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Muffler Development for Diesel Hybrid Vehicle

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Abstract

The paper describes a systematic procedure for the development of a muffler for a 1.5L diesel hybrid vehicle. The conventional diesel vehicle and the diesel hybrid drive train modes are described. The hybrid vehicle drive train modes such as starting, cruise, acceleration, deceleration, braking and stop are matched with the attenuation requirement of the Noise Vibration Harshness (NVH) characteristics of the muffler. 1D WAVE simulation is performed to develop various options of the muffler internals to get the required transmission loss and back pressure. The 1D simulation results are correlated with the experimental results obtained in the LMS test bench. The back pressure is obtained through 3D flow thermal simulation. The LMS Virtual lab analysis is performed and the simulation results are correlated with experimental transmission loss results. The volume of the muffler and the internal components are optimized for NVH requirement. The back pressure obtained for the muffler from 1D WAVE code and CFD code are 155 mbar and 175 mbar respectively. Finite element analysis is performed to establish the structural integrity of the muffler and the exhaust system.

Keywords: *Diesel hybrid, Conventional power train, Wave analysis, Transmission loss, LMS virtual lab, Noise vibration harshness, Simulation software, Finite element analysis.*

1. Introduction

Ways and means to reduce global warming and searching for alternate fuel and power train to minimize the total fuel consumption are the thrust research areas of the 21st century [1-2]. Hybrid power train not only reduces the fuel consumption but also provides driver comfort for a definite driving segment [3-4]. Further, it offers solution for the stringent emission regulation. However, developing a muffler in the space constrained power train to meet the tightest pass by noise regulation (<75dB) is a challenge [5-6]. In our attempt to develop a hybrid power train exhaust, we considered a 1.5L diesel engine along with a battery power as alternate for the conventional 2.2L diesel engine operated vehicle. By rule of thumb, 2.2L engine uses a muffler volume of 22L where as we developed a 15L muffler for the 1.5L diesel hybrid. The purpose of the muffler is to attenuate the flow through noise coming out of the engine. There are two ways of muffler attenuation, one by absorption and the other by reflection. Absorptive silencers contain either fibrous or porous material, and depending upon their absorptive properties they reduce the noise levels. Sound energy is reduced as their energy is converted into heat in their absorptive material. It is based on the use of flow resistive materials, again normally in the form of porous acoustic linings. The reflective muffler uses the phenomenon of destructive interference to reduce the noise. For complete destructive interference to occur, a reflected pressure wave of equal amplitude and 180 degree out of phase needs to collide with the transmitted pressure wave. Reflections occur when there is a change in geometry or an area discontinuity.

1.1 Conventional Power Train

Environmentalists pose issues regarding the emissions of automobiles, which is a direct result of how the combustion takes place in the engine. Consequently, engineers and scientists are challenged with minimizing the emitted gases and particles as well as maximizing the torque and power. Another problem that every car manufacturer is faced with is the amount of fuel consumed per mile travelled. Car engine manufacturers must pass through all these difficult stages to be able to manufacture the optimum engine in conventional power train, the combustion of a fuel occurs with an oxidizer in a combustion chamber without any secondary source for driving the power train.

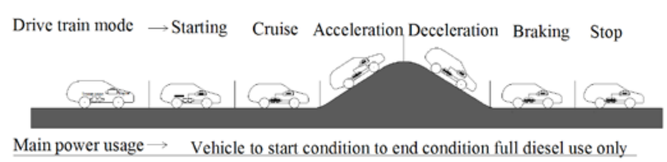


Fig. 1 Conventional diesel engine operated vehicle movement

This obviously leads to more fuel consumption at the time of cruising and climbing up the hill as shown in Figure 1.

1.2 Hybrid Power Train

In Hybrid power train, it finds the right balance between diesel engine power and electric motor power for any driving condition, providing quiet yet powerful acceleration as explained below (Figure 2)

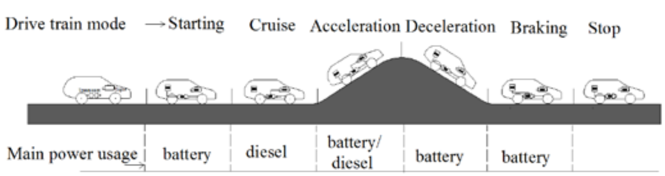
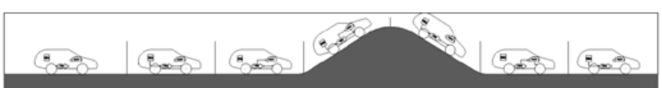


Fig. 2 Diesel hybrid vehicle movement

In starting, instant electric power is achieved at the time of initial acceleration from a standstill position. At this mode, the vehicle is powered with only electric power. **In cruising**, the required efficiency of the vehicle is achieved with the diesel engine for optimum fuel efficiency. **In acceleration,** both the diesel engine and the electric motor combine to give maximum required power and torque to the vehicle at low rpm. **In deceleration,** the vehicle gets back the energy which was created by the engine. The system automatically cuts off diesel engine and energy is recovered by a motor to start recharging the battery.

