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Countermeasures to Reduce Muffler Shell Radiation Noise

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Abstract

Acoustic design of exhaust mufflers focuses on reducing engine exhaust noise and to control the muffler shell radiation noises. In order to meet the government regulations and comfort zone of passengers, vehicle manufactures set targets for the exhaust tail pipe and muffler shell radiation noise levels. In cases of muffler shell with less stiffness, shell radiation noise affects the overall exhaust tail pipe noise level and passenger ear level noise inside the vehicle cabin. The aim of this paper is to establish various countermeasure techniques to control radiation noise from the exhaust which are practical to implement in muffler design achieved through simulation and physical testing. From several experiments and case studies it is found that the shell radiation noise can be reduced at an average of 2 to 6 dB (A) across all vehicle operating ranges for both gasoline and diesel vehicles.

Keywords: *Engine**,** Exhaust noise, muffler, Shell radiation noise, shell stiffness.*

1. Introduction

One of the functions of exhaust muffler is to reduce the engine exhaust noise without affecting engine performance. In recent years automotive industries are focusing on achieving sound signatures. The exhaust system is developed to control not only the vehicle pass-by-noise but also the vehicle interior noise. The structure borne noise created through the exhaust system also a major contributor to the overall exhaust performance level. The radiation noise from the exhaust in certain frequency affects the rear seat passenger ear noise level which should be avoided. The radiation noise targets differ from vehicle to vehicle and will differ based on engine capacity, fuel type, vehicle application etc. so a standard development methods should be depicted for controlling radiation noise. The exhaust system design should be focused on tail pipe noise and shell orifice noise reduction. This paper will be focused on depicting tactical solutions to control shell radiation noise with precise technological methods without affecting the exhaust performance and achieve desirable outcomes during the process of exhaust system design.

Various studies and researches are done in the area of exhaust system noise control Sakurai, M [1] have made a successful study for distinguishing the differences between pulsating noise and shell radiation noise from the exhaust. The study clearly differentiates the noise characteristic of both the noises and their influence in overall noise performance of the exhaust. Elnady, T. Abom, M, and Yang, Y [2] made a successful study on controlling shell radiation noise during the vehicle in idle condition only. In this paper case studies are done for controlling shell radiation noise through vehicle run up condition. Siano, D. and Iadevaia, M [3] made a simulation study using 3D software and mixed numerical approach for predicting the radiated noise from the exhaust. In this paper vibro- acoustical approach is used for predicting the shell radiation noise.

Shell stiffness is one of important parameter to resolve radiation noise problem. The increased shell stiffness will result in reduced radiation noise. Meanwhile stiffness of shell depends on geometry (shape of cross section), mass of the system, material and boundary condition (welding) etc. Each and every system has its own natural frequency. Similarly muffler shell along with end cap and internal components such as baffle plates, pipes has its own natural frequency. More displacement along the shell creates the acoustical and structural resonance in the engine operating frequencies. Hence the muffler natural frequency should not be equal to the engine firing frequencies. The stiffness of the muffler shell should kept to the maximum level in order to increase the natural frequency of the system to avoid vibration from the muffler shell creating structure borne noise. For developing exhaust muffler and controlling radiation noise vibro-acoustical approach is followed along with vehicle level test for validation. In this paper various countermeasure techniques are adopted and case studies are done

2. Muffler Shell Radiation Noise

Muffler shell radiation noise is generated mainly due to exhaust gas flow and pressure pulses hitting on muffler surface and shell structural vibrations which are shown in figure 1. The shell radiation noise creates significant resonance which increases the vehicle interior noise level. In the case of muffler system with shorter tailpipe this shell radiation noise affects the overall exhaust orifice noise level and creates acoustical resonance. In order to identify the impact of shell radiation noise in exhaust

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orifice noise measurement and in cab noise, exhaust noise isolation test is conducted in vehicle. The noise effect in the interior of the cabin and orifice noise level is affected in all engine RPM ranges and the dominant frequency range of radiation noise is between 500 to 800 Hz.

