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Structural Analysis of Passenger Car Exhaust System by Using Hypermesh

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Abstract – The Automobile exhaust system is used for silencing the noise caused by the high pressure exhaust gases are releasing in to the atmosphere. It is important to control the emissions and a part of combustion. Exhaust systems are a special type of size and geometry, the constraints placed in the design of a car. It is found that the induced vibrations are spread along the exhaust system and the forces are transmitted to the car body. To reduce the forces, adding of decoupling elements like flex-couplings and isolators are used. The vibrations could induce structural noise in the passenger car. The adopting procedure includes a correlation and model updating step can be done by using Finite element method and optimization technique.

Index Terms – Automobile, Exhaust, Hypermesh.

1. INTRODUCTION

Every increasing demand for durability, lighter and cost effective designs of automotive products have led to more frequent usage of powerful Numerical techniques for solving structural problems. In the automotive industry, the detection of structural failures has traditionally relied on proving ground road load tests. It is generally recognized that developing designs through testing and retesting using several prototypes is not helping in accelerating the product development. Hence virtual structural calculations of automotive components have become an essential part for vehicle manufacturers. The laboratory test offers durability evaluation for the exhaust system, which could provide information. Comparing to laboratory tests, CAE is another tool, which could be employed for improving durability performance of exhaust components while reducing significant product development costs and time. CAE not only evaluate durability performance, but also explores many possible design options and promises to yield optimum design with significant experimental cost and time savings.

2. LITERATURE REVIEW

H. Bartlett et al., [01] this paper presents the modelling and analysis of variable geometry, exhaust gas systems. An automotive example is considered whereby the pulsating exhausts gas flow through an exhaust pipe and silencer are considered over a wide range of speeds.

Dr. S. Rajadurai et al., [02] this paper deals, to evaluate the durability of exhaust system components by CAE Simulation. Finite element simulation are carried out and the results are explained for the typical exhaust system components considering the durability loads such as engine vibration loading, proving ground road loads. The durability issues associated with the exhaust system components such as muffler-pipe system, brackets and hanger designs are analyzed.

Johan Wall Karlskrona, [03] describes the Low vibration levels are a critical objective in automobile exhaust system design. It is therefore important for design engineers to be able to predict, describe and assess the dynamics of various system design proposals during product development.

Sanjay S. Patiletal., [04] deal with dynamic analysis of a modular automotive exhaust system where it is directly mounted on power train pack. Selection of dynamic loads, processing of the test data, and effect of assembly loads along with material property variation due to temperature are explained.

3. OVERVIEW OF EXHAUST SYSTEM

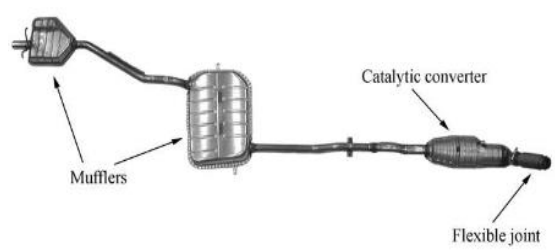


Figure 1Typical exhaust system design.

Exhaust system plays an important role in the performance of the vehicle. It carries out all the burnt gasses from engine to atmosphere. As a traditional procedure, track tests are made to assure the proper structural design of vehicles and life determination. There is a worldwide trend to use more computer simulation structural behavior and decreases the time to market and coasts. A complicated real world environment seen by an exhaust system in the vehicle can be simplified and modelled using numerical simulation. By using engineering experience and time-tested assumptions, valuable information can be acquired in relatively cost and time-effective way, thanks to the computation power boosted in recent years.

3.1. Components of passenger car exhaust system are

1. Catalytic Converter.
2. Exhaust Manifold
3. Exhaust - pipe system Muffler Bracket design.
4. Exhaust Clamps, Hangers and Brackets
5. Mufflers
6. Exhaust Flange
7. Vibration isolator
8. Flexible Coupling
9. Tail pipe