During braking, the energy that would have been wasted as heat in conventional vehicles are recovered in the battery through generative braking. Thus smart saving of energy is a achieved. During the vehicle stop at the signal or traffic, complete silence is maintained and no fuel is wasted and no exhaust gas is emitted.



Drive train mode	Starting	Cruise	Acceleration	Deceleration	Braking	Stop
Main power usage	Battery	Diesel	Diesel / Battery	Battery	Battery	-
Engine/ Mass flow rate	-	1.5L,<390 kg/hr	1.5L,>390 kg/hr	-	-	-
Intake noise	-	63 dB	63 dB	-	-	-
Engine noise	-	69 dB	69 dB	-	-	-
Flow through noise	-	69 dB	69 dB	-	-	-
Tire noise	68 dB	68 dB	68 dB	68 dB	68 dB	68 dB
Transmission noise	60 dB	60 dB	60 dB	60 dB	60 dB	60 dB
Interior road noise	60 dB	60 dB	65 dB	65 dB	60 dB	60 dB
Combined noise	< 60 dB	>75 dB	>75 dB	< 60 dB	< 60 dB	< 60 dB
Muffler function	NA	Yes	Yes	NA	NA	NA
Others	Diesel will take over at any point when the battery power is not available					

Fig. 3 Hybrid drive train functionals.

2. Muffler Design Methodology

A hybrid vehicle requires a muffler to reduce the amount of noise emitted by a vehicle. A representative muffler with internals along with the nomenclature is illustrated in figure 4.

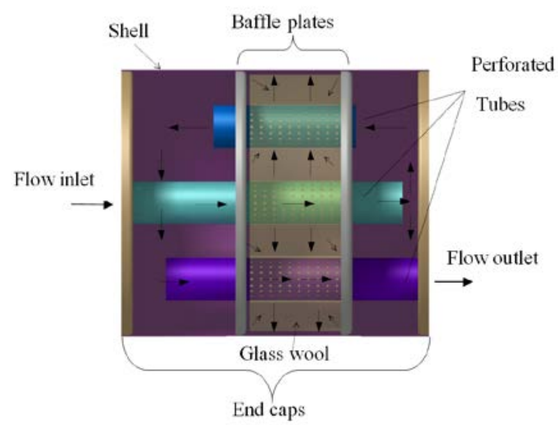


Fig. 4 Muffler nomenclature

In our muffler development, we considered different drive train modes of the hybrid vehicle such as starting, cruise, acceleration, deceleration, braking, stop to match with the muffler functional requirement as shown in figure 3**.** As seen in the figure, the muffler attenuation is highly demanded in cruise and acceleration modes. A detailed flow chart for the muffler development process is shown in figure 5. From the input data and the targets, the concept muffler options are developed. 3D modeling using CATIA is developed to support the CAE work. The optimized option is chosen for proto sample making and structural durability study.

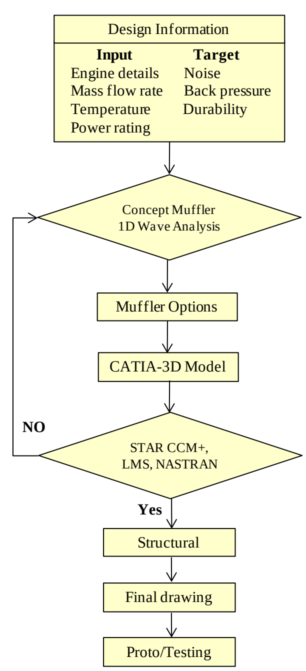


Fig. 5 Muffler design flow chart.

2.1 Material Used

In our current study, we used glass wool (Advantex) as absorption material. Glass wool is a light weight insulation material, which has a fine long, inorganic glass fibers bonded together by high temperature binder. We used 120 kg/m^3 density glass wool in our application. Stainless Steel 409 and SACD 60/60 are used for muffler proto sample.

