

Field Failure Resolution of a Tractor Engine Exhaust System Using Constrained Single Objective Optimization and Stochastic Analysis

Solairaj Perumal, Abhay Kumar, Arun Mahajan, Dinesh Redkar, and Sureshkumar Balakrishnan
Mahindra & Mahindra, Ltd.

ABSTRACT

The tractor engine related mounting brackets are very critical due to different aspects of vehicle performance, durability and noise. These mounting bracket have been designed as a framework to support engine external parts like muffler, exhaust tail pipe, alternator etc. Vibration and fatigue has been continuously a concern which may lead to structural failure and performance issues. Various such failures are faced regularly by automotive industry and finite element based analysis are used to resolve them. The resolution is done by playing with the component thicknesses, material, by providing additional support etc. However, due to large degree of uncertainty associated with the loading, boundary conditions, manufacturing, environmental effects; still there is some probability of failure. This paper focuses on a field failure issue of an exhaust system of a tractor and subsequent concern resolution. Multiple field failures like Under Hood Muffler (UHM) lug failure and UHM mounting bracket failure were reported during different tractor applications. A finite element model was generated; static, modal and force frequency response analyses were performed and the field failures were simulated. As there were multiple failure modes, a multi-constrained single objective optimization problem was formulated and an optimum solution was obtained. To start with, few key influencing design parameters were identified, design of experiments (DoE) were conducted, a transfer function was developed and finally an optimum solution was derived. To evaluate the robustness of optimum design under uncertainty of material properties, thicknesses, exhaust temperature; a stochastic analysis were performed to find out the probability of success. No probability of failure was observed for all the objectives.

CITATION: Perumal, S., Kumar, A., Mahajan, A., Redkar, D. et al., "Field Failure Resolution of a Tractor Engine Exhaust System Using Constrained Single Objective Optimization and Stochastic Analysis," *SAE Int. J. Commer. Veh.* 10(1):2017, doi:10.4271/2017-26-0233.

INTRODUCTION

The fundamental purpose of exhaust system is to route the exhaust gases from the engine and keep the gases from entering the passenger Compartment. An exhaust system is usually tubing used to guide reaction exhaust gases away from a controlled combustion inside an engine. The entire system conveys burnt gases from the engine and includes one or more exhaust pipes. Depending on the overall system design, the exhaust gas may flow through one or more of: Cylinder, Exhaust manifold, muffler, Stub Pipe & tail pipe etc.

Muffler components and tail pipe assembly receive heat from the hot exhaust gas by convection. This heat is transferred to other components by conduction and radiation; to external cooling air by convection and some heat is stored in the muffler components. The yield strength and young's modulus of most materials (especially metals) gradually reduces when subjected to elevated temperatures [4].

While designing, structural strength is extremely important for the exhaust system. An engine exhaust system on its mounting bracket was excited by different field tractor application [1] & [3]. There are several tests for validating the exhaust system and its mounting brackets under different loading conditions. For example, Torture Track (TT) and Rough Coarse (RC) test is used to test all engine related mounting brackets. TT and RC test track is mapped from

different application of tractor field condition to validate the exhaust system [9]. Torture track test helps to capture those field excitation. Due to engine excitation, vibration is transferred from engine to exhaust system and then transferred to entire body structure. Engine excitation is considered for validation of mounting brackets [2] & [8].

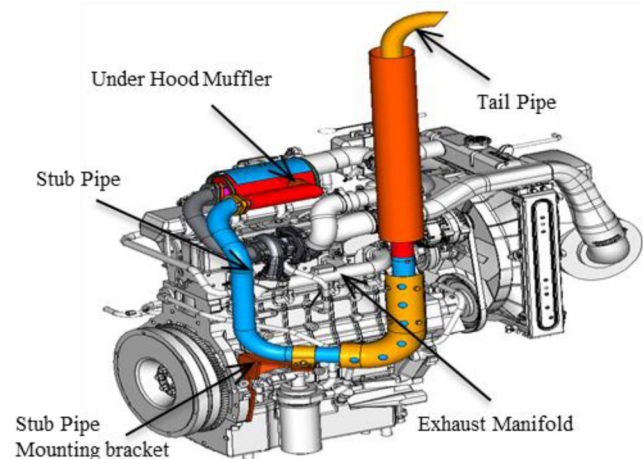


Fig.1. Typical exhaust system design.