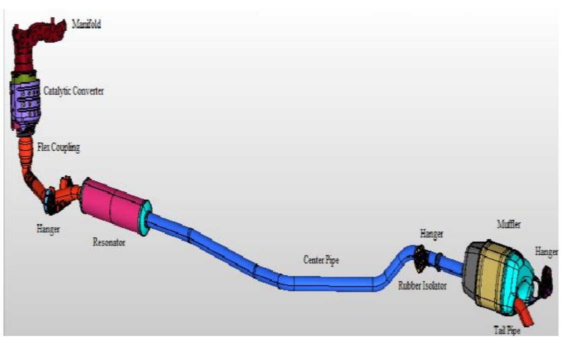


Figure 2 Schematic Diagram Of passenger Car Exhaust System

Automobile exhaust system refers to a group of independent but interrelated automotive components used to direct the waste exhaust gases out of the combustion chamber of an engine. Based on its design the exhaust system comprises several different parts such as a cylinder head and exhaust manifold, a turbocharger to enhance engine power, catalytic converters for air pollution reduction, a muffler or a silencer to reduce noise and one or more exhaust pipes.

4. STATEMENT OF THE PROBLEM

The automotive industry is heading in the direction of signing off the exhaust system durability based on computer simulation rather than rig simulation and physical vehicle testing. This is due to the cost, time and availability of prototype vehicles and test track. Use of Finite Element Method (FEM) enables to assure the structural integrity of the exhaust system and also contribute to better understanding of the system behavior in the various operating conditions and evaluation of structural strength.

4.1. Objectives of the Project

The main Objectives of the Projects are:

- To generate a finite element model of the Exhaust system
- To carry out the all necessary checks on the model
- To determine the Natural frequency of the Exhaust system[Normal mode analysis]
- Stress analysis on the whole exhaust system model under 1G and road load condition.
- To determine the Max displacement and Reaction forces on the Bracket and hanger location under 1G and 5G static loading.[Static analysis]
- To determine the Max Displacement, under dynamic loading [Modal Frequency response] at different location in the exhaust system.
- The natural frequencies obtained from the normal mode analysis are compared with the experimental results.

4.2. Scope of the Project

- Modal analysis (SOL103) is carried out for complete exhaust system to determine the first natural frequency of exhaust system and also to check the resonance frequency.
- Static analysis (SOL101) is carried out to check the distribution of displacement and reaction forces at the rubber mount location of the exhaust system.
- Dynamic analysis is performed to check the displacement at different location of the exhaust system.
- Comparison study for normal modal analysis for exhaust system assembly by experimental and numerical approach.

4.3. Methodology

In this project, Finite Element analyses were used to determine the characteristics of the Exhaust system. All methodology principles and theories discussed were utilized to achieve the project's objectives. The combination of all the analysis results were used to develop virtual model created using FEM tools and the model was updated based on the correlation process.

The research methodology flowchart for this project was shown in Figure 3.