3. Computational Software for Muffler Development

The Computational Software and simulation procedure used for the muffler development is explained in details figure 6.

Softwares	Input	Details	Application
Wave	Engine Files	Engine : 1.5l, 4 cylinder, Diesel Engine speed - 4800rpm Mass flow rate - 390 kg/h Exhaust gas temp - 800°C	Transmission loss Backpressure
CATIA	Concept	Shape - Ellipse Shell dimension* - 280x225x324L Perforation tubes* - Ø45x1.2t Baffle and end caps* - 1.2t Weight : 5.8kg	3D model and 2Drawing
Star CCM+	CAD model/ Hyper Mesh	Mass flow rate - 390 kg/h Exhaust gas temp - 800°C Porous media assumption High Reynolds k-epsilon model	Uniformity Index and Back Pressure
LMS	Hyper Mesh	Material and fluid properties : Density of air - 1.22kg/m³ Sound velocity - 340 m/s Glass wool type : Advantex Amount of glasswool - 400 gram	Transmission loss test
Nastran	FEA	Taylor's series, Finite element methods, Natural frequency -125Hz	Structural validation and System intergerity
			* - The units are in mm

Fig. 6 Computational software for muffler development

4. 1 D modeling for Concept Development

WAVE model creates general and complex compressible-flow fluid networks in terms of modeling elements, which include constant-area or tapered pipes/ducts, junctions of multiple ducts, orifices, and termination points such as infinite plenums (ambient) and anechoic boundaries. The engine models are made and predictions of engine performance and acoustics are analyzed (Figure 7).

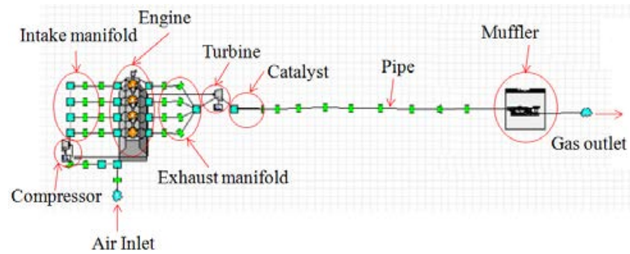


Fig. 7 Wave engine simulation model for 1.5l engine

The above figure shows the engine 1D model by using Ricardo wave software using the inputs from Ricardo Library. Bore diameter and stroke length is 78.1 and 82 mm respectively (the total displacement is 1.5L). The Engine brake power is checked in WAVE post and it is made sure that it is in 73 kW mark range at the mass flow rate of 390 kg/h and the temparature in the exhaust outlet is around 800ºC. The maximum torque is 220 Nm at 1800-2800 rpm. The brake power and torque graph with repect to Engine rpm is shown in Figure 8 and 9. In 1000 rpm the engine produces 42 Hp and at 4000 rpm it produces 88 Hp to meet the requirement.

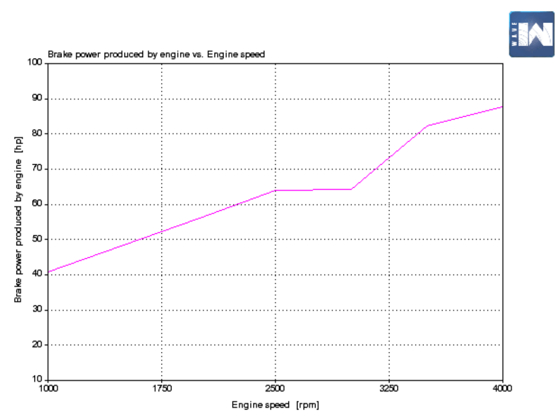


Fig. 8 Brake power Vs Engine speed

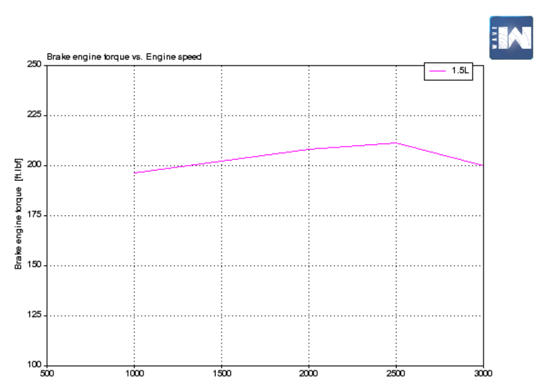


Fig. 9 Torque vs. Engine speed

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The engine produces the required maximum torque 220 Nm at 2500 rpm. The sound pressure level at 1000 rpm is 70 dBA and the maximum sound pressure level is 85 dBA at 4000 rpm. The muffler in the exhaust system in the hybrid power train reduces much of the sound pressure level (Figure 10).

