Effect of Manufacturing Defects in the form of Internal Leakages on the Acoustic Performance of Mufflers

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Abstract: The presence of manufacturing defects in the form of incomplete welding and missing perforated holes leads to internal leakages in mufflers. This results into unintended acoustic impedance modifications as well as the Herschel-Quincke effect. The narrow region acoustics model of COMSOL Multiphysics is used to simulate the thermoviscous losses associated with the leakages. The transmission loss is compared with test results for both reactive and hybrid (made up of reactive and dissipative elements) configurations. It is observed that presence of leaks has a significant effect on the acoustic performance of mufflers.

Keywords: Manufacturing defects, leakages, acoustics, transmission loss, mufflers.

1. Introduction

A new and stringent pass-by noise limit was introduced by the European Union effective from 1st July 2016. For M1 category cars with less than 120 kW/1000Kg, the new noise limit value is 72 dB(A) which will gradually reduce by 2dB to 70 dB(A) from 1 July 2020, and then finally reduce to 68 dB(A) from 1 July 2024 [1]. According to a study by Kim et al., the exhaust noise sources was found to be the strongest contributor to the new total pass-by noise. They suggest that exhaust system design should be given the highest priority for noise improvement efforts [2].

It is expected that similar reduction in pass-by noise limit will be implemented in India sooner or later. This would necessitate not only better design of mufflers but also improved manufacturing quality control. The acceptable margin of manufacturing variation will reduce. The work presented here highlights the effect of manufacturing defects in the form of internal leakages due to incomplete welding and missing perforated holes on the transmission loss of a production reactive and hybrid mufflers.

The muffler geometry is shown in Fig. 1 where the first chamber is a Concentric Tube Resonator (CTR) and the second chamber is a combination of uniform pipes, extended inlet, and reversal end chamber with perforated end plate. The third chamber is coupled with the second chamber only through the impedance of the perforated plate and the rigid end plate. A pipe originating from the second chamber takes a 180 degree turn in the first chamber and passes through the second and third chamber to form an outlet pipe. In a nutshell, the compact muffler is an assembly of selected acoustic elements. In the hybrid configuration, the first and third chambers are filled with Silentex® glasswool with filling densities of 45 g/l and 200 g/l, respectively.

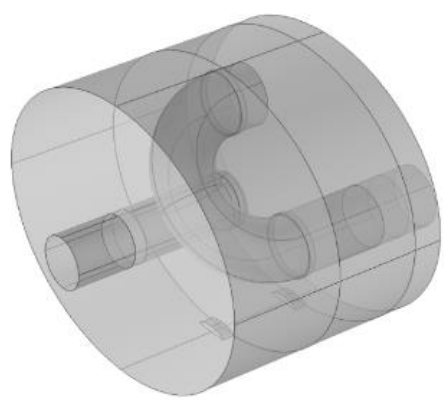

Figure 1. Muffler Geometry

2. Theory

The working principle of mufflers is based on the reflection and dissipation of acoustic waves. The reactive muffler is made up of acoustic reflective elements whereas the hybrid muffler is made up of a combination of reflective and dissipative acoustic elements [3]. For the reactive case, Sullivan and Crockers' [4] acoustic impedance is used for the perforates. For the hybrid case, Kirby and Cummings' [5] impedance formula is used for the perforates. The absorptive material is a texturized fiber glass roving manufactured by the SilentexTM process. The present study uses the texturized fiber glass roving manufactured by the Silentex^{TM} process and the Delany and Bazley model [6] of complex characteristic impedance and wave number extended to low frequencies by Mechel [7].

3. 3D FEM model in COMSOL Multiphysics®

The frequency domain pressure acoustic module is used to model the transmission loss of the mufflers. The plane wave radiation boundary condition is used at the inlet and outlet of the muffler.

