Engine Exhaust Transfer Connection Design based on High Back Pressure in Exhaust Brake Applications

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Abstract— **High back pressure condition in automotive exhaust piping is an important consideration in the design and optimization of exhaust systems which uses exhaust brakes. The complex geometry of the exhaust line and the special flow conditions complicate the process of designing robust exhaust connections. In our project work we initially summarize the current status of knowledge, from various literature sources, regarding exhaust piping design in automotive exhaust systems. An automotive case is then undertaken, where the need is to improve exhaust piping reliability against high back pressure loads of 5 bars along with high thermal loads. The turbocharger outlet pipe design is thus optimized ensuring structural integrity against high back pressure and thermal loads and also ensuring that the restrictions to exhaust gas flow are within acceptable limits. Design and analytical procedures are outlined enabling the optimization of exhaust gas components. The design verification by FEA analysis and design validation by prototype testing ensures a reliable design. Finally, with results discussion and conclusions we share our learning for any similar work in the area of engine exhaust system.**

***Keywords*—CFD approach, Exhaust back pressure, exhaust outlet pipe design, Stress to strength ratio.**

I. INTRODUCTION

In many automotive applications it is desirable to provide an auxiliary braking system to extend the life of the vehicle service brakes and to relieve the service brake cooling load. Guillotine or butterfly exhaust brakes restrict exhaust flow in order to the force the engine to pump against high restriction and provide a braking effect to the vehicle. During normal engine and vehicle operation, the exhaust brake is fully open allowing normal exhaust flow and no braking action. When the brake application is requested, the electronic and/or pneumatics controls close the valve to restrict the exhaust flow forcing the engine to pump against the restriction. The brake is configured so when the exhaust brake is engaged, the back pressure in the exhaust system may exceed upto the maximum limit. The piping, seals, and clamps, etc. must be designed to withstand the maximum allowable back pressure without leakage or failure. Incapability to withstand added exhaust back pressure will result in serious engine damage.

The exhaust outlet piping transfers the engine exhaust gas from the turbocharger outlet to one or more mufflers and then away from the vehicle. The large temperature gradient in the overall exhaust system can cause remarkable thermal stress in exhaust pipes. The key design aspects of the exhaust systems which can impact the engine performance are: restriction, structural integrity, and mounting. Other areas, such as the acoustic performance of the muffler, water intrusion prevention and exhaust dispersion, are not detailed in this paper.

Our work is based on the customer need to introduce the exhaust brakes in the system which will impose increased back pressure load of 5 bars in place of earlier 1.5 bars. To meet this added back pressure sustainability requirement under high temperature conditions, a systematic design and analysis procedure was carried to optimize the turbo outlet pipe design. The base engine components of exhaust system (manifold, turbocharger) were already proven to meet the new load requirements and hence do not fall under our scope of work.

I.1 OBJECTIVE

The primary challenge was to provide a design which is robust against combined thermal and back pressure loads. The secondary requirement was that this improved design should put minimum possible restriction to exhaust gas flow. The overall exhaust restriction in the system is a result of the design of the exhaust piping, muffler, and the engine exhaust gas flow [3]. It is necessary to limit the exhaust restriction in each of the components to maintain engine power output, engine efficiency and to control internal engine component temperatures.

In combination with above two, another key area of concern with customer was clearances of this outlet pipe from surrounding components as oil filter. The current design could not meet packaging constraints and had a low minimum clearance of 7.8 mm from crankcase mounted oil filter. This was seen as a problem by the engine manufacturer and hence need was to address this also in our work.

The objective of the project is thus to optimize the current design in order to prevent high thermal and back pressure stress of the exhaust piping.

Hence, the objective is Y = f(x1+x2+x3+x4. . . .)

where

Y = Design of New Exhaust System Component

X1= Unrestricted Gas Flow Existing Specification

X2= Natural Frequency Existing Specification or 3rd order frequency of engine

X3= Structural Strength Existing Specification or low stress to strength ratio

X4= Clearance from Lubrication Components ¿ Existing Specification or 25 mm.

I.2 LITERATURE REVIEW

The literature relevant to my research work falls under different categories to form a wide spectrum of knowledge shared under the different headings, for example – FEA analysis, CFD, pipe flow, exhaust system basics, new age materials and so on.