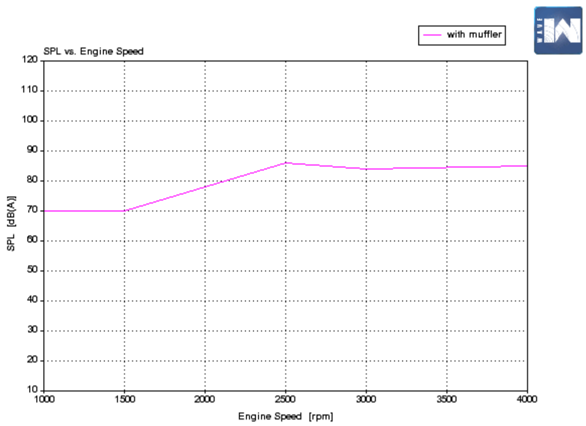


Fig. 10 SPL Vs Engine speed

WAVE simulation provides concept mufflers with different internals showing transmission loss and back pressure. Various options derived are shown in figure 11.

Description	Model-1	Model-2	Model-3	Model-4 (Selected)
WAVE Model				
Internal parts	2 Perforated tubes 2 Perforated baffles (45 holes in RH) No Glass wool	3 Non- perforated tubes 1 Perforated baffle No Glass wool	3 Perforated tubes 2 Perforated baffles 200 gram of Glass wool	3 Perforated tubes 2 Non- Perforated baffles 400 gram of Glass wool
Transmission loss (TL)graph				
Back pressure	145 mbar	142 mbar	165 mbar	155 mbar
Remarks	Low TL loss, High tail pipe noise	Low back pressure, High tail pipe noise level	Medium TL level, But flow noise high, Back pressure high	Optimal back pressure, Good TL level, Less tail pipe noise

Fig. 11 Different muffler options

Muffler performance is selected based on the noise and back pressure target.

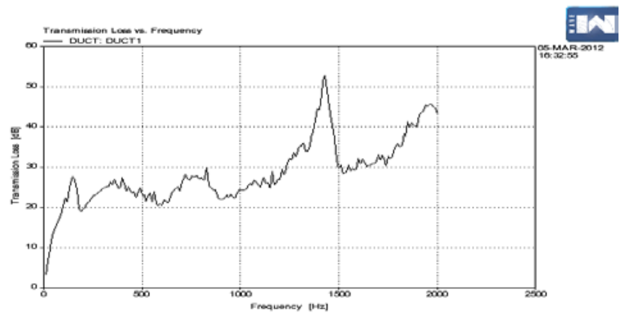


Fig. 12 Transmission loss Vs Frequency (1D)

5. 3D Modeling

The best performing muffler option from the 1D Wave simulation is selected. The elliptical shape muffler with the dimensions shown in the figure is considered for 3D modeling. A dual layer outer shell (0.8t mm layer) is used. 45 mm OD perforated tube with Ø3.5 mm holes is used for the muffler internal.

6. CFD Pressure and Velocity Contour

The CFD analysis is performed to predict the back pressure and velocity profile of the muffler (Figure 13). The pressure drop obtained is found to be 175 mbar.

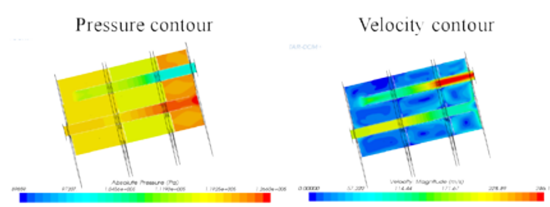


Fig. 13 Pressure and Velocity

7. Proto Sample

2D drawing has been developed for the muffler as per 3D CAD model. The proto samples are developed as shown in figure 14.

Fig. 14 Proto sample

The proto sample weight is 7.4 kg against to the CAD weight of 6.6 kg.

8. Transmission Loss Measurement

Transmission loss is defined as the loss in the incident sound transmitted. The incident sound energy is the energy developed by the engine. Leuven measurement system equipment is used to measure the transmission loss using impedance tube setup as shown in figure 15.