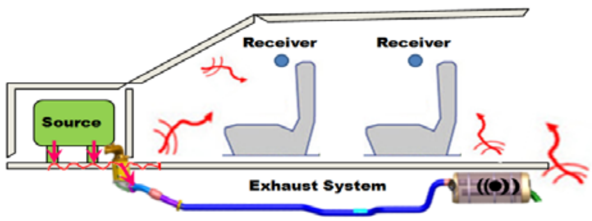


Fig. 1 Muffler shell radiation noise effect in vehicle interior.

3. Noise Measuring Conditions

3.1 On-Road noise measuring conditions

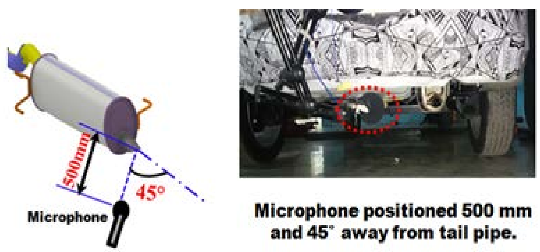


Fig. 2 Exhaust tailpipe noise measuring condition.

As shown in Figure 2, the exhaust orifice noise is measured by placing the microphone 500mm and 45° away (ISO 5130) from the exhaust tail pipe while vehicle operated in 3rd gear wide open throttle (WOT) condition.
Generally the measuring range is from 1000 to 6000 RPM for gasoline and from 1000 to 4000 RPM for diesel vehicle.

3.2 Muffler shell radiation noise measuring conditions

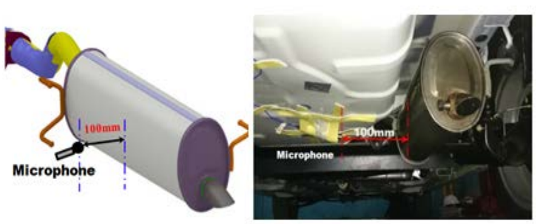


Fig. 3 Muffler shell radiation noise measuring condition.

As shown in Figure 3.The muffler shell radiation noise is measured by placing microphone 100mm away from the muffler shell center point and vehicle is operated in 3rd gear wide open throttle (WOT) condition from 1000 to 6000 RPM for gasoline vehicle and from 1000 to 4000 RPM for diesel vehicle.

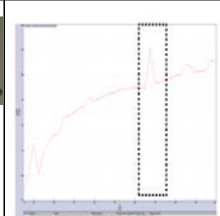
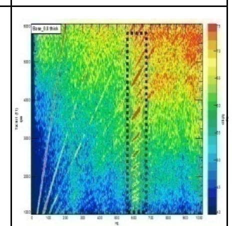
4. Countermeasure Techniques for controlling Shell Radiation Noise

A) Increasing shell thickness
B) Adding support baffle
C) Adding glass wool in resonating chamber
D) Clearing resonance by reducing baffle distance
E) Locating shell weld seam position
F) Double layer shell with insulation
G) Adding embossing in shell
Each countermeasure techniques are discussed with an example .

4.1 Case A - Increasing shell thickness

For controlling the radiation noise muffler shell must be stiffer. In order to increase the stiffness the muffler shell thickness is increased. In Case A a 1.4L gasoline vehicle muffler shell thickness is increased from 0.8 mm to 1.0 mm for reducing shell radiation noise. Acoustic analysis and testing is carried out for two mufflers with same internals, materials and boundary conditions, only difference in muffler shell thickness. Increasing muffler shell thickness alone doesn't have any impact in exhaust orifice noise levels. Muffler Sample 1 (0.8mm shell thickness) and muffler Sample 2 (1.0mm shell thickness) analysis and test results are shown Table 1.
Vibro-acoustic analysis is conducted using LMS Virtual Lab the radiation noise analysis is carried out by placing microphone 100mm away from muffler shell. Sound pressure level dB (A) is plotted with respect to frequency domain (Hz). The resulted sound pressure level is due to the displacement of muffler shell in modal analysis (Free-Free field condition). This analysis doesn't include radiation due to exhaust gas flow.