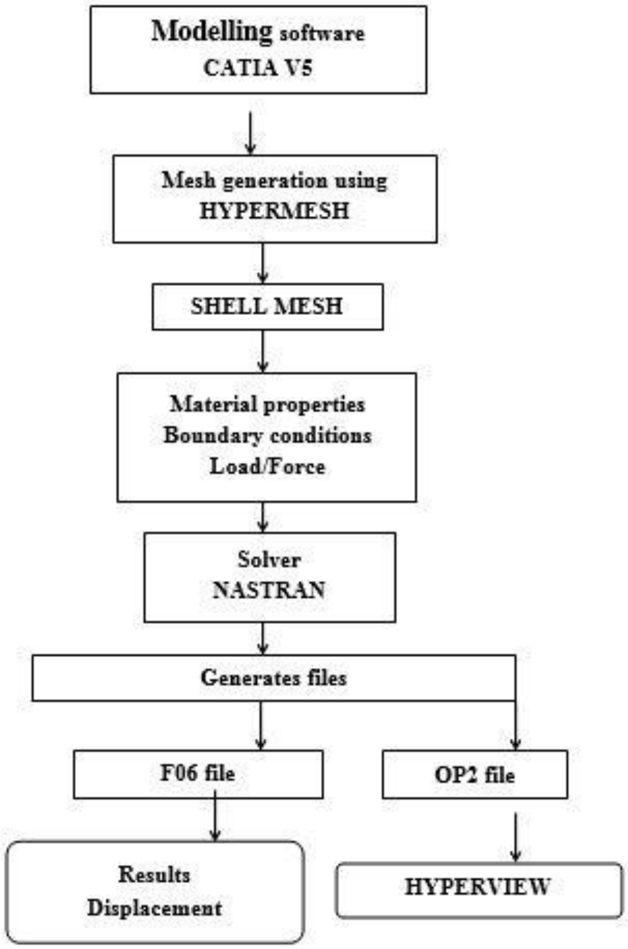


Figure 3 Flow chart of different stages in the project

5. GEOMETRICAL CONFIGURATION AND MATERIAL PROPERITY OF THE EXHAUST SYSTEM

5.1. CAD Model

The CAD model of Hyundai i10 passenger car exhaust system for analysis is provided by Sharda Motor Industries Limited, Chennai. The present exhaust system is taken over for analysis.

5.2. 2D Drafted CAD Model

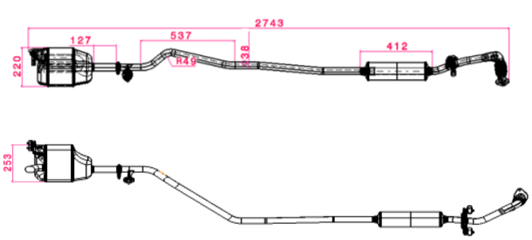


Figure 4 Schematic front and bottom view of 2D drafted model

5.3. 3D catiaV-5 Model

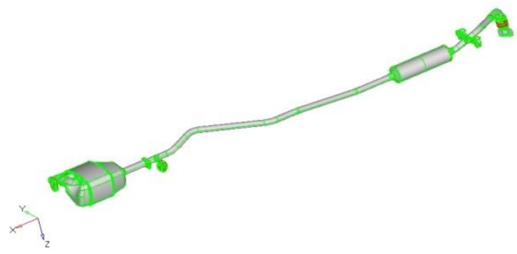


Figure 5 Representation of exhaust system in 3D view

5.4. Material Property

Stainless steel started to be used as material for decoration in automobile. However, in recent years, it is mostly used as material for the exhaust system. It is because those stainless steels with good performance of high temperature characteristics and high corrosion resistance meet the social needs for clean exhaust gases and reduced weight for better fuel economy. Material used for structural analysis of Exhaust system is Stainless Steel (SUS 304B).The isotropic material properties used in a FEA analysis are as follows:

S.No	Mechanical property of Stainless Steel	
1	Young's Modulus(E)	$2.08x10^5$ N/mm^2
2	Poisson's Ratio(ν)	0.31
3	Density(ρ)	$7.85x10^{-9}Ton/mm^3$
4	Yield Stress(σ_y)	350 N/mm^2
5	Ultimate Strength(σ_u)	450 N/mm^2

Table1 Mechanical properties of steel material used in Exhaust system

5.5. Geometrical Overview

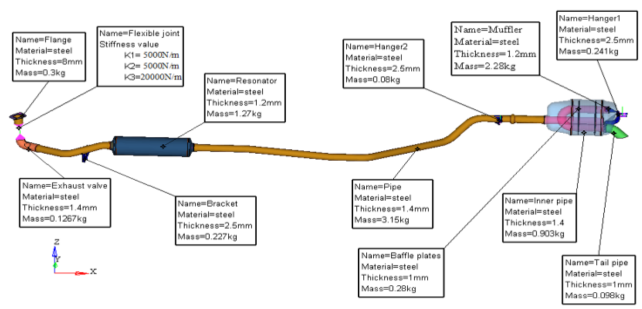


Figure 6 Complete Representation of Exhaust System

6. FINITE ELEMENT METHOD

6.1. Introduction to Finite Element Method

Engineering analysis can be broadly classified as shown in the Figure 7.

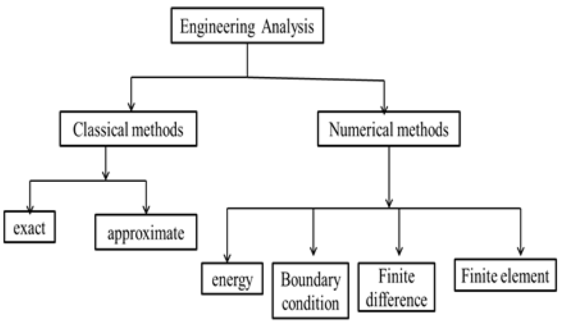


Figure 7 Engineering Analysis

The finite element analysis is a numerical analysis technique to obtain the solution of partial differential equations. The mathematical procedures such as Galerkin's weighted residual method and Rayleigh-Ritz methods are used to obtain the finite element formulation of the partial differential equation. The geometrical domain describing the engineering field problem is divided into sub domains, referred to as finite elements, and the variation of the primary variable in the finite element is described using piece-wise continuous functions within each elements.

