlet and outlet ports are protruded within the chamber.

1.1 Extended Tube Expansion Chamber Muffler (ETECM)

Extended tube Expansion Chamber Muffler" (ETECM) is the muffler in which the inlet and outlet tubes are extended into the expansion chamber [6], Figure 2. The lengths of inlet and outlet ports inside the chamber are so chosen that l_1=L/2 and l_2=L/4

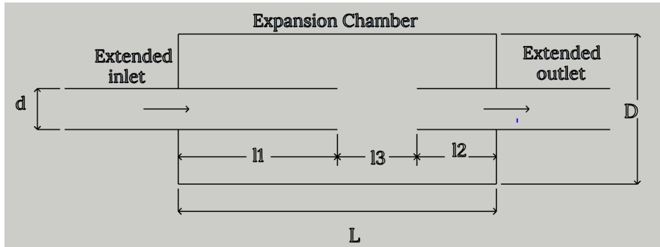

Fig 2. Extended tube Expansion Chamber Muffler

respectively. Above this, the Acoustic length of this muffler exceeds the physical or geometrical length of annular resonator by an end correction (δ) which is due to the generation of higher order evanescent modes. Hence, actual geometric lengths ofextended inlet and outlet will be

$$l_1 = \frac{L}{2} - \delta \text{ and } l_2 = \frac{L}{4} - \delta \tag{4}$$

$$\text{Hence, } l_3 = L - \left(\frac{L}{2} - \delta + \frac{L}{4} - \delta\right) \tag{5}$$

and,

$$\delta = \mathrm{d}\left\{[0.005177] + \left[0.0909\frac{D}{d}\right] + \left[0.537\frac{t_w}{d}\right] + \left[-0.008594\left(\frac{D}{d}\right)^2\right] + \left[0.02616\frac{D}{d}\frac{t_w}{d}\right] + \\ + \left[-5.425\left(\frac{t_w}{d}\right)^2\right]\right\} \tag{6}$$

Where, t_w= thickness of pipe wall and l_3 is total effective length of chamber[6]

Measuring transmission loss in case of muffler is crucial part as it requires anechoic termination at one end of muffler which may not be available in lab. Simulation, on the other hand, is the useful tool for calculation of transmission loss[8], as it gives the user the freedom of changing parameters without any destruction to original lab grade muffler, improving its performance[1]. The mufflers M-1 with m=4.78, M-2 with m=7.27 and M-3 with m=12.14 are studied for performance at lower frequency and also by applying end correction, ie by tuning a muffler.

2 Methodology

2.1 Simulation Method/Algorithm for ETECM

Step 1. Lab grade muffler M-1 is considered for parametric study of Transmission Loss using MATLAB programming.

Step 2. Length of chamber is chosen L=0.6m

Step 3. Evaluation of Transmission Loss using transfer matrix method[9]

Step 4. Application of end correction using equation 4, 5 and 6.

Step 5. Graph analysis

Step 6. Repeat step 1 by changing muffler

Mufflers M-1, M-2 and M-3 are considered separately for different lengths.TL curves are compared for dependence on ratio of cross section 'm' keeping length of chamber constant at 0.6m, for Simple Expansion Chamber, ETECM and double tuned ETECM considering end correction. The graphical representation of the same is shown in Figure 3.

Figure 3 shows significant increase in TL value with increase in ratio of cross section 'm' (m value for M-1< M-2< M-3)[10] The dependence of TL on 'm' is emphasized by equation 1. ETECM lifts the first three troughs up but fails in uplifting 4^{th}. The trend remains same for next i.e., 8^{th} 12^{th}…. troughs. It shows nearly10dB improvement in value of TL as well. The end correction applied to inlet do not change the trend shown by ETECM but it increases the performance of muffler at resonant frequency related to first trough. The first trough is lifted up quite significantly. The end correction applied to both inlet and outlet shifts the frequency corresponding to second trough. The results are in excellent agreement with that put forth by Kale et. al.[9].