S. N.	REFERE NCES	LEARNING / RELEVANCY
1	[6] , [9], [10], [27], [7]	Material impact on the system performance; Effects of alloy composition, density, and process parameters on performance; Advancement; Various material tests;
2	[8], [11], [24], [15], [3]	Function of each of the exhaust system components; List of key components; Exhaust brake development
3	[23], [25]	Thermo-structural analysis of exhaust manifolds; One dimension model for heat transfer in exhaust system
4	[26], [17], [20], [21], [2], [1]	CFD analysis; pressure drops of perforated tube silencers; vibration analysis; sensitivity analysis of an exhaust system thermal model
5	[22], [32], [19], [31]	ultrasonic probes to test vehicle exhaust flow; hot wire anemometer; leak flow measurement method
6	[29], [30], [33], [34], [28], [5]	effect of a range of surface roughness values on the performance; developed a new exhaust system; exhaust brake performance

Table 1. Summary of Literature Surve

II. RESEARCH METHODOLOGY

To achieve the objective of high back pressure capacity and least clearance with surrounding installations on the engine, the combination between computational fluid dynamics (CFD) with finite element (FE) is introduced. A systematic process flow of design optimization is followed in our work. Existing component structural strength and flow restriction will be first analyzed so as to create a baseline data for further work. The current and possible designs are studied and undertaken for fluid dynamics study to ensure low exhaust restriction. Then chosen design will be studied in detailed for integration on vehicle layout and for possible risks of failure. These risks are covered by the design verification analysis i.e. FEA. Then experimentation validation and design finalization follows.

In order to meet the requirement, the following design procedure was followed:

1. Need Assessment
   a) Current System Study – data collection
   b) Design Variation Analysis (D.V.A.) of current system
   c) Baseline component analysis
2. Literature Review
3. Design Optimization – concept creation
   a) Pipe design improvement matrix
   b) Pugh Decision Matrix creation
   c) CFD of selected concepts
4. Design finalization – risk assessment
   a) Final layout study
   b) D.F.M.E.A. of finalized concept
   c) New system Design Variation Analysis (D.V.A.)
5. Design Verification
   a) Structural FEA
   b) Modal FEA
6. Experimental Validation (includes detailed drawing and prototype creation)
7. Result study and Conclusion.

III. EVALUATION OF BASELINE DESIGN

We checked the system and component properties, studied its 3D CAD model and layout, carried D.F.M.E.A. and D.V.A. In D.V.A. the Worst Case Minimum Distance Between Oil Filter and the Current Design was found to be 7.845 mm.

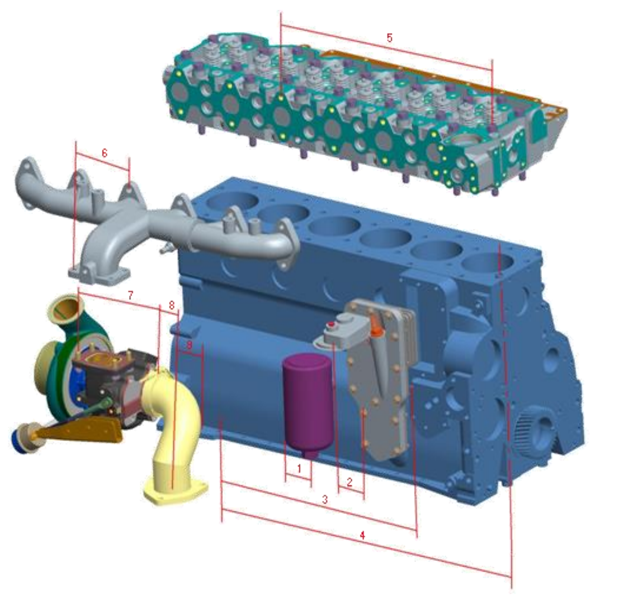

Figure 1: Design Variation Analysis of current design

Then proceeded with Thermal and Structural Analysis of current concepts. With the given loading condition, the current exhaust outlet connection do not meet acceptance limits for tensile dominated stress to strength ratio values in Analysis.