6.2. Introduction to Hypermesh

HyperMesh is the world's most widely used pre/post-processing software for Finite Element Analysis (FEA) for provided solid modeling, meshing, and analysis setup for MSC Nastran, Marc, Abaqus, LS-DYNA, ANSYS, and Pam-Crash.

Designers, engineers, and CAE analysts tasked with creating and analyzing virtual prototypes are faced with a number of tedious, time-wasting tasks. These include CAD geometry translation, geometry cleanup, manual meshing processes, assembly connection definition, and editing of input decks to setup jobs for analysis by various solvers. Pre-processing is still widely considered the most time consuming aspect of CAE, consuming up to 60% of users' time. Assembling results into reports that can be shared with colleagues and managers is also still a very labour intensive, tedious activity.

6.3. Mesh Model Details

S.NO	Type of element	No of element
1	Quad4	67490
2	Tria3	129
3	Penta5	1296
4	Hexa8	479
	Total	69394

7. STRUCTURAL ANALYSIS

Structural analysis is probably the most common application of the finite element method. The term structural implies not only civil engineering structures such as bridges and buildings, but also naval, aeronautical, and mechanical structures such as ship hulls, aircraft bodies, and machine housings, as well as mechanical components such as pistons, machine parts and tools.

7.1. Normal Modal Analysis

The results of the modal analyses are sometimes compared to the physical test results. A normal modes analysis can be used to guide the experiment. In the pretest planning stages, a normal modes analysis can be used to indicate the best location for the accelerometers. After the test, a normal modes analysis can be used as a means to correlate the test results to the analysis results. Design changes can also be evaluated by using natural frequencies and mode shapes.

7.1.1. Natural Frequencies

The natural frequencies of a structure are the frequencies at which the structure naturally tends to vibrate if it is subjected to a disturbance. For example, the strings of a piano are each tuned to vibrate at a specific frequency. Some alternate terms for the natural frequency are characteristic frequency, fundamental frequency, resonance frequency, and normal frequency.

7.1.2. Mode Shapes

The deformed shape of the structure at a specific natural frequency of vibration is termed its normal mode of vibration. Some other terms used to describe the normal mode are mode shape, characteristic shape, and fundamental shape. Each mode shape is associated with a specific natural frequency. Natural frequencies and mode shapes are functions of the structural properties and boundary condition.

7.2. Dynamic analysis

Important Conditions in Frequency Response Analysis:

- Oscillatory loading is sinusoidal in nature.
- The steady state oscillatory response occurs at the same frequency as the loading.
- The response may be shifted in time due to damping in the system.

Modal frequency response analysis is an alternate approach to computing the frequency response of a structure. This method uses the mode shapes of the structure to reduce the size, uncouple the equations of motion and make the numerical solution more efficient.

8. BOUNDARY CONDITIONS

8.1. Loads

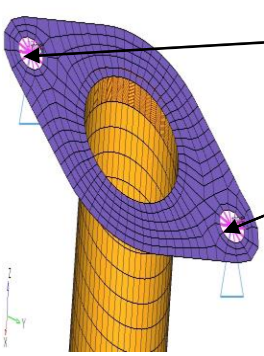
Because of frequency-varying nature, it is more complicated to apply dynamic loads than it is to apply static loads. Therefore, it is important to verify that the dynamic loads are correctly specified and that there are no discontinuous loads. The best way to verify proper dynamic load specification is to plot the loads as a function of frequency.

Major loads acting on the exhaust system is due to its self-weight and some engine vibrations also transferred through exhaust system. These loads led to breakage of clamping/hanger locations. Hence different values of gravity force are applied to analyze static and dynamic behavior.

8.2. Boundary conditions

The proper specification of boundary conditions is just as important for dynamic analysis as it is for static analysis. The improper specification of the boundary conditions leads to incorrect answers. One such improper specification of boundary conditions is forgetting to fully constrain the structure.