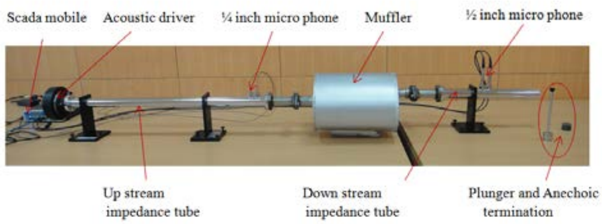


Fig. 15 Transmission loss measurment

1D WAVE acoustic simulation has been performed to determine the targeted transmission loss of 20 dB. The transmission loss measurement obtained is plotted as a function of frequency shown in Figure 16.

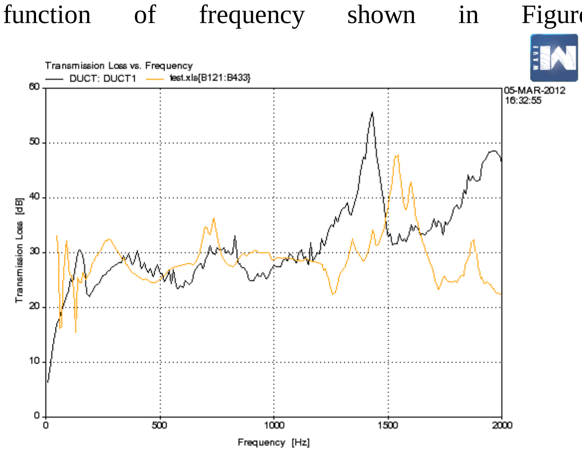


Fig. 16 1D Wave simulation TL & Experimental result

The experimental result is compared with the 1D simulation result.

9. LMS Virtual Lab

LMS Virtual Lab offers an advanced method for simulating acoustics. It helps predict and improve the sound and noise performance of various systems. The transmission loss is predicted with the specified boundary conditions shown in Figure 6. The sound transmission loss as a function of frequency is shown in figure 17.

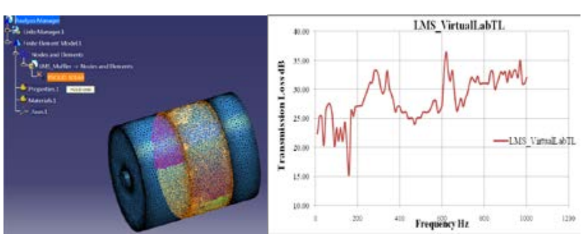


Fig. 17 LMS Virtual Lab Transmission loss

The results of the sound transmission loss predicted by LMS virtual lab is compared with the experimental result (Figure 18).

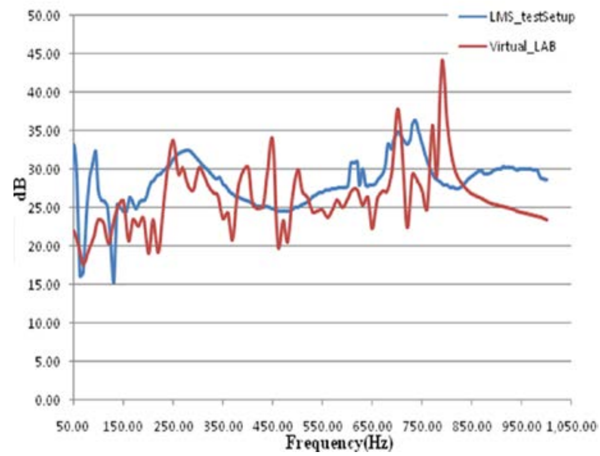


Fig. 18 LMS virtual lab STL Vs Experimental result

10. Structural Analysis

Structural integrity of the exhaust system is performed by finite element analysis (FEA). Thermo-Mechanical analysis has been performed on the system by considering surface temperature as thermal load with structural boundary condition to determine the thermal stresses on the components. Non-linear material properties has been considered during analysis to predict the equivalent plastic strain within the target in order to evaluate thermal failure.
Model analysis (sol 103 in Nastran) has been performed to predict the mounting location or hanger rod location of the system by considering boundary condition as inlet flange is fixed in all degree of freedom and checked for nodal and anti-nodal points in the mode shape has been considered as the preferred mounting location on the exhaust system. Modal analysis (sol 103 in Nastran) has been performed after the prediction of hanger mounting to check for resonance frequency of the system by considering boundary condition as all the mounting location & inlet flange bolt holes are constrained in all degrees of freedom.
The model is checked for first vertical bending mode and its natural frequency. This frequency has been compared with excitation frequency which is calculated from engine rated speed and number of cylinders. The required condition from this analysis is the natural frequency of the exhaust system which was not matched with the engine frequency.
Static linear structural analysis (sol 101 in Nastran) was performed to predict the hanger location on the system by considering unit gravity (1G) static load and boundary condition as all the mountings are constrained in all degrees of freedom.