Table 1: Case A-Muffler Sample 1 (Simulation Result vs. Test Result)

Tested Sample	Simulation Result	Test Result
 Sample 1 Shell thickness 0.8mm		

From Table 1. the simulation result clearly shows a peak value in 630-660 Hz frequency range. The same muffler sample 1 is made as a prototype and tested in vehicle

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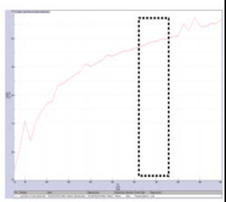
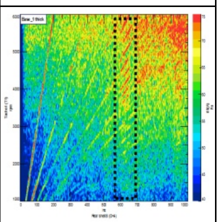
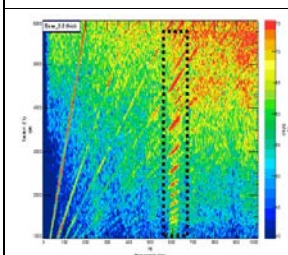
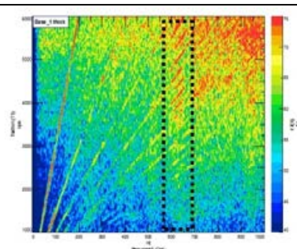
running condition by using LMS Test Lab hardware and software. The Campbell diagram is plotted in terms of frequency vs. Engine speed vs. Sound pressure level. In test result also there is a resonance found in same frequency range from 630 - 650 Hz. In order to reduce this radiation resonance, the muffler shell thickness is increased from 0.8mm to 1.0mm (muffler sample 2) with same internal design. Both acoustic simulation and test were carried out for muffler sample 2.

Table 2: Case A- Muffler Sample 2 (Simulation Result vs. Test Result)

Tested Sample	Simulation Result	Test Result
 Sample 2 Shell thickness 1.0mm		

From Table 2, the muffler shell with 1.0mm thickness produces very less radiation noise in both simulation and tested result. There is no resonance found in 630 - 660 Hz frequency range. The radiation noise level drastically reduces with increase in shell thickness.

Table 3: Case A- Test Result Campbell Diagram (Muffler Sample 1 vs. Muffler Sample 2)

Vehicle Test Result : Campbell Diagram	
 SAMPLE 1	 SAMPLE 2

From Table 3, the Campbell diagram comparison of radiation noise level for both the samples clearly indicates that increasing shell thickness from 0.8 to 1.0mm reduces the radiation noise in the frequency range of 630 - 660 Hz.

4.2 Case B - Adding support baffle.

In order to increase the shell stiffness and to avoid muffler radiation a support baffle plate can be introduced in the muffler. Adding support baffles doesn't affect the exhaust tail pipe overall noise performance. In this case baffles don't affect the flow path of the exhaust gas inside the muffler. Here two mufflers, with and without support baffles are tested in vehicle running condition. In Figure 4 Muffler Sample 1 has two perforated baffle with glass wool in second room, Sample 2 has same two perforated baffles with glass wool, additionally one support baffle is placed inside the second room. Both mufflers have shell thickness of 1mm. Since the support baffle has large open flow area it does not affect the exhaust overall noise level.