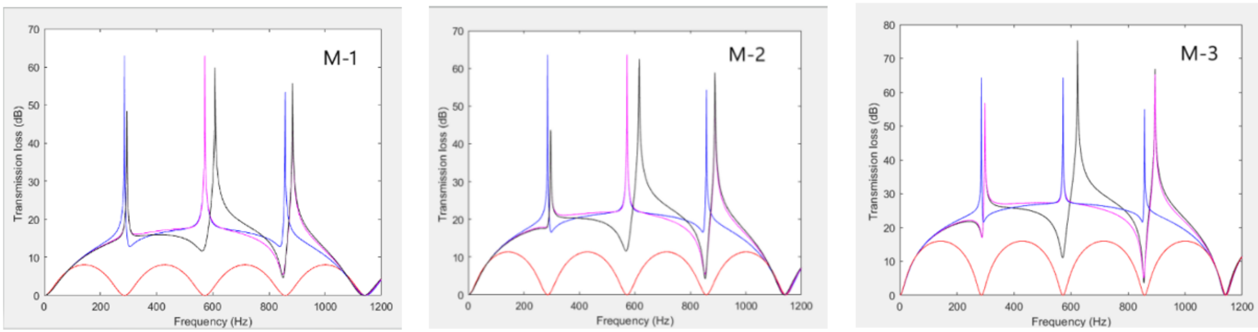

Fig 3. Graph of Transmission Loss versus Frequency for mufflers M-1, M-2 and M-3 for L=0.6m for SECM (Red), ETECM (Blue), ETECM with end correction applied to inlet (Magenta) and ETECM with end correction applied to both inlet and outlet (Black)

2.2 Extended perforated Concentric Tube Resonator (ECTR)

The extended inlet and outlet connected with a perforated tube as shown in Figure 4, acts like a bridge and helps in guiding the flow. The study of effect of perforation on performance of muffler is done by changing the geometry of muffler[11] but here the study is expanded to other parameters such as % perforation, grazing flow etc.

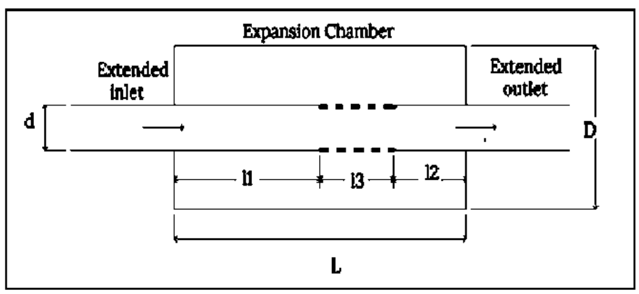

Fig 4. Extended perforated Concentric Tube Resonator

With the addition of perforated bridge between extended tubes of ETECM, decrease in back pressure as well as increase in mechanical strength and durability is noted[12]. Impedance added due to the perforation plays an important role in calculation of TL[6] hence, this perforation impedance introduced is given by[12].

$$\zeta = \theta + i\,\chi \tag{7}$$

where, $\theta = Re\left(\frac{jk}{\sigma C_D}\left(\frac{t_w}{F(\mu')} + \frac{\delta_{re}}{F(\mu)} f_{int}\right]\right\} + \frac{1}{\sigma}\left(1 - \frac{2J_1(kd)}{kd}\right] + \frac{0.3}{\sigma} M_g + \frac{1.15}{\sigma C_D} M_b$

$$\chi = \mathrm{Im}\left\{\frac{\mathrm{jk}}{\sigma \mathrm{C_D}}\left[\frac{\mathrm{t_w}}{\mathrm{F}(\mu')} + \frac{0.5\ \mathrm{d}}{\mathrm{F}(\mu)}\mathrm{f_{int}}\right]\right\} \tag{8}$$

as, t_w - orifice thickness =3mm, d - orifice diameter, σ is porosity, k (wave number) =ω/c, c - speed of sound, C_D - orifice discharge coefficient=0.8, J is Bessel function, μ -adiabatic dynamic viscosity, μ' =2.179 * μ, M_g is grazing flow Mach number, M_b is bias flow Mach number taken as 0,

k= $\sqrt{-\frac{j\omega}{\upsilon}}$ and k'=$\sqrt{-\frac{j\omega}{\upsilon'}}$

υ= μ / ρ_0 is kinematic viscosity and ρ_0 is fluid density

$$\delta_{re} = 0.2d + 200d^2 + 16000d^3 \tag{9}$$

$$f_{int} = 1 - 1.47\sqrt{\sigma} + 0.47\sqrt{\sigma^3} \tag{10}$$

Greater porosity is as good as open space but influence of impedance due to porous pipe is underlined by the difference in the graphs of ETECM and ECTR shown in Figure 5.

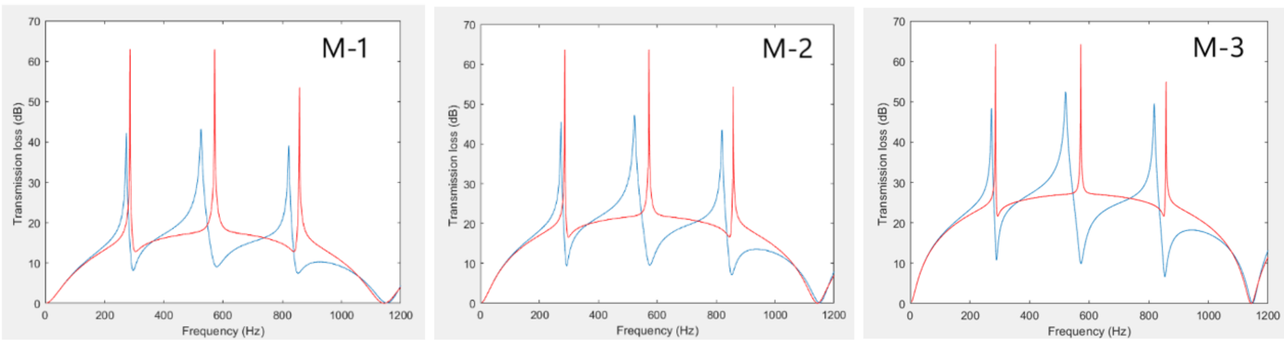

Fig 5. Comparison on TL curve for ETECM (Red) and ECTR(Blue) for L=0.6m, Mg=0 and porosity=27%

