

Design of the Exhaust Manifold of a Turbo Charged Gasoline Engine Based on a Transient Thermal Mechanical Analysis Approach

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ABSTRACT

The present paper describes a CAE analysis approach to evaluate the design of exhaust manifold of a turbo charged gasoline engine. It allows design engineers to identify structural weakness at the early stage or to find the root cause of exhaust manifold failures. A transient none-linear finite element method is used to calculate the plastic deformation and thermal mechanical behaviors of the exhaust manifold assembly during thermal shock cycles, which include rated speed full load, rated speed motored and idle speed conditions. A transient heat transfer simulation is performed to provide thermal boundary conditions for the nonlinear stress/strain analysis. The finite element model includes a part of cylinder head, exhaust manifold, gaskets, turbo charger housing, catalytic converter, brackets, bolts and nuts. The results show that plastic deformation is the main cause of manifold cracking and the manifold flange distortion causes the exhaust leakage. The simulation results indicate that predicted crack locations and leak area are in agreement with that from the engine durability test. Based on the baseline calculation results, local geometric modifications are made, which include changed shape of the inlet flange, changed location of anchor bolt hole and removing the internal baffle. For the modified design of the exhaust manifold, the cumulated equivalent plastic strain and the gasket sealing pressure at the end of third cycle meet the guideline limits. The modified exhaust manifold successfully passed all tests. Finally, general design recommendations of exhaust manifold are summarized in the paper.

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INTRODUCTION

Because of increasing performance and emission demands, turbo charged gasoline engines are becoming popular in the passenger car market. These downsized engines have higher thermal loads and experience increased levels of vibration. The exhaust manifold metal temperature can rapidly increase from ambient temperature to about 900°C and large transient temperature gradient can occur. The larger temperature variation causes a larger thermal stress on the structure. Due to cyclic thermal loads, thermo mechanical fatigue cracks on exhaust manifold and gasket sealing failure are often observed during engine durability tests, such as thermal shock test. [Table 1](#) summarizes the failure mode analysis of exhaust manifolds of turbo charged gasoline engines.

In this paper we take the example of a new 1.5 liter turbo charged gasoline engine, i.e. NSE 1.5T, to demonstrate the CAE assisted approach to solve the above mentioned exhaust manifold durability problems. The NSE 1.5T, as shown in [Figure 1](#), was developed by SAIC Motor, which has been in mass production since 2013. The engine's specifications are listed in [Table 2](#).

The material type of the exhaust manifold is cast iron D5S "GGG Ni Si Cr 35 5 2". The maximum temperature of this material is in the range of 850°C - 1050°C. The maximum exhaust gas temperature is limited by engine calibration so that metal temperature does not exceed the temperature limit.

CAE engineers play an important role to find the weakness of an exhaust manifold layout at the early stage of the engine development. During the design phase of the exhaust manifold development, it is important to develop a concept, which allows local thermal mechanical restraining to be relieved and temperature level and temperature gradients to be lowered. Besides, the exhaust manifold has also to be designed to meet engine performance target and emissions target, with the consideration of tight package requirements and challenging underhood cooling conditions with a large heat shield.

During the validation phase of the engine development process, exhaust manifold cracks and gasket leakage were observed during thermal shock tests. As shown in [Figure 2](#), the crack locations are at (a) the collector rib, (b) the internal baffle and (c) the area on the exterior side of the internal baffle near the runner #3. To solve the test failure problems, CAE tool was used in the iterative design process, in which the analysis not supplements testing investigations and provides directions of design modification.

Under automotive operation conditions, thermal mechanical fatigue damage of exhaust manifolds is influenced by many factors, which include material properties, mechanical strain range, strain rate, temperature, and the phasing between temperature and mechanical strain. A thermal-mechanical fatigue (TMF) lifetime-prediction model needs to consider damage through mechanical fatigue, creep and oxidation mechanisms and part of the interactions between these mechanisms. There is no TMF model which is valid under general load conditions for all types of materials. The uncertainty of TMF prediction are due to such factors as temperature prediction accuracy, material properties, phase of temperature and mechanical loads, material variation, failure criteria, etc [1]. According to Sehitoglu [2] Damage from each mechanism is summed to get an estimation of the total fatigue life. Manson-Coffin formula is widely used to describe the fatigue life [3, 4], in which plastic strain amplitude is used. The fatigue ductility coefficient and fatigue ductility exponent have to be obtained from TMF tests. Taira proposed a relation between thermal fatigue and low cycle fatigue durability [5]. This model is modified in [6,7].