1. Boundary Condition at the flange region



Bolt holes of Flange connecting to Exhaust manifold is constrained in all dof(Ux, Uy, Uz, Rx, Ry, Rz = 0) with rigid element RBE2.

Figure 8 Boundary Condition at the flange region

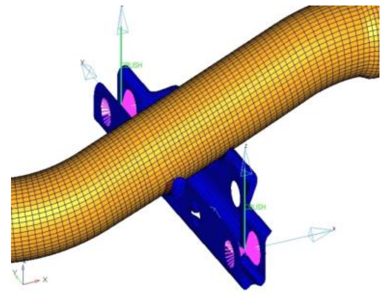


Figure 9 Boundary Condition at the Bracket region.

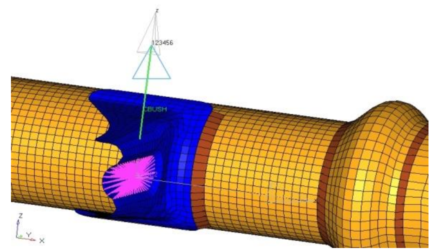


Figure 10 Boundary Condition at the centre of the exhaust pipe on hanger region

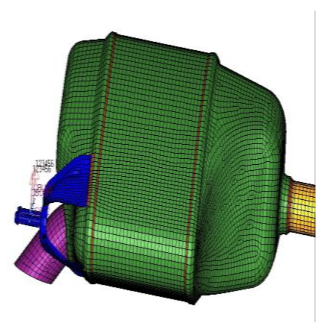


Figure 11 Boundary Condition at the rear muffler region.

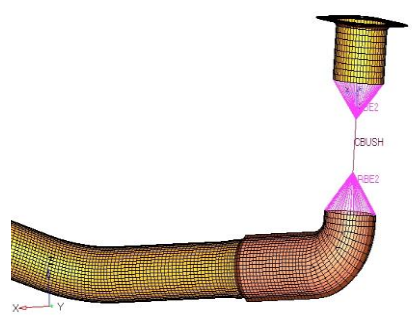


Figure 12 PBUSH element is used in region of Flexible Joint.

9. RESULT AND DISCUSSION

9.1. Normal Mode Analysis

The usual first step in performing a dynamic analysis is determining the natural frequencies and mode shapes of the structure with damping neglected. These results characterize the basic dynamic behavior of the structure and are an indication of how the structure will respond to dynamic loading.

9.1.1. Natural Frequency and Mode Shapes

S No	Modes shapes	Description	Natural frequency (Hz)
1	1^{st} Mode	Torsion mode	13.35
2	2^{nd} Mode	Bending mode	14.73
3	3^{rd} Mode	Linear mode	17.33
4	4^{th} Mode	Lateral mode	19.81
5	5^{th} Mode	Mixed mode	23.17
6	6^{th} Mode	Torsion mode	28.69
7	7^{th} Mode	Mixed mode	35.05
8	8^{th} Mode	Bending mode	44.45
9	9^{th} Mode	Lateral mode	56.25
10	10^{th} Mode	bending mode	74.90

Table 2 Mode Shapes at Different Natural Frequency

9.1.2. Mode Shapes of Exhaust System

In the above figures (13, 14) the first mode is observing the torsion movement at the region of middle pipe of the exhaust system and in the rear muffler region. The second mode gives the bending mode at the rear muffler region.