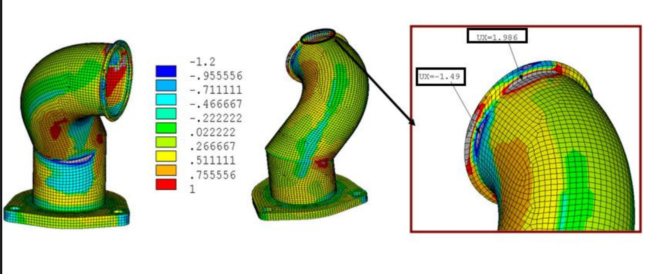

Figure 2: Structural Analysis Result of Baseline Design

IV. DESIGN OPTIMIZATION

We created seven possible designs of the transfer connection, four of which were casting parts. A schematic study of each of the concept designs was carried to ensure suitability.

	IMPACT / CHANGE	Flow Restriction	Emission performance	Acoustic performance	Corrosion resistance	Structural Integrity	Vibration Isolation
1	**Diameter reduction**	**Y**	**Y**	**Y**	**N**	**Y**	**Y**
2 x	**Length**	**N**	**N**	**N**	**N**	**N**	**Y**
3	**Bend Radius increase**	**N**	**N**	**N**	**N**	**N**	**N**
4	**Bend Radius decrease**	**Y**	**N**	**Y**	**N**	**Y**	**N**
5	**Material/ Coating**	**N**	**Y**	**N**	**Y**	**Y**	**N**

Table 2. Impact of design change in exhaust piping

Also as created, the heads in "Pugh matrix" for decision on suitable design concepts included: surrounding clearances, manufacturability, ease of assembly and estimated structural integrity. The Pugh matrix helped in first level filtering of concepts and hence the good concepts were taken for CFD analysis for flow restriction values.

1. CFD analysis –

CFD analysis is required to evaluate the flow performance (in terms of loss coefficient (1)) of different concepts of Exhaust connection elbow.

$$\text{Loss Coefficient} = \frac{\text{Total pressure loss from inlet to outlet}}{\text{Dynamic pressure at outlet}} \quad (1)$$

2. CFD Results (Table II, and Fig. 3) –

It is found that Concept 4 is giving less loss coefficient among the concepts analyzed (Less than baseline) and Concept 6 is giving higher loss coefficient among the concepts analyzed

	Baseline	Concept 4	Concept 6	Concept 7
Pressure Drop (in Pascal)	941	518	1660	1334
Loss Coefficient	**0.26**	**0.15**	**0.42**	**0.35**

Table 3. Pressure drop for Baseline and various concepts

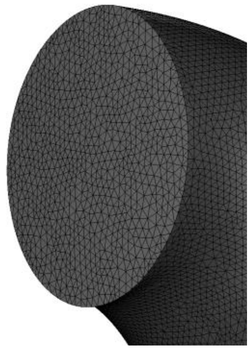

Figure 3: The CFD Mesh

V. NEW DESIGN FINALIZATION

We proceed with the further detailed study and analysis of this concept 4 to finalize the solution proposal. The first step in design detailed study is D. V. A. of new concept so as to ensure the minimum clearance requirement of the given engine configuration. Additionally, the layout study of new components was carried at two levels - firstly engine layout and secondly vehicle layout. As a part of this study, we checked the new component support bracket compatibility and ease of assembly also. The final concept of exhaust connection elbow is thus a cast design supported by simple L type sheet metal bracket. The detailed drawing of part was also prepared as first step to prototype creation.

VI. DESIGN VERIFICATION (SIMULATION)

The CAD model after being analyzed for suitability on engine and vehicle layouts, is then saved for next step that is FEA analysis. Similar to the Finite Element Analysis of baseline exhaust connection elbow, the concept elbow is also considered for FEA. The steps for FEA of this new concept assembly is same as:

1. 3D CAD model finalization
2. Preparation of FE Mesh
3. Thermal Analysis
4. Structural Analysis

In addition to above, we also carried a schematic Modal Analysis of this concept design in ANSYS WorkBench itself. Modal Analysis was carried because the elbow and its support bracket assembly was entirely a different geometry and hence CG of the components was different in the two cases and this will bring different natural frequencies.