The muffler is divided into different domains which are then discretized into small finite elements. By using the acoustic pressure as the independent variable, the wave propagation is solved in the frequency domain using the time harmonic pressure acoustic mode in COMSOL [8]. The governing equation is the modified version of the 3D Helmholtz equation:

$$\nabla.\left(-\frac{\nabla p}{\rho}\right) - k^2 \frac{p}{\rho} = 0 \qquad (1)$$

where $k = \omega/c$, ρ, c and ω are the density, speed of sound and angular frequency respectively. The following boundary conditions are used to simulate the system [8]:

3.1 Boundary conditions

1. At the solid boundaries, which include the outer walls of the muffler, the baffles between the chambers and the walls of the inner pipes, sound hard (wall) boundary conditions are used:

$$\left(-\frac{\nabla p}{\rho}\right).n = 0 \qquad (2)$$

here n is the unit normal vector.

2. At the inlet boundary, a combination of an incoming and outgoing plane waves is assumed:

$$\left(-\frac{\nabla p}{\rho}\right).n = \frac{i\omega}{\rho c} p - \frac{2i\omega}{\rho c} p_0 \qquad (3)$$

where $p_0 = 1$ Pa is the applied pressure at entrance to the inlet pipe and i is the imaginary unit.

3. At the outlet boundary, an outgoing plane wave radiation condition with a vanishing reflection coefficient (anechoic termination) for normally incident waves is used:

$$\left(-\frac{\nabla p}{\rho}\right).n = \frac{i\omega}{\rho c} p \qquad (4)$$

4. The specific acoustic impedance of perforates at the inner pipe and perforated baffle are modelled by using equations (5) and (6) for the reactive and hybrid configurations, respectively.

$$Z_0 = \rho c\left(0.006 + ik(t_h + 0.75 d_h)\right)/\sigma \qquad (5)$$

$$Z_c = \rho_w c_w \left\{0.006 + ik\left(t_h + 0.375 d_h\left(1 + \frac{\rho_w c_w k_w}{\rho c k}\right)\right)\right\}/\sigma \qquad (6)$$

where t_h, d_h, ρ_w, c_w, k_w and σ are the thickness, perforated hole diameter, density of

3.2 Modeling without internal leakages

Assuming perfect manufacturing quality, the physics and boundary condition in this condition is as described in section 3.1.

3.3 Modeling with internal leakages

The manufacturing defects that are observed are incomplete welding and missing perforated holes as shown in Figs 2 to 4.