Mode 1

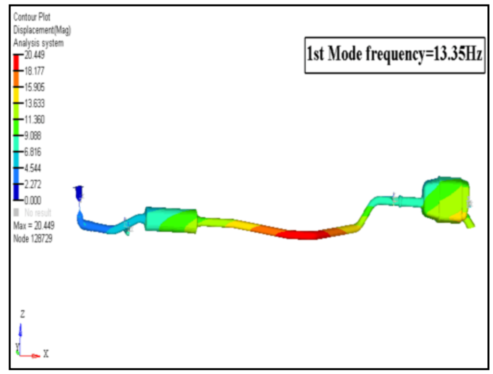


Figure 13 1^{st} Mode Shape Natural Frequency 13.35 Hz

Mode 2

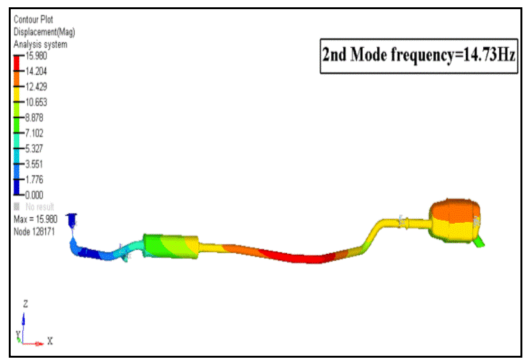


Figure 14 2^{nd}mode Shape Natural Frequency 14.73 Hz

9.2. Static Analysis

Static analysis is performed to know the maximum stress developed on the Exhaust system and also the displacement and reaction forces at the hanger and bracket location. The name Static indicates that the load on the Exhaust system is constant, that is load not varying with respect to time.

For static analysis under 1g load condition (-z)

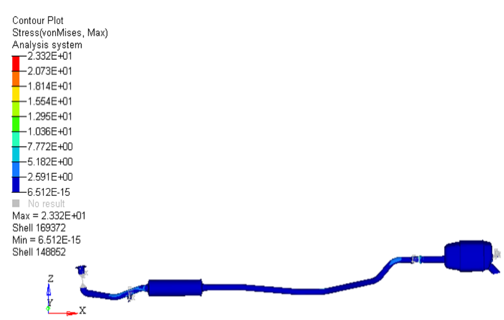


Figure 15 VonMises Stress contour (Max 23.32 MPa)

For road load condition under (x=5g,y=5g,z=-10g)

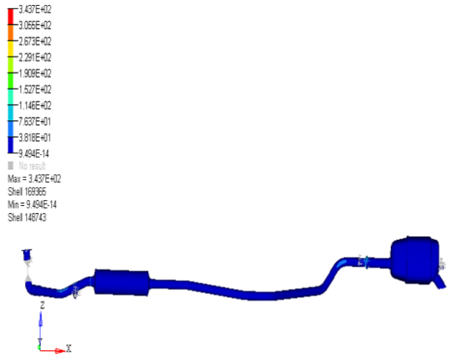


Figure 16 VonMises Stress contour (Max 343.7 MPa)

9.2.1. Reaction forces and Displacement at bracket and hanger location

For road load condition under (x=5g,y=5g,z=-10g)loading

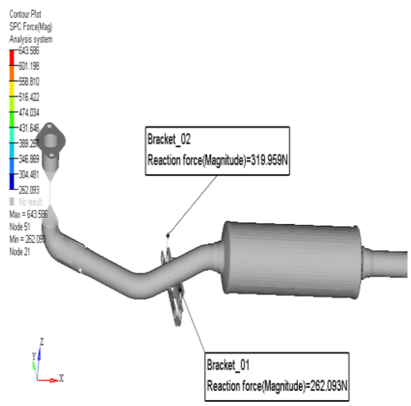


Figure 17 Reaction forces at bracket location for road load condition.

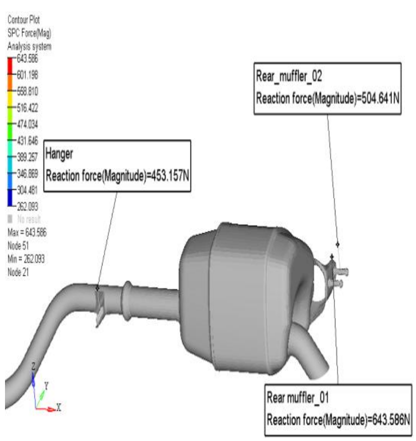


Figure 18 Reaction forces at hanger location for road load condition

9.2.2. Observation of Stresses At The Different Location Of The Exhaust System

Sl. NO	Component	Static stress at 1G (N/mm2)	Static stress at 5G (N/mm2)
1	Flange	0.8	5.56
2	Resonator	3.14	36.40
3	Exhaust Pipe	9.71	102.9
4	Muffler	4.05	29.95
5	Tail Pipe	1.25	5.62
6	Hanger 01	23.32	343.54
7	Hanger 01	8.3	74.2
8	Baffle Plates	2.15	25.42
9	Exhaust Hole	2.15	25.95
10	Connector	1.24	13.61
11	Bracket	6.78	79.32

Table 3 Von Mises Stress on individual components

9.3. Dynamic Analysis

Dynamic analysis is more complicated than static analysis because of more input (mass, damping, time and frequency varying loads) and more output (time and frequency varying results).