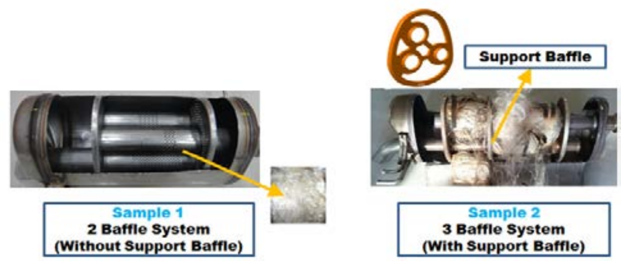


Fig. 4 Muffler sample with and without support baffle plates

Vehicle Test Result : 2D Plot

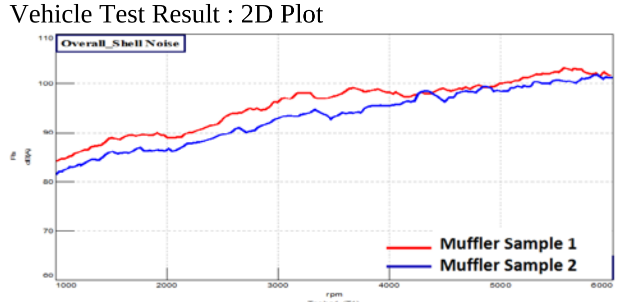
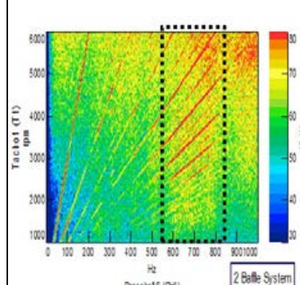
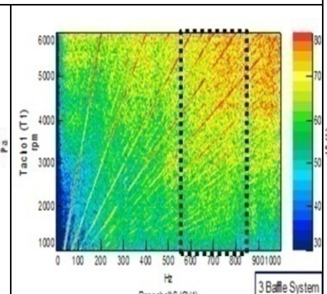


Fig. 5 Case B vehicle test results-2D Plot

From Figure 5, muffler sample 2 (with support baffle) has better noise level compared to muffler sample 1(without support baffle). Here sample 2 has a noise level improvement up to 4 dB (A) from 1000 to 4200 RPM and 1.5 to 2 dB (A) improvement in higher RPM range.

Table 3: Case B - Test Result Campbell Diagram (Muffler Sample 1 vs. Muffler Sample 2)

Vehicle Test Result : Campbell Diagram	
 SAMPLE 1	 SAMPLE 2

From the Campbell diagram, sample 2 has better radiation noise than sample 1 at 600 to 800 Hz .

4.3 Case C - Adding glass wool in resonating chamber

Another possible way to reduce muffler shell radiation noise is by avoiding the direct impact of exhaust gas hitting on the muffler shell. When the exhaust gas flow hits the low stiffness shell it will create high radiation noise from the muffler. Hence this direct impact can be eliminated by adding glass wool inside the weakened resonating chamber inside the muffler. In case C adding glass wool has a overall effect in exhaust system noise performance particularly improving in higher frequency range. In this case two muffler samples of a 1.6L gasoline engine with same shell thickness of 1.0mm are tested in the vehicle. Sample 1 has no glass wool in the first chamber and in sample 2 glass wool amount of 500g is added in first chamber for reducing shell radiation noise which is shown in Figure 6.

Fig. 6 Muffler sample with and without glass wool.

Vehicle Test Result: 2D Plot

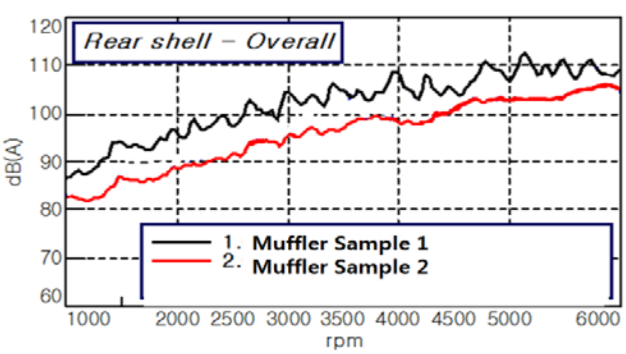
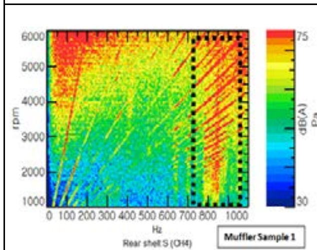
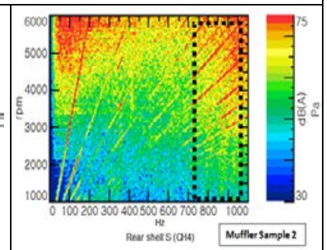


Fig. 7 Case C vehicle test results-2D Plot

As shown in Figure 7, Overall noise level graph of muffler sample 2 (with glass wool) in first chamber has very low shell radiation noise comparing to muffler sample 1(without glass wool). Sample 2 has an average of 6 dB (A) improvement throughout the RPM range from 1000 to 6000 RPM.