Fig.2. Test Track

Present work is focused on structural and dynamic response of exhaust system was analyzed using finite element analysis. To predict the possible failure, static analysis was carried out to predict the structural strength & dynamic simulation was carried out to get frequency response [2].

Structural properties like stiffness of the engine exhaust system can be optimized by using Design of Experiment (DoE). Performing DoE Study of engine exhaust system adds value in terms of improving the quality and saving the cost by reducing the mass and avoiding re-work. The present work utilizes the DoE and Stochastic studies for exhaust system of the tractor using multi-constrained single objective optimization problem was formulated and an optimum solution was obtained. In finite element model, some physical uncertainty factors such as thickness, material properties of the several mounting brackets are considered for stochastic analysis to find out the probability of success [11].

The aim of this work is to identify the possible causes of the failure during different tractor field application and suggest proposals in order to solve this problem.

CASE STUDY 01: FAILURE ANALYSIS OF UHM LUG

The tractor under hood muffler lug failure is observed in the fillet location (Fig 3.0) during field testing like ploughing and puddling operation at different location. Muffler lug is mounted on cylinder head cover through mounting bracket and its weld with muffler. Finite element analysis was used to find out the possible root cause of failure and suggested suitable design modification to meet the design requirement.



Fig.3. Photograph of UHM Lug failure

PROCESS METHODOLOGY

The exhaust system durability analysis process comprises of the following steps in computer aided engineering (CAE).

- Existing design of solid modeling.
- Generated finite element model by using hypermesh software.
- Normal modal analysis of exhaust system for identifying most damaging frequencies
- Linear static analysis for von mises stress distribution at failure zone by using torture track load case.
- Structural Fatigue analysis for predicting minimum life cycle.
- Prediction of possible failure zone.
- Suggesting design modification & Re analysis

CAD model of exhaust system can be generated in any modeling software like Catia, Pro-E and Unigraphics etc., then transferred to finite element method software as shown in Fig.4 & Fig.5. The exhaust system is meshed with commercially available pre-processing software like hypermesh, Simlab etc.

The exhaust system consist of exhaust manifold, elbow pipe, muffler, stub pipe, tail pipe and its mounting brackets. Exhaust manifold is meshed with second order tetrahedrons. All pipe flanges are meshed with eight noded hexahedral element. Pipes, muffler assembly, lug, tailpipe and its mounting brackets are meshed with shell elements linear four noded quadrilateral elements. Weld is modelled between lug and muffler by a row of linear four node quadrilateral shell elements Bolt head is modelled with rigid element and bolt shank is modelled as a 1D beam element. The exhaust system is constrained at all mounting location as shown in Fig.6.

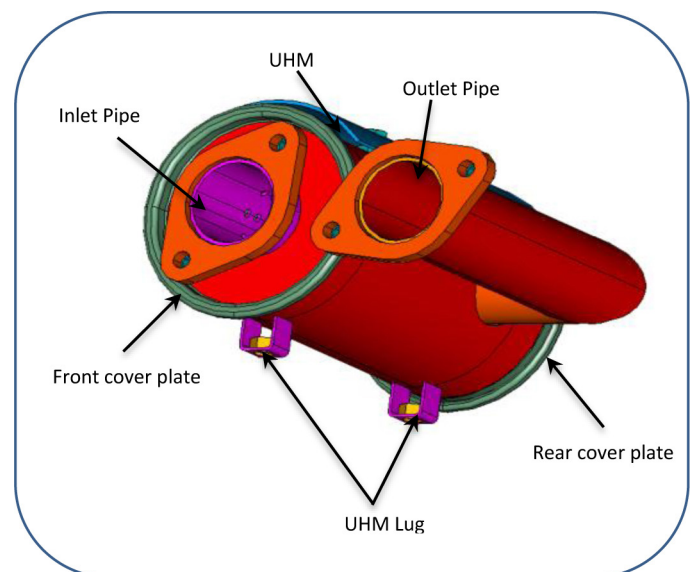


Fig.4. Sub-assembly of Under Hood Muffler (UHM) assembly

frequency is found lesser than ground level (10 Hz) frequency. Resulting two frequency were identified as most critical damaged frequencies and it is tabulated in [Table.1](#)