Equation of Motion: This equation, which defines the equilibrium condition of the system at each point in time, the equation of motion accounts for the forces acting on the structure at each instant in time. Typically, these forces are separated into internal forces and external forces. Internal forces are found on the left-hand side of the equation, and external forces are specified on the right-hand side. The resulting equation is a second-order linear differential equation representing the motion of the system as a function of displacement and higher-order derivatives of the Displacement.

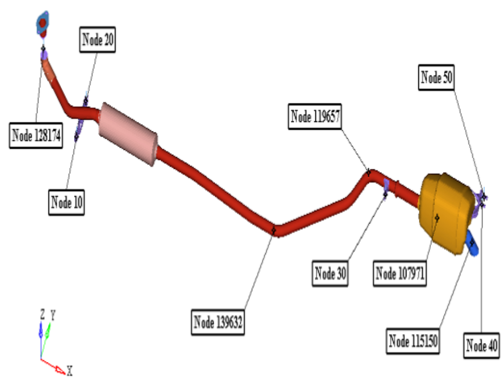


Figure 19 Nodal location in which the Accelerometers are attached

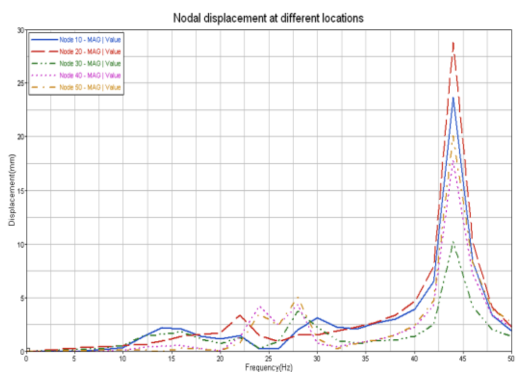


Figure 20 Graph for Displacement V/S Frequency at critical regions.

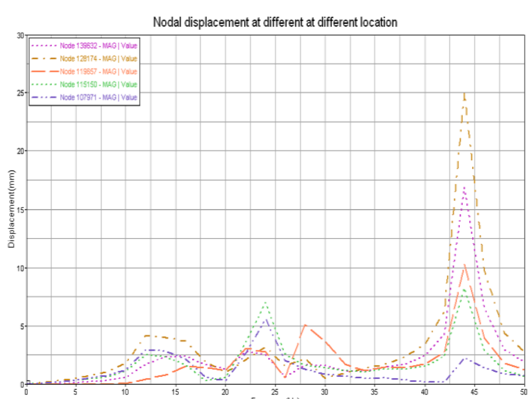


Figure 21Graph for Displacement V/S Frequency at other locations.

In the above graphs the maximum displacement shown at the bracket location it is due to the excitation produced from the engine. The brackets are welded to the exhaust pipe which is nearer to the engine hence more displacement occurs at that region.

10. CONCLUSION

The present work illustrates meshed model of exhaust system satisfied all quality criteria's hence the results are accurate. Typical road conditions are considered for loading. Static 1g load is preferred for smooth road, whereas road load for rough road which is included with pot holes, bumps etc., Loads and boundary conditions are accurately simulated to obtain the realistic loading conditions.

From the static analysis the maximum stress observed in exhaust system at road load condition is 343.7 MPa, as an obtained value is less than the yield stress of the material used hence the design is safe. In static analysis both 1g and road load conditions are considered. In both the cases the displacement at the either side of the bracket and hanger region is almost same, so we can say that the model is equally balanced.

From the structural design point of view the structure is considered safe as the stress levels are well below the ultimate stress. It was verified that numerical models validated with are a powerful tool during the development phases of vehicle, reducing project time and costs.

11. SCOPE FOR FUTURE WORK

- Similar analysis approach can be followed for any type of Exhaust system, in general any hanging component.
- Dynamic analysis can be carried out for the Impact loading and random changes of the load on Exhaust system due to uneven road.
- Fatigue life estimation of each component can be performed for Exhaust system.
- Thermal analysis can be performed to know the thermal stress on individual components of Exhaust system.
- Acoustic analysis can be conducted for the muffler region to check the noise.

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