Table 4: Case C - Test Result Campbell Diagram (Muffler Sample 1 vs. Muffler Sample 2)

Vehicle Test Result : Campbell Diagram	
	
SAMPLE 1	SAMPLE 2

From the Campbell diagram the muffler sample 1 has a strong resonance in between 795 to 870 Hz. In muffler sample 2 this structural resonance is eliminated by adding the glass wool in the same chamber. It can also improve the exhaust tail pipe noise level in higher frequency ranges.

4.4 Case D - Clearing resonance by reducing baffle distance

In Case D a simply supported beam as shown in Figure 8, having column distance 500mm (Case 1) and 300mm (Case 2) having same point load acting at its center. In general the deflection of beam at its center in Case 2 will be lower than Case 1. In muffler assembly baffles and shell acts like a simply supported beam. If the distance between two baffles is very high, the shell gets weaker at its center and makes more vibration. In structural point of view short distance between the baffles is recommended to avoid shell weakness in mufflers.

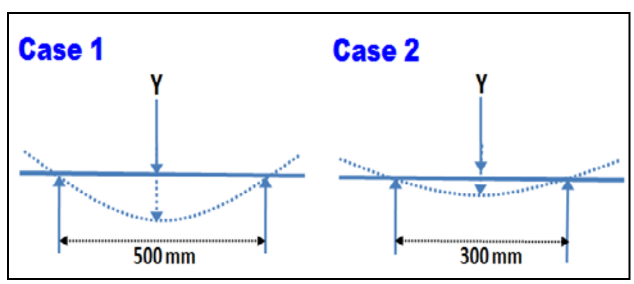


Fig. 8 Example of simply supported beam with 500 and 300mm distance

Here two samples with same shell thickness of 1.0mm is measured in vehicle running condition. In sample 1 baffle A is placed at a distance of 182mm away from end cap and in sample 2 baffle A is placed at 150mm away from end cap. In order to reduce vibration in 1st chamber, baffle A in sample 2 is moved 32mm towards the end cap.

Modal Analysis: Contour Plot

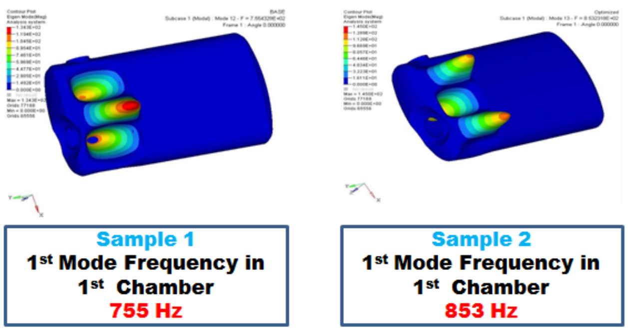


Fig. 9 Modal analysis result plot with first mode frequency

From Figure 9, the modal analysis results shows reducing baffle distance increase the frequency in the same chamber. Since natural frequency and stiffness are directly propotional, increasing natural frequency increases the shell stiffness.

Vehicle Test Result : 2D Plot

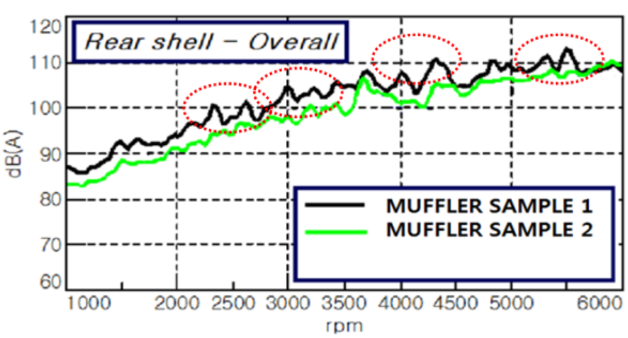
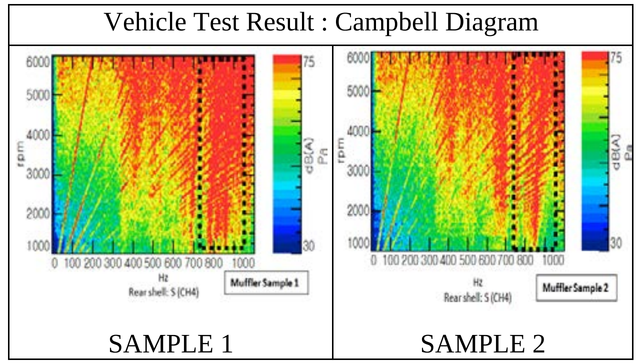


Fig.10 Case D vehicle test result - 2D Plot

From Figure 10, muffler sample 1 has high significant resonance from 2200 RPM to 5600 RPM (highlighted area). After reducing the baffle distance in sample 2 this resonance is well reduced. Here muffler sample 2 has an average of 1.5 to 2 dB (A) noise improvement from 1000 to 6000 RPM.