1. Thermal and Structural Analysis –

The aim of this analysis is to determine stresses in the new exhaust connection due to loads from exhaust brake application. This finds the Yield stress to Yield strength ratio values of Exhaust outlet connection to check its structural integrity under given loading conditions. It is carried in ANSYS Workbench.

Engine Condition	Area component	Temperature (deg C)	Convective Coefficient (W/m^2.K)
At Torque Peak	Inner area of outlet connection	720	540
Ambient	Outer area of outlet connection	32	45

Table 4. Thermal Boundary Conditions

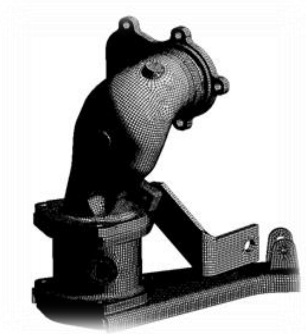

Figure 4: The FEA Mesh

Following loads have been considered for the analysis

- Load case 1= Thermal Load
- Load case 2 = Thermal Load + 1.5 Bar Internal Pressure
- Load case 3 = Thermal Load + 5.0 Bar Internal Pressure

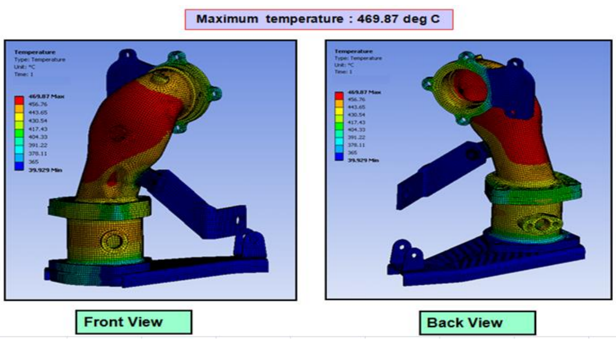

Figure 5: Thermal Analysis Results

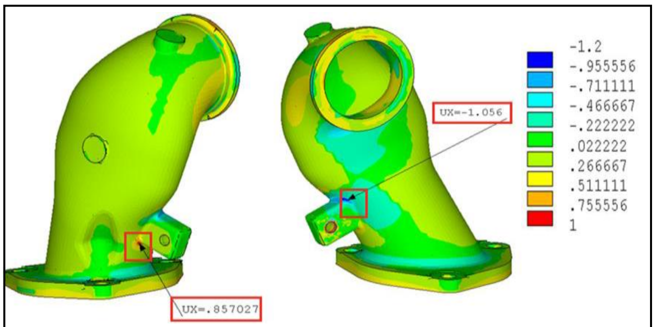

Figure 6: Stress Ratio Plot of New Concept Design

2. Results of Structural Analysis –

- For all three load cases, the new exhaust outlet connection is meeting acceptance limits for tensile dominated stress to strength ratio values. Maximum tensile dominated stress to strength ratio value induced in exhaust outlet connection is 0.85892 for 3rd load case (i.e. Thermal load + 5.0 bar internal pressure).
- For all three load cases, Exhaust outlet connection is meeting acceptance limits for Compressive dominated stress to strength ratio values. Maximum compressive dominated stress to strength ratio value induced in exhaust outlet connection is -1.109 for 3rd load case (i.e. Thermal load + 5.0 bar internal pressure).
- Internal pressure of exhaust gas is having less effect on Tensile and compressive dominated stress to strength ratio values.

3. Modal Analysis –

The aim of Modal analysis is to determine first 6 Modal frequencies of the exhaust outlet connection. This analysis is also carried in ANSYS Workbench. This analysis is carried for both the new concept design as well as the baseline design.

Results of Modal Analysis

- First natural frequency of Baseline exhaust outlet assembly is 251.87 Hz which is more than Engine 3rd order firing frequency.
- First natural frequency of New exhaust outlet assembly is 249.97 Hz which is more than Engine 3rd order firing frequency.
- First mode of Baseline exhaust connection assembly is vertical bending.
- Second mode of Baseline exhaust connection assembly is Twisting mode
- Third mode of Baseline exhaust connection assembly is Twisting mode.