The porosity value selected is 27% which is known to be acoustically transparent, the TL performance is expected to be similar to that for ETECM [6]. However, the frequency at which TL peak occurs, is changing due to impedance introduced by perforates. The TL peaks are lowered by say 20dB, the nature of curve is also changed.

The nature of TL plot depends not only on ratio of cross section of chamber and inlet pipe but also on thickness of tube, grazing flow and porosity [6]. The study of TL versus Frequency plot by varying one parameter and by keeping all other handles constant will help in creating ready reckoner for further advanced modeling of muffler. The simulation is using following algorithm.

2.3 Simulation Method/Algorithm for Concentric tube resonator

Step 1. Lab grade muffler M-1 is considered for parametric study of Transmission Loss using MATLAB programming.
Step 2. Evaluation of Transmission Loss using transfer matrix method [9] and comparing the same with ETECM
Step 3. Study of TL curve by varying grazing flow by keeping all other parameters constant
Step 4. Study of TL curve by varying porosity by keeping all other parameters constant
Step 5. Application of end correction using equation 11
Step 6. Graph analysis
Step 7. Repeat step 1-6 by changing muffler

3 Result and Discussion

3.1 Effect of Grazing flow on TL

Extended perforated CTR shown in Figure 4 is considered with porosity 27% and grazing flow M_g is increased in the steps of 0.05 from 0 to 0.15. The length of muffler is 0.6m. The change in TL is plotted against frequency as shown in Figure 6.

The maximum value of TL is decreasing with increase in grezing flow. The impedance offered by higher values of grazing flow will affect the transmission loss of muffler. The band width is increasing with increase in grezing flow.

3.2 Effect of Porosity on TL

Porosity ie. The number of holes per unit surface area is changed from 10% to 27% by keeping the grazing flow M_g constant at 0. Length of muffler is adjusted at 0.4m.

From Figure 7, it is clearly seen that response of fully perforated expansion chamber muffler is nearly same as that of simple expansion chamber for lower frequencies but, TL is non-zero for troughs at higher frequencies. For values of frequencies greater than 1KHz, TL is decreasing with increase in porosity.

For l_1 = L/2 and l_2 = L/4 i.e., perforated ECTR with length of perforate l_3= L- (l_1+ l_2), TL value increases with increase in porosity. Figure 8 shows the same graphically.

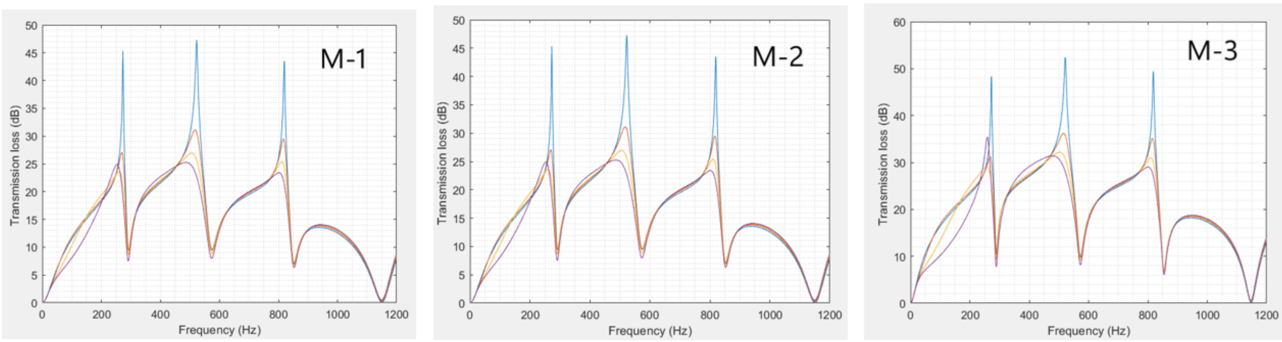

Fig 6. ECTR with total length of chamber L=0.6m, grezing flow value- 0(blue), 0.05(Red), 0.1(Yellow), 0.15(Violet) and porosity 27%