Table 5: Case D - Test Result Campbell Diagram (Muffler Sample 1 vs. Muffler Sample 2)



In Campbell diagram (Table 5) sample 1 had a resonance in 850 Hz. But in sample 2 this resonance is cleared in the same frequency range by reducing the baffle distance. Thus keeping shorter baffle distance improves radiation noise from the muffler.

4.5 Case E - Locating shell weld seam position

Since shell radiation noise depends on muffler shell, the manufacturing method also needs to be considering in development process. There are different types of shell joints used in muffler. Among them commonly used types are high frequency weld, roll and spot, lock seam etc.
As shown in Figure 11, muffler shell with High Frequency (HF) welding in different location was tested in vehicle running condition. Two samples having same shell thickness of 1.0mm and same internal design, only difference between these samples is location of muffler shell weld seam position. In Muffler sample 1 the HF weld is placed in mid section while in Muffler sample 2 welds are located at the side region.

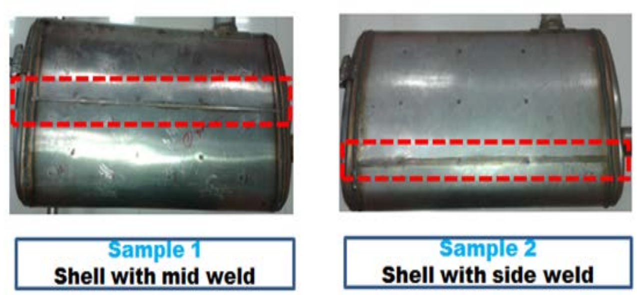


Fig. 11 Muffler samples with different weld seam locations.

Vehicle Test Result: 2D Plot

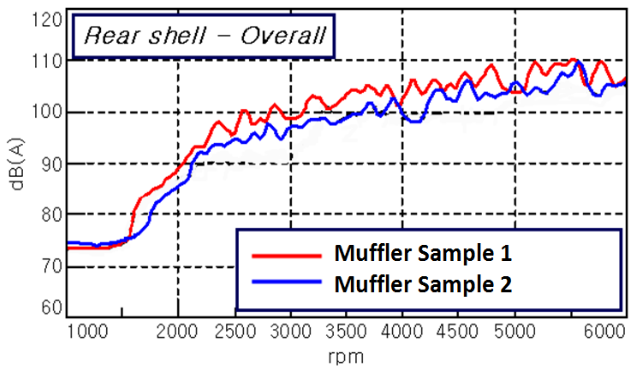


Fig. 12 Case E vehicle test result - 2D Plot

As shown in Figure 12, Muffler sample 2 has an average of 2 dB (A) noise level improvement than sample 1 from 1600 to maximum RPM range. Changing weld position doesn't clear the resonance frequency in muffler shell. It only reduces the amplitude of noise level, this is because of changes in strain energy parameter. Modal strain energy is a useful quantity in identifying candidate elements that create problem frequencies. Elements with large values of strain energy in a mode indicate the location of large elastic deformation energy. These elements are those which most directly affect the deformation in a mode. Therefore, the elements with large strain energy should have effect on muffler shell. Hence low strain energy is recommended for less deformation of shell.