VII. EXPERIMENTAL VALIDATION

The component prototype was manufactured by traditional sand casting process. This prototype was then visually inspected for casting defects and was checked for dimensional accuracy to be within specified tolerances.

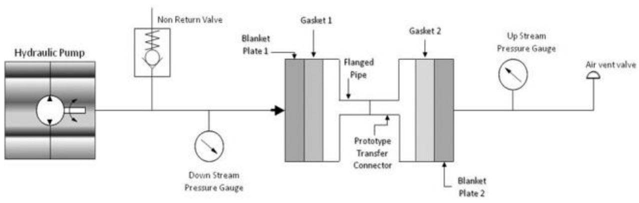

Figure 7.: Experimental Setup

1. Hydrostatic Pressure Test –

1) Applied Pressure – 20 kg/cm^2
2) Acceptance Criteria - The prototype connection should withstand the applied hydraulic pressure and hence should not show any red/pink color spots in dye penetration test.
3) As per IS: 3589-1981.

2. Leakage Test –

The compressed air as fluid is supplied to the same assembly and checked for leakage by dipping under water.

The prototype components passed both these tests and no dye (pink color) was seen on the surface of the component after application of defined pressure for the given time.

Also the leakage test did not show any undesired flow from joints.

VIII. RESULTS

S.N.	Parameter	Baseline Design	New Concept
1.	Stable temperature in static thermal analysis	472 ^{0}C	469.82 ^{0}C
2.	Max Deformation due to worst case load	1.84 mm	1.61 mm
3.	First Natural Frequency	241.87 Hz	234.97 Hz
4.	Experimental Validation results	-	Passed

Table 5: Results

CONCLUSION

The engine exhaust backpressure under high speed and high temperature as operating conditions may put damaging effects on exhaust line. In our work, a schematic method is followed to optimize the design of exhaust outlet pipe against exhaust pressure for internal combustion engines when equipped with exhaust brakes.In this paper, a method is developed to design exhaust outlet pipe against exhaust pressure for internal combustion engines equipped with exhaust brakes.

First, CFD Analysis was conducted to ensure low restriction to exhaust. This Analysis also proved useful to understand the influence of internal geometry on the performance of the connection, as shown in below figure. For design verification, the ANSYS Workbench mesh is first undertaken for thermal analysis, providing input conditions to upcoming thermo-mechanical loading on the FE mesh. The Structural Analysis was then carried out to determine the effect of combined thermal stress and pressure stress. Based on stresses, the acceptability of new design is estimated. All these analyses indicated that the optimized design reasonably sustains the thermal and back pressure stress behavior. The experimental validation of new design prototype shows satisfactory results in Hydrostatic and Leakage tests. The Numerical Analysis of design case further assured the suitability of new concepts.

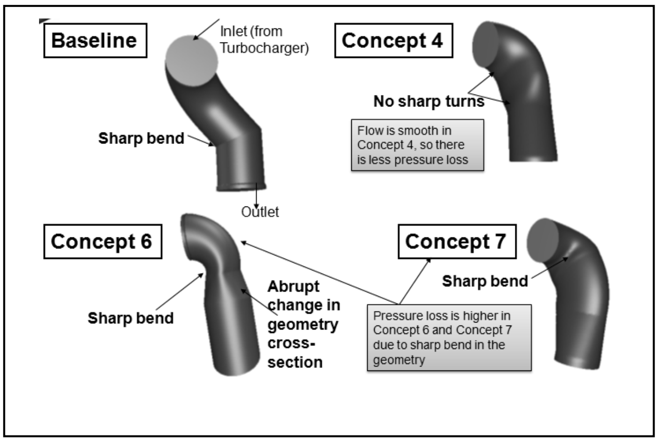

Figure 8: Geometry of design concepts

Additionally, as a part of design process, the decision making and risk assessment tools as Dimensional Variation Analysis (D.V.A.), Pugh Decision Matrix, and Design Failure Mode and Effect Analysis (D.F.M.E.A.) are utilized. Based on the findings from these design tools, recommendations were given to optimize the exhaust pipe design.

SCOPE FOR THE FUTURE WORK

- Engineering change release of the new assembly by a cross functional team,
- Engine and Vehicle OEMs will validate the new design.

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