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. This paper initially summarizes the current status of knowledge regarding exhaust piping design in automotive exhaust systems. An automotive example is then considered, where the need was to improve exhaust piping reliability against high back pressure loads of 5 bars along with high thermal loads. The turbocharger outlet pipe design was 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 general analysis of exhaust gas systems. In this example, along with CFD analysis, Structural and Modal analysis results are studied which simulate the impact of exhaust brake operation. Simulation results show the effect of heavy back pressure streams through exhaust.

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.

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. To achieve the objective, the combination between computational fluid dynamics (CFD) with finite element (FE) is introduced. Existing component structural strength and flow restriction were first analyzed so as to create a baseline data for further work.

First, CFD analysis is conducted to obtain temperature distribution, providing conditions of the thermo mechanical loading on the FE mesh. Next, FE analysis is carried out to determine the thermal stress. The interpolation of the temperature data from CFD to FE is done by binary space partitioning tree algorithm. To accurately quantify the thermal stress, nonlinear material behavior is considered.

Based on stresses and strains, the acceptability of new design can be estimated. All these analysis indicate that the optimized design reasonably sustains the thermal and back pressure stress behavior. Also, 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 Faliure Mode and Effect Analysis (D.F.M.E.A.) are utilized. Additionally, the influence of internal geometry on the performance of the conection was discussed in detail. Based on the results, recommendations are given to optimize the exhaust pipe design and operation.

II. DESIGN METHODOLOGY

A major area of exhaust system design is the size and configuration of the exhaust piping between the engine turbocharger outlet and muffler(s) inlet and any piping after the muffler(s). Good design practice is to use as large diameter piping as practical with the fewest bends possible, keeping any bends as large a radius as possible [3]. Pipe diameter and bend radii are the design factors, which have the greatest influence on piping system restriction.

The design optimization of exhaust outlet pipe can be carried in a manner motioned in Table I.

In order to meet the requirement of high back pressure capacity and least clearance with surrounding installations on the engine, the following design procedure was followed:

I. Need Assessment
- **a) Current System Study**
- **b) D.V.A. of current system**
- **c) Baseline data collection (CFD of current system)**

II. Literature Survey

III. Design Optimization – concept creation
- **a) Pipe design improvement matrix**
- **b) Pugh Decision Matrix creation**
- **c) CFD of selected concepts**

Table I - Impact of design change in exhaust piping

	IMPACT / CHANGE	Flow Restriction	Emission performance	Acoustic performance	Corrosion resistance	Structural Integrity	Vibration Isolation
1	Diameter reduction	Y	Y	Y	N	Y	Y
2	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

IV. Design finalization – risk assessment
- **a) Final layout study**
- **b) D.F.M.E.A. of finalized concept**
- **c) New system D.V.A.**

V. Design Verification
- **a) Structural FEA**
- **b) Modal FEA**

VI. Detailed drawing creation and part fitment check

VII. Result study and Conclusion

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.

III. CFD & FEA

A. CFD analysis

CFD analysis is required to evaluate the flow performance (in terms of loss coefficient (1)) of different concepts of Exhaust connection elbow. In this study, all CFD simulations are performed using the commercial CFD software package ANSYS FLUENT 13, and the computational grids are generated using the commercial grid-generation software ICEM-CFD. CFD analysis is done at rated operating condition of the engine.

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

1) CFD Modeling Assumptions [1]

Since computer simulation can never completely represent the reality, the following assumptions were made in CFD model:

- Since combustion products are over 70% nitrogen by volume, properties for air are valid for use in representing the exhaust.
- Soot particles are ignored since they have little effect on gas flow.

2) Modeling Setting

- Steady state Flow
- Compressible Flow
- Node based solver

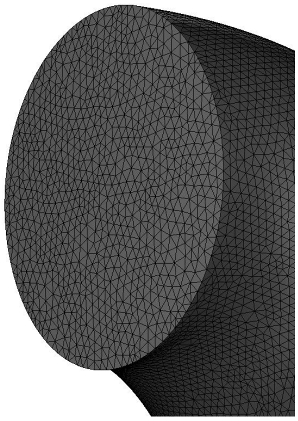

Fig. 2 - The CFD Mesh

- Realizable k-epsilon Turbulence model
- Second order discretization for momentum

3) CFD mesh

- Total number of cells: ~1.2 million
- Mesh type: Tetrahedral mesh
- Element type: Hex elements

4) Fluid Properties

- Fluid: Air
- Density: Ideal gas
- Specific heat: 1006.43 j/kg-k
- Thermal Conductivity: 0.0242 w/m-k
- Viscosity: 3.704 e-05 kg/m-s (at 515°C, and atmospheric pressure)

5) Boundary Conditions

- Inlet (Mass Flow Inlet)
  - Mass Flow Rate: 0.2451* kg/s
  - Turbulence intensity: 5 %
- Outlet (Pressure Outlet)
  - Gauge pressure: 1 bar gauge (static pressure)
  - Turbulence intensity: 5 %
- Operating pressure: 1 bar

Mass flow rate is calculated corresponding to exhaust gas flow rate 33 m3/min at rated condition

6) CFD Results (Table II, and Fig. 3)

B. Modal Analysis

The aim of Modal analysis is to determine first 6 Modal frequencies of the exhaust outlet connection The Modal analysis is necessary if:

- The current system has not been resonant dwell tested in the past.
- The new outlet increases the mass significantly or moves the CG of the component significantly farther

Table II - Pressure drop for Baseline and various concepts (not exact values)

	Baseline	**Concept 4**	**Concept 6**	**Concept 7**
Pressure Drop (in Pascal)	**930**	**430**	**1560**	**1234**
Loss Coefficient	**0.26**	**0.15**	**0.42**	**0.35**

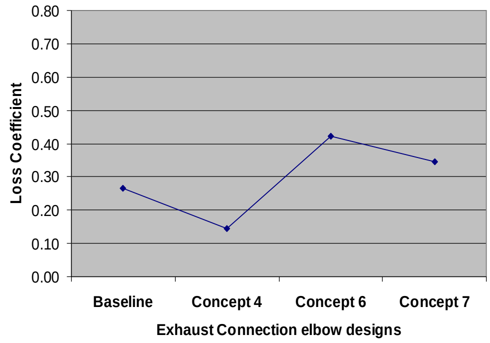

Fig. 3- Loss coefficient comparison

away from the turbo.