Table 1. Natural frequency of an exhaust system (Failure Model)

Mode#	Natural Frequency (Failure model)
1	9.9
2	13.3
3	33.5
4	41.6
5	59.8
6	61.5
7	74.4
8	91.2
9	109.6
10	132.1

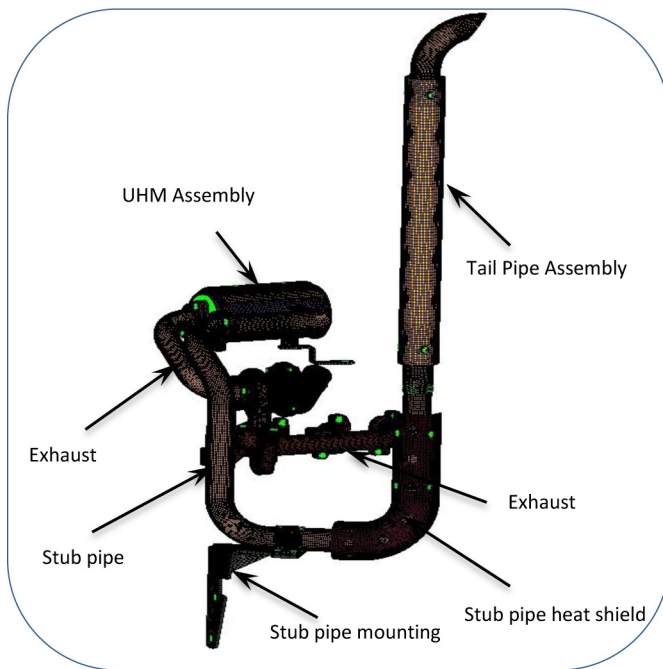


Fig.5. Finite element model of the exhaust system with tailpipe assembly

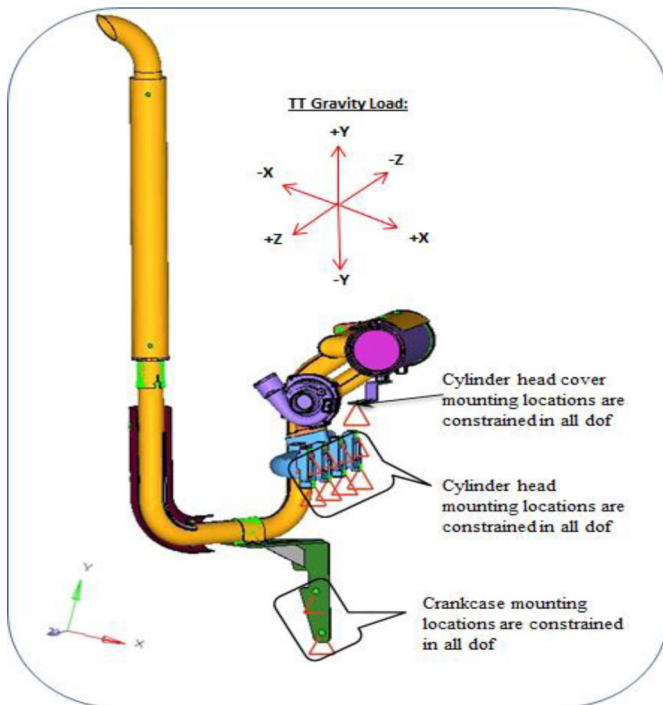


Fig.6. Load and boundary conditions for Static analysis.

Material used for structural analysis of Exhaust System is Stainless Steel and ERW tube. The isotropic material properties used in a FEA analysis. Material properties change significantly with temperature; material stiffness is reduced by the increased temperatures and has significant effect on the vibration characteristics. So material properties is changed with respect to temperature. Constrained modal analysis is carried out to find out the dynamic characteristic like mode shape and natural frequency of the exhaust system as shown in [Fig.7](#) & [Fig.8](#). Normal mode dynamic analysis gives modal strain energy at each location of the exhaust system. From modal analysis first