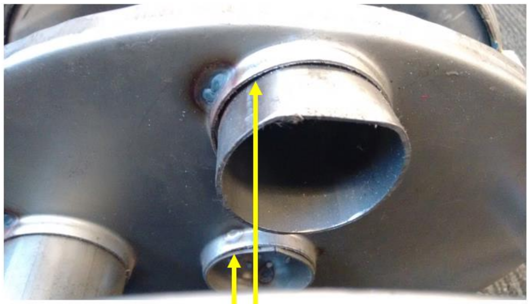

Figure 2. Incomplete welding

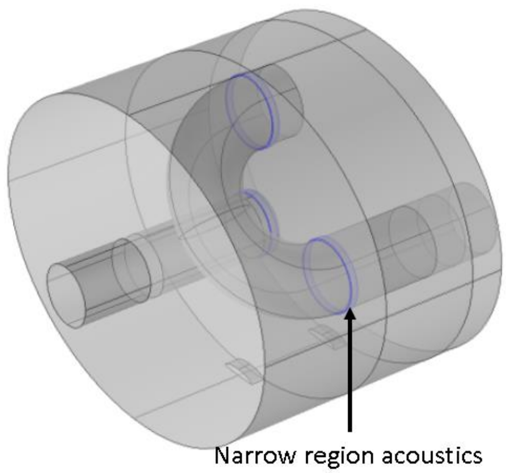

Figure 2a. Incomplete welding modeled as narrow region acoustics

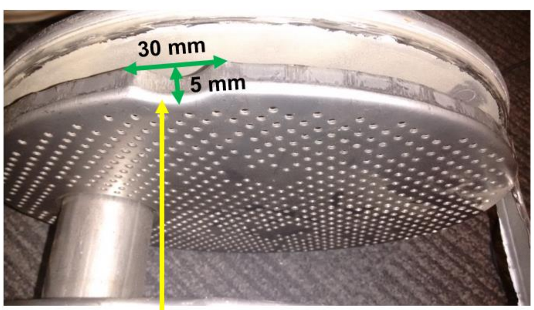

Figure 3. Weep holes

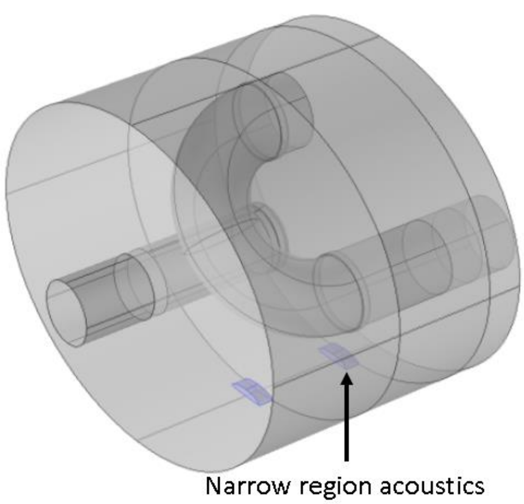

Figure 3a. Weep holes modeled as narrow region acoustics

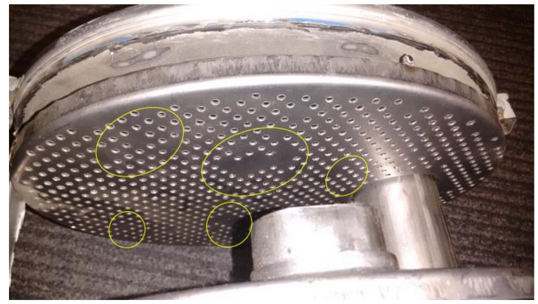

Figure 4. Missing perforated holes

Incomplete welding and weep holes (to reduce internal corrosion) leads to internal leakages which in-turn cause impedance modifications and the Herschel-Quincke effect. Missing perforated holes leads to impedance modifications.

The incomplete welding regions are modelled using the narrow region acoustics physics in COMSOL which takes into account the viscous and thermal losses. The geometry of the leakages is modeled as slits. The complex specific acoustic impedance of the slit is given by

$$Z_c = \frac{Z_0}{\sqrt{\psi_v(\gamma-(\gamma-1)\psi_h)}}, Z_0 = \rho c \quad (7)$$

where ψ_v and ψ_h are geometry and material dependent functions and γ is the specific heat ratio of the gas.

For slit of height h, the values of the ψ functions are obtained from equation (8) [8]

$$\psi_j = 1 - \frac{\tan(k_j h/2)}{k_j h/2} \quad (8)$$

3.3 Transmission Loss (TL)

The Transmission Loss is expressed in terms of the ratio of the incident acoustic power at the inlet, $W_{incident}$ using the applied pressure, p_0 and the transmitted acoustic power at the outlet, $W_{transmitted}$ using the computed pressure, p_c at the outlet as

$$TL = 10\log_{10}\left(\frac{W_{incident}}{W_{transmitted}}\right) dB \quad (9)$$

where $W_{incident} = \oint \frac{{p_0}^2}{2\rho c}$ and $W_{transmitted} = \oint \frac{{p_c}^2}{2\rho c}$

Here p_0 is the pressure associated with the incident wave, and pc is the pressure associated with the wave transmitted into an anechoic termination.

4. Results

The transmission loss of the muffler is compared with the test results for both reactive and hybrid configurations. It can be seen from Fig. 5 that the presence of internal leakages affects the TL curve considerably. This is due to the viscous damping effect of the narrow openings in the form of leaks in the baffle plate, and is in agreement with the observations made by Verma and Munjal [9].

For the hybrid configuration, it can be seen from Fig. 6 that the effect of leaks is not as profound as compared to that of the reactive configuration. This may be due to the protective effect of the absorptive medium by dissipating the acoustic waves in the form of heat before it can reach the leak areas. From the same figure, it may be noted that the presence of a protective layer in the form of a plastic cover (Glasswool cover) which is used for logistic purposes provides an improvement of about 3.2 dB at the low frequency TL trough of 255 Hz and a sacrificial deterioration of TL at the mid-frequencies as compared to that of the TL without the plastic cover. This is in agreement with the results presented by Munjal and Thawani [10,3] and also with the 1D plane wave analysis using Integrated Transfer Matrix Method (ITMM) [11].