Modal Analysis: Contour Plot

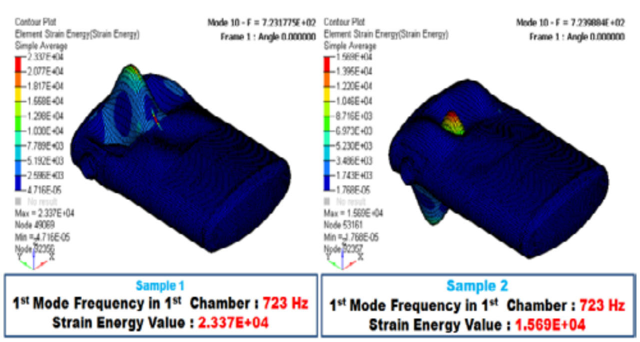


Fig. 13 Modal analysis simulation result

From Figure 13, both muffler samples has an same first mode frequency of 723 Hz, but the strain energy for sample 2 is less than sample 1. In muffler sample 1 shell with mid weld has more strain energy. While changing this weld seam position in sample 2 this strain energy is reduced significantly from $2.337E^{+4}$ to $1.569E^{+4}$, resulted in noise level improvement.

4.6 Case F - Double layer shell with insulation

Radiation noise for muffler sample with double layer shell without any acoustic insulation is compared with muffler sample with insulation material.Thickness configuration of Muffler sample 1 is (0.6+0.6)mm and for muffler sample 2 shell thickness is (0.6+0.6)mm with 2mm ceramic paper between two layers. Since this muffler samples are designed for diesel vehicle shell radiation noise is measured from 1000 to 4000 RPM.

Table 6: Muffler samples without and with acoustic insulation

Muffler Sample 1	Muffler Sample 2
	
Double Layer Shell without insulation	Double Layer shell with insulation

Vehicle Test Result: 2D Plot

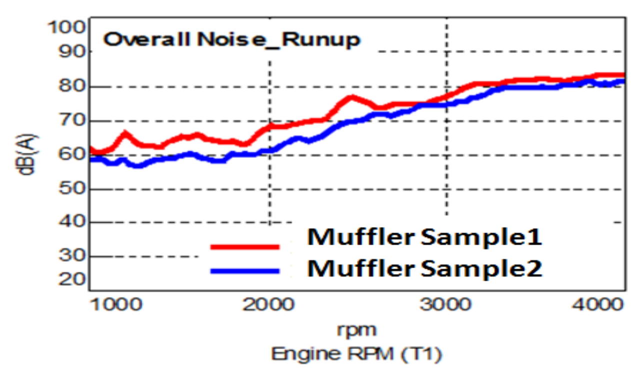
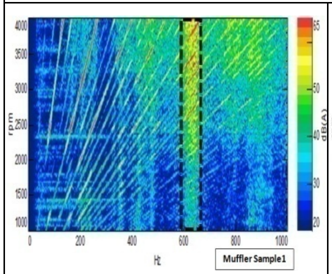
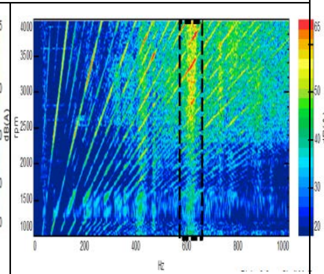


Fig. 14 Case F vehicle test result - 2D Plot

From Figure 14, Muffler sample 2 has an average of 4 dB (A) noise reduction from 1000 to 2600 RPM compared to the Muffler sample 1. In higher range from 2700 to 4000 RPM sample 2 has an average of 1.7 dB (A) noise reduction.

Table 7: Case F - Test Result Campbell Diagram (Muffler Sample 1 vs. Muffler Sample 2)

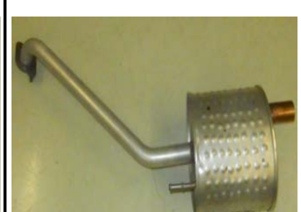
Test Result : Campbell Diagram	
	
SAMPLE 1	SAMPLE 2

In Table 7, Campbell diagram Muffler sample 1 has a resonance at 620 Hz. After introducing the ceramic paper between two shells in muffler sample 2 this shell resonance is reduced in the same frequency range. This ceramic paper also acts as a thermal insulation for the muffler shell.