- An additional support is added to the structure. In this case a modal analysis should be performed to understand the effect of the new support on the system.

1) Modal Analysis Approach

- This analysis is carried in ANSYS Workbench.
- Assembly containing exhaust outlet connection, mounting bracket1, gaskets exhaust connection, and mounting bracket2 is considered for analysis.
- All components are connected through bonded contacts.
- Mounting brackets edge is constrained in all direction.
- Steady state thermal analysis has been carried out with standard manifold thermal boundary conditions to determine temperature distribution across exhaust outlet connection.
- Finally modal analysis of exhaust outlet connection assembly is carried out with thermal loads as input condition.

2) Acceptance Criteria

First natural frequency should be more than Engine 3rd order firing frequency at high idle.

3) 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

C. Structural Analysis

The aim of this analysis is to determine stresses in the exhaust connection due to loads as per 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.

In case of Baseline Exhaust connection high value of Stress to strength ratio is observed at front side of exhaust connection since bracket is connected to exhaust connection through bonded contact, which is not allowing exhaust connection to expand under thermal load.

1) Structural Analysis Approach

- All components are connected through bonded contacts.
- Mounting brackets edge is constrained in all direction.
- Steady state thermal analysis has been carried out with standard manifold thermal boundary conditions to determine temperature distribution across exhaust outlet connection.

Fig. 4 – The FEA Mesh

- Finally the analysis of exhaust outlet connection assembly is carried out with thermal loads as input condition.

2) Acceptance Criterion

- All tensile stress to strength ratio for exhaust connection should be less than 1.
- All compressive stress to strength ratio for exhaust connection should be less than 1.2

3) Loading conditions

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

4) Boundary conditions

Thermal Boundary Connections [5] used for analysis are given in below Table III (these are not exact values due to confidentiality requirement).

- The edge of mounting holes of turbine casing flange (art of turbocharger assembly) are constrained in all directions.
- Bonded connection is used between exhaust outlet connection, and turbine casing flange (turbocharger end).
- Edge of mounting brackets are constrained in all direction
- Bolt holes of bracket are constrained in all direction
- Frictional connection is used between the mounting bracket (other end) and its washer.

5) 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.

Table III – Thermal Boundary Conditions

Engine Condition	Area component	Temperature (deg C)	Convective Coefficient (W/m².K)
At Torque Peak	Inner area of outlet connection	720	540
Ambient	Outer area of outlet connection	32	45

CONCLUSION

Engine exhaust backpressure is a critical parameter in the calculation of the volumetric efficiency and exhaust gas recirculation flow of an internal combustion engine. The backpressure under high speed and load engine operating conditions may put damaging effects on exhaust line.

In this paper, a method is developed to design exhaust outlet pipe against exhaust pressure for internal combustion engines equipped with exhaust brakes.

The computational fluid dynamics (CFD) approach is used to calculate the flow restriction of exhaust line elements with flow. The pressure drops of exhaust transfer connections are predicted by performing the analysis using CFD. The pressure drop of the bent type sheet metal exhaust pipe connection is much higher than those of cast designs at the same flow conditions, and the pressure drop of the cast pipe increases when a sharp bend or sudden change in the cross-section is there in the geometry (Fig. 5).

An important understanding about CFD results is that for concept selection, absolute values of pressure drop should be considered, and comparative selection should only be done if the difference in pressure loss is significant. Also velocity counters show that velocity is low at sharp bend due to recirculation in flow.

In case of structural analysis, high value of Stress to strength ratio is observed at front side of exhaust connection when the bracket is connected to exhaust connection through bonded contact, which is not allowing exhaust connection to expand under thermal load. Bonded connection between exhaust connection and bracket is not realistic since there will be some slip between two components during thermal loading. Frictional contact between exhaust outlet connection and bracket may give realistic results at front side of exhaust outlet connection. The FEA analysis results of the casting design concept are within the acceptable limits.

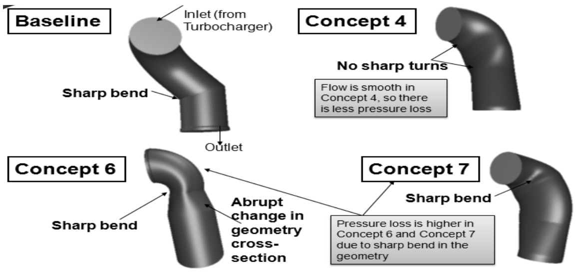

Fig. 5 – Geometry of design concepts

ACKNOLEDGEMENT

The author would like to thank Dr. D. R. Panchagade, Head of Department, Department of Mechanical Engineering and Dr. R. S. Bindu, Associate Professor, Department of Mechanical Engineering, D. Y. Patil College of Engineering, for providing their expert guidance.

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