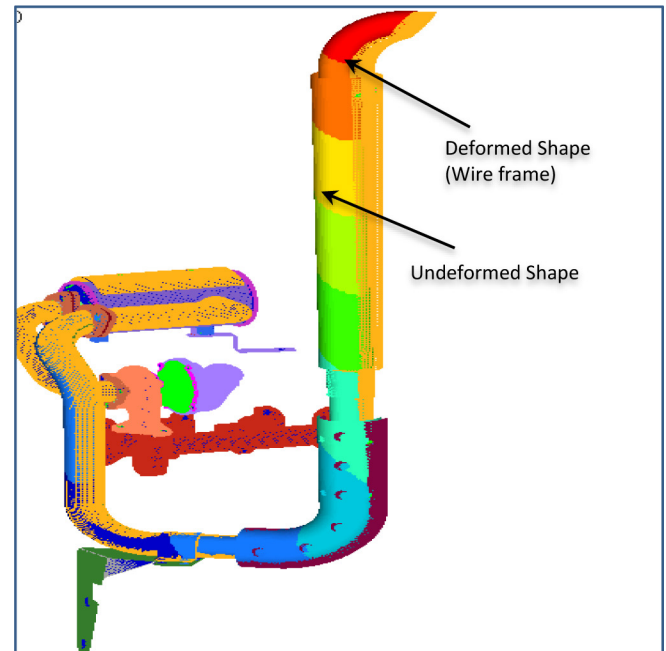


Fig.7. First mode shape of an exhaust system

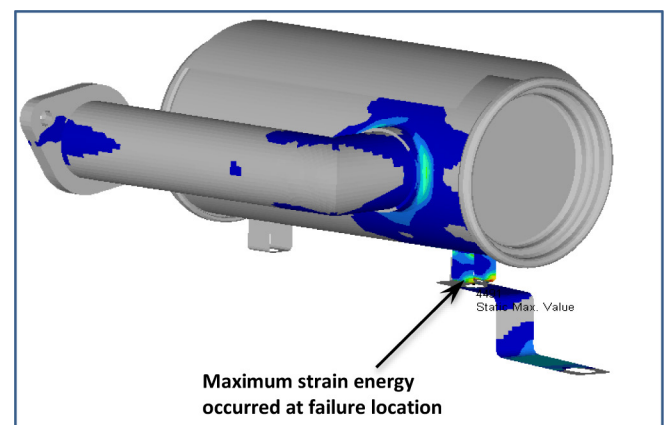


Fig.8. Strain energy contour plot for modal analysis

Linear static analysis was performed for exhaust system assembly. The torture track test gravity load was applied in all three direction. Maximum Von mises stress at failure zone were observed from linear static analysis. The Existing lug field failure is shown in Fig.10. At failure location, stresses are exclusively very high and more than Endurance Strength, so that fatigue life calculation were carried out to get the fatigue life cycle of the component. The resulting fatigue life is not meeting the test standard.

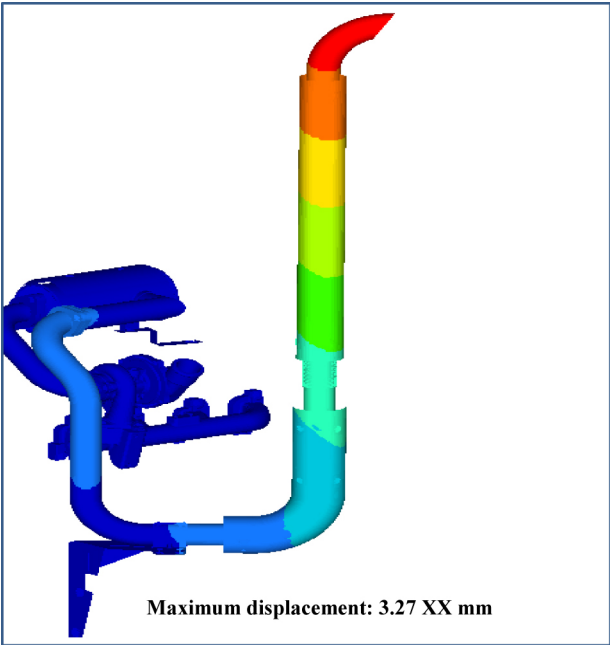


Fig.9. Failure model displacement contour plot for static analysis.