4.7 Case G - Adding embossing in shell

Commonly practised technology for reducing shell radiation noise is adding of an embossing in muffler shell. Adding embossing increases the shell stifness and makes less vibration along the shell surface, which will reduces the shell radiation noise. As shown in table 9, Shell configuration of muffler sample 1 has two plain layers (0.6+0.6)mm, and for muffler sample 2 configuration includes a 0.6mm plain shell with 0.6mm embossed layer. Radiation noise measurement is done for the two samples to distinguish the acoustical difference.

Table 8: Muffler samples without and with embossed shell.

Muffler Sample 1	Muffler Sample 2
	
Plain Shell Muffler	Embossed Shell Muffler

Vehicle Test Result: 2D Plot

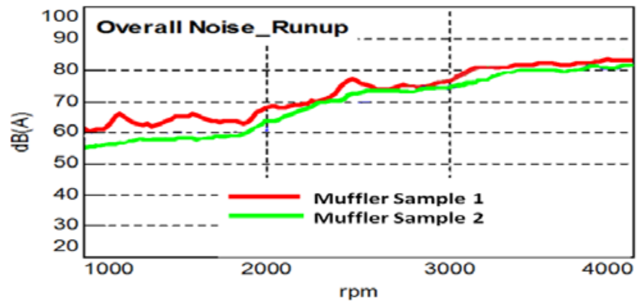


Fig. 15 Case G vehicle test result - 2D Plot

From Figure 15, Muffler sample 2 has an average of 3.4 dB (A) noise reduction from 1000 to 2200 RPM compared to muffler sample 1. In higher RPM range from 3000 to 4000 RPM sample 2 has average a of 1.2 dB (A) noise reduction than sample 1. Thus adding an embossing design in muffler shell clearly reduces the radiation noise from the muffler.

5 Result and Summary

Table 9: Shell radiation test results

Case	Countermeasures	Average Shell Radiation Noise Reduction
A	Increasing muffler shell thickness	3 dB (A) throughout the RPM range
B	Adding support baffle plates	4 dB (A) from 1000 to 4200 RPM 2 dB (A) from 4700 to 6000 RPM
C	Adding glass wool in resonating chamber	6 dB (A) throughout the RPM range
D	Clearing resonance by reducing baffle distance	2 dB (A) throughout the RPM range
E	Locating shell weld seam position	2 dB (A) throughout the RPM range
F	Double layer shell with insulation	4 dB (A) from 1000 to 2600 RPM 1.7 dB (A) from 2700 to 4000 RPM
G	Adding Embossing in shell	3.4 dB (A) from 1000 to 2200 RPM 1.3 dB (A) from 3000 to 4000 RPM

6 Conclusions

From the case studies all the seven countermeasure techniques are very effective in reducing the muffler shell radiation noise compared to their base design. Based on requirements, constrains and performance targets, any of this countermeasures can be incorporated in the muffler design to reduce the shell radiation noise in an average of 2 dB (A) to maximum 6 dB (A) in the vehicle operating range to have an overall impact in the exhaust noise performance for both gasoline and diesel vehicles.

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As a corporate executive in the United States and India for over three decades, Dr. Rajadurai managed strategy on power train development and emission control for low, ultra low, super ultra low and partial zero-emission systems. From 1990-1996, he was the Director of Research at Cummins Engine Company. He was the Director of Advanced Development at Tenneco Automotive between 1996 and 2002 and subsequently Emission Strategist and Director of Emissions at ArvinMeritor until 2004. From 2004-2009, he was Vice-President of ACS Industries and since 2009 as Head of R&D Sharda Motor Industries Ltd.

Dr. Rajadurai has held leadership positions on the Board of Directors for the U.S. Fuel Cell Council, Manufacturers of Emission Control Association (MECA), Chairman of MECA Committee on Advanced Technologies and Alternate Fuels and Walker Exhaust India. He is an active participant in Clean and Green Earth Day demonstrations since 1997 and US Clean Diesel School Bus Summit (2003). He was a panelist of the Scientists and Technologists of Indian Origin, New Delhi 2004. He is a Fellow of the Society of Automotive Engineers. He was the UNESCO representative of India on low-cost analytical studies (1983-85). He is a Life Member of the North American Catalysis Society, North American Photo Chemical Society, Catalysis Society of India, Instrumental Society of India, Bangladesh Chemical Society and Indian Chemical Society.

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