Dynamic analysis (model frequency response analysis -sol 111) has been performed by considering dynamic load as engine excitation load and road load (RLDA) with considered boundary condition. Stress peak and displacement peak response curve under particular frequency to be obtained from this analysis. Direct frequency response (sol 108 in Nastran) was performed for the frequency where peak response shown in previous analysis to check the Von-misses stress on the exhaust system. These stresses are checked with the material yield strength to evaluate the structural or vibrational failure. Plastic equivalent strain on the system was checked for the target of 2% to 6% of the Non-linear material properties. The FEA analysis results are shown in figure 19-21.

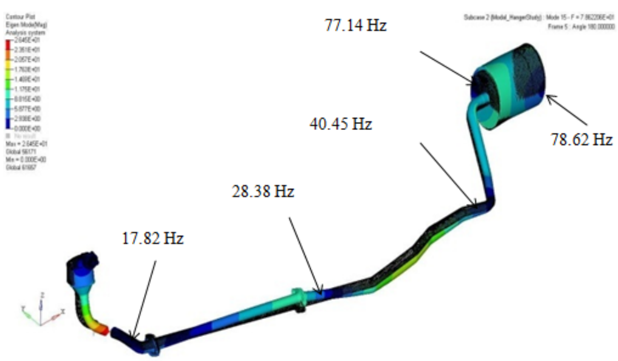


Fig. 19 Repeating nodal points

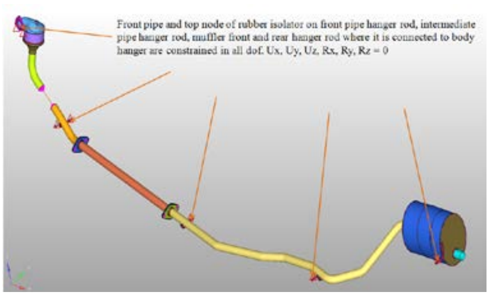
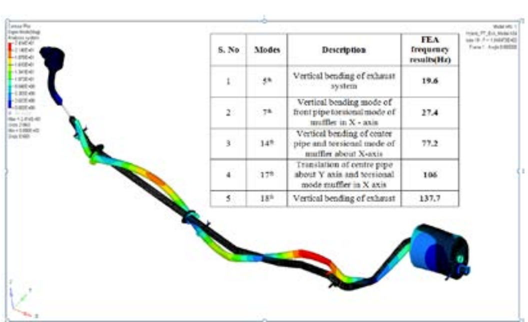


Fig. 20 Modal analysis boundary conditions



S. No	Modes	Description	FEA frequency results(Hz)
1	5th	Vertical bending of exhaust system	19.6
2	7th	Vertical bending mode of front pipe torsional mode of muffler in X - axis	27.4
3	14th	Vertical bending of center pipe and torsional mode of muffler about X-axis	77.2
4	17th	Translation of centre pipe about Y axis and torsional mode muffler in X axis	106
5	18th	Vertical bending of exhaust	137.7

Fig. 21 Natural frequency modal

11. Conclusion

A muffler is developed for the 1.5L diesel hybrid vehicle. The Noise Vibration Harshness (NVH) characteristics of the muffler is matched with the attenuation requirement for different drive train modes of the hybrid vehicle. 1D WAVE simulation was performed to develop various options of the muffler internals to get the required transmission loss and back pressure. The 1D WAVE simulation results are correlated with the experimental results obtained using LMS test bench. 3D back pressure is obtained through flow thermal simulation. The sound transmission loss was also predicted using LMS Virtual lab and correlated with the experimental results. The muffler back pressure from 1D code was 155 mbar whereas the back pressure from CFD analysis is 175 mbar, within the acceptable deviation of 10-15%. Finite element analysis was performed to establish the structural integrity of the muffler.

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Dr. Rajadurai had various leadership positions such has the Director of Research at Cummins Engine Company, Director of Advanced Development at Tenneco Automotive, Director of Emissions at ArvinMeritor, Vice-President of ACS Industries and since 2009 he is the Head of R&D Sharda Motor Industries Ltd. 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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