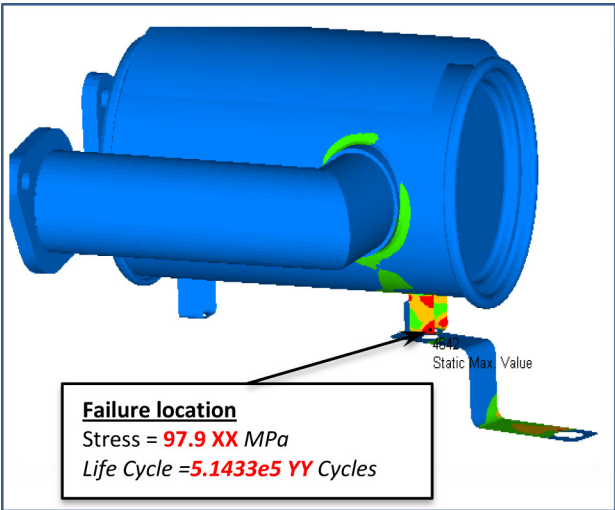


Fig.10. Failure model Stress contour plot for static analysis.

To avoid this field failure, CAE suggested design modification (Fig.11). Existing UHM Lug design of single mounting support is changed to double mounting support; lug design is also changed to get the maximum support from the muffler side. Again same loading and boundary conditions were applied and recommended design was analyzed for dynamic and static strength.

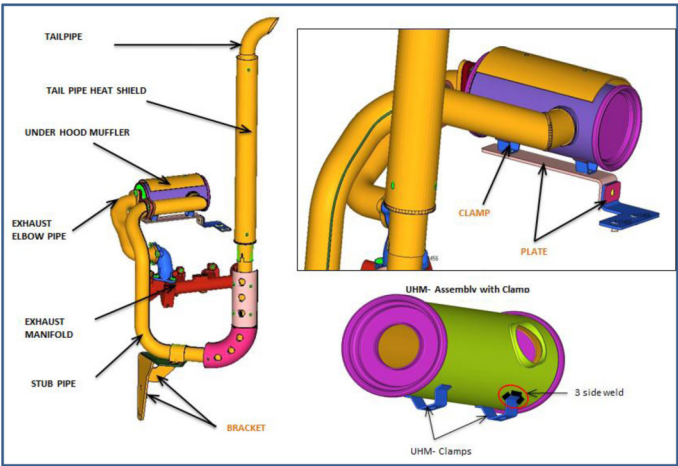


Fig.11. Recommended design modification of exhaust system & UHM Lug

As per CAE analysis, stresses in the recommended design were observed to be within the permissible limit as shown in Fig.12, Fig.13. & Fig.14. From modal analysis first frequency were more than ground level frequency and other natural frequencies is not meeting with engine operating frequency range as shown in Table.2. Recommended design successfully completed Torture track test condition.

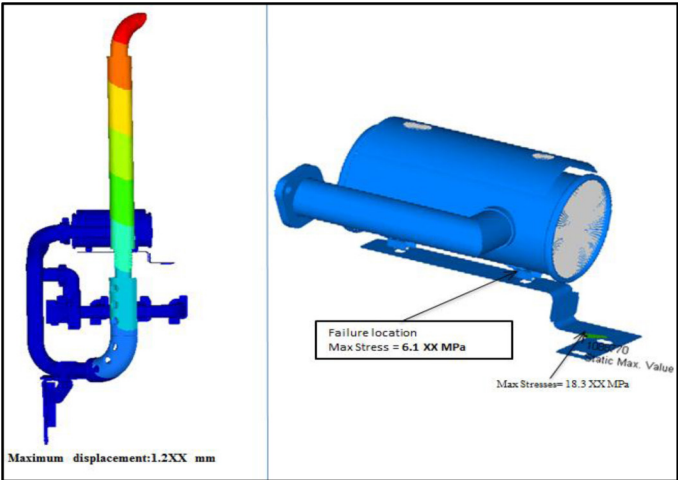


Fig.12. Modified model displacement and Stress contour plot for static analysis.

Table 2. Modified model Natural frequency of an exhaust system

Mode#	Natural Frequency (Failure model)	Natural Frequency (Modified model)
1	9.9	14.6
2	13.3	16.0
3	33.5	50.9
4	41.6	60.4
5	59.8	76.2
6	61.5	121.5
7	74.4	135.9
8	91.2	144.2
9	109.6	194.4
10	132.1	195.5