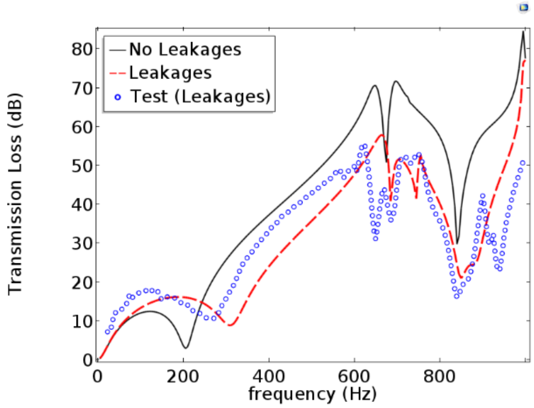

Figure 5. Transmission Loss of reactive muffler

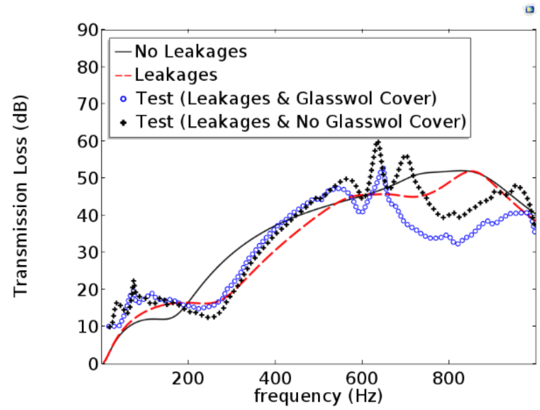

Figure 6. Transmission Loss of hybrid muffler

5. Conclusions

The following conclusions can be drawn from the preceding analysis:

1.Internal leakages leads to unintended impedance modifications and Herschel-Quincke effect.
2.Manufacturing defects can deteriorate the acoustic performance of production mufflers.
3.Effect of weep holes should be taken into account by modeling it as narrow region acoustic in the muffler design and simulation process.
4.Precise modeling of muffler internal constructions is needed to obtain accurate transmission loss results.

6. References

1.“Regulation (EU) No 540/2014 of the European Parliament and of the Council of 16 April 2014 on the Sound Level of Motor Vehicles,” *Official Journal of the European Union*, (2014)
2. Kim, U., Maunder, M., Grant, P., and Mawdsley, D., "Developing a Car to Meet New Pass-By Noise Requirements using Simulation and Testing," *SAE Technical Paper* 2015-01-2319, doi:10.4271/2015-01-2319 (2015).
3. M.L. Munjal, Acoustics of Ducts and Mufflers, Second Edition, Wiley, Chichester, UK, (2014).
4. Sullivan, Joseph W. and Crocker, Malcolm J., 1978, “Analysis of concentric-tube resonators having unpartitioned cavities,” *J. Acoust. Soc. Am*., **64(1)**, 207-215 (1978)
5. R. Kirby and A. Cummings, “The impedance of perforated plates subjected to grazing flow and backed by porous media”, *J. Sound Vibr.*, **217(4)**, 619-636, (1998).

6. M.E. Delany and E.N. Bazley, "Acoustical properties of fibrous absorbent materials", *Applied Acoustics.*, **3(2)**, 105-116, (1970).
7. F.P. Mechel, "Extension to Low Frequencies of the Formulae of Delany and Bazley for absorbing Materials", *Acta Acustica united with Acustica*, **35(2)**, 210-213, (1976).
8. COMSOL Multiphysics, Acoustic Module User's Guide, COMSOL 5.2a, October (2016)
9. A. Verma, and M.L. Munjal, "Flow-Acoustic Analysis of the Perforated-Baffle Three-Chamber Hybrid Muffler Configurations", *SAE Int. J. Passeng. Cars – Mech. Syst.* **8**(1): (2015), doi:10.4271/2015-26-0131.
10. M.L. Munjal, and P.T. Thawani. "Effect of protective layer on the performance of absorptive ducts", *Noise Control Engineering Journal*, **45**(1), 14-18, (1997).
11. D. Neihguk et al, "Acoustic Analysis of a Compact Muffler for Automotive Application", *SAE Int. J. Vehicle Dynamics*, *Stability and NVH (Under review)*.

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