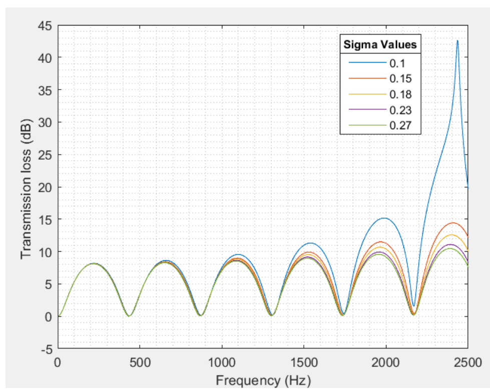

Fig 7. M-1 with L=0.4m, M_g = 0 and porosity varying from 0.1 to0.27, for fully perforated CTR (l_1=l_2=0)

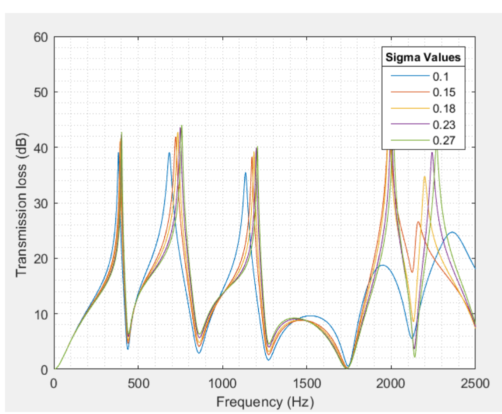

Fig 8. M-1 with L=0.4m, M_g= 0 and porosity varying from 0.1to 0.27 for perforated ECTR (l_3= L- (l_1 + l_2))

The TL values shown by perforated ECTR are nearly same as that put forth by Deery et. al.[3] which are claimed after using acoustic meta materials. The trend of uplifting troughs is maintained which is not seen in TL trend reported by Faisal et. al[1] by using in homogeneous micro perforated panel into expansion chamber. Although the TL values are lowered, the muffler can be used for a range of frequencies instead of a selected value.

3.3 End Correction

End correction required due to the generation of higher order evanescent modes is to be subtracted from length of the chamber and hence, actual geometric lengths ofextended inlet and outlet will be $l_1 - \triangle$ and $l_2 - \triangle$ respectively.

The end correction for this muffler is given by

$$\triangle = d(0.6643 - 2.699\sigma + 4.522\sigma^2) \tag{11}$$

Table 1. End correction factor for 3 mufflers for L=0.6m

Porosity	Δ for M-1 in mm	Δ for M-2 and M-3 in mm
0.1	21.98	22.86
0.15	18.06	18.78
0.18	16.25	16.9
0.23	14.14	14.70
0.27	13.26	13.79

By applying this end correction, the graphs are plotted for M-1, L=0.6m and studied by keeping porosity once as 10% and then at 27%. Figure 9 is an illustration of the same. By applying end correction to both inlet and outlet, one can have good response to a range of frequencies but by compromising with the TL value at peaks. A shift in frequency corresponding to second peak is also noted which is due to application of length correction.

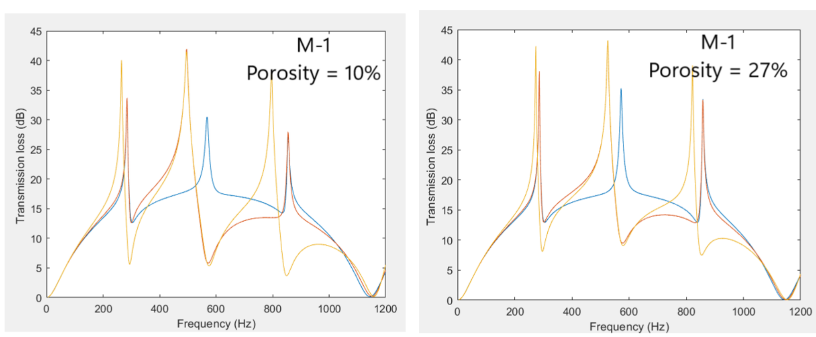

Fig 9. End correction applied to both inlet and outlet (blue), applied to only inlet (red) and no end correction applied (Yellow) for M-1, L=0.6m, Mg=0, having porosity 10% and 27%

4 Conclusion

A self-developed simulation tool in MATLAB is used to demonstrate the potentiality of the method. The noise attenuation can be studied with the help of simulation before physical changes to be done to the mufflers. The lab grade mufflers, now, can be modified to ETECM or ECTR as per the resonant frequency required. This user-friendly tool is proved to be an effective way to foster noise-reduction including optimization, offering the choice of the components and their characteristic dimensions in order to obtain the desired noise reduction with given design constraints.

The ECTR helps in reducing the back pressure if the concentric tube is perforated. The length of perforate is playing a key role in changing the behaviour of muffler. The muffler can be tuned to a particular frequency by selecting between fully perforated and partly perforated muffler and also the percentage porosity.

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