$$N = \lambda(T_{eq}) \cdot \Delta \varepsilon_{eq}^{\beta} \quad (1)$$

$$\Delta \varepsilon_{eq} = \int_{cycle} \sqrt{\frac{2}{3} \dot{\varepsilon}^p : \dot{\varepsilon}^p} dt \quad (2)$$

Here N is the number of cycles to failure, $\Delta \varepsilon_{eq}$ is the equivalent plastic strain accumulated between two cycles. The coefficient $\lambda(T_{eq})$ is dependent on an equivalent temperature and several empirical constants. To determine these material constants, different thermal mechanical cyclic tests are required, in which different maximum temperatures and dwell times are considered. For simplicity and practicality, in this work the thermal fatigue life is estimated based on the equivalent plastic strain increment during the third cycle and the equivalent accumulated plastic strain in three cycles. In addition, the level of metal temperature is also considered for risk assessment.



Figure 1. The NSE 1.5T engine.

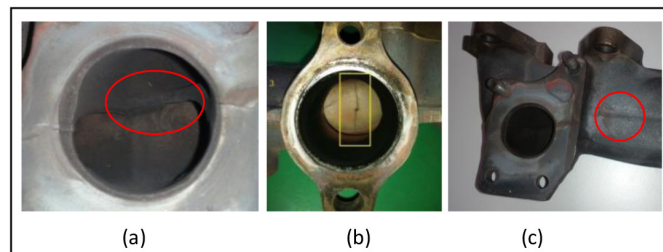


Figure 2. Cracks on the exhaust manifold.

Table 1. Failure mode analysis of cast iron exhaust manifolds

Type of Issues	Root causes	Influencing factors
Cracks on exhaust manifold	Extreme magnitude of gas temperature	Engine calibration
	High metal temperature gradient	Manifold shape design
	Extreme vibration level (HCF)	Vibration mode of exhaust system
	Material property not meet requirements	
	Local stress exceeds the yield stress under high thermal loading, cyclic plastic straining of the material (TMF)	Geometric shape and stiffness distribution, thermal expansion
	Casting defect	
Exhaust leak at the interface between cylinder head and exhaust manifold	Wall thickness not meet design guideline	
	Exhaust manifold flange distortion	Flange shape and thickness, bolt pattern, bolt number, Temperature distribution
	Interface deformation between cylinder head and exhaust manifold	Temperature distribution
	Exhaust gasket failure	Gasket material type, multi-layer gasket, bead design, coating
	Loosen bolts	Plastic deformation of bolt, thread length, anchor hole, engine vibration
Exhaust leak at the interface between exhaust manifold and turbo housing	Loosen nuts	bolt pretention, tightening sequence, vibration level, washer, strength grade of nut
	Flange distortions at the manifold side and/or at the turbo side	Bolt pattern, claspboard design, ribs from turbo housing flange to runners.
	gasket failure	Material type, layers, bead design, coating
	Loosen nuts	bolt pretention, tightening sequence, turbo bracket design, washer, strength grade of nut

Table 2. Engine specifications

Engine	NSE 1.5T
Configuration	In Line 4
Charging System	Turbo charged
Fuel Injection System	MPFI
Bore×Stroke	75mm×84.8mm
Displacement/L	1.499
Valves per cylinder	4
Compression Ratio	9.5:1
Valve train	DOHC, inlet VCT
Max. Power /kW(@r/min)	115 (@5500)
Max. Torque /N.m(@r/min)	215(@2000)
Fuel Type	Gasoline, 95 RON
Emissions Standard	Euro 5

THERMAL ANALYSIS

Temperature peak and temperature distribution of exhaust manifold are dominant factors in TMF durability assessment, since the thermal fatigue crack and gasket leakage can be initiated by thermal deformation due to spatial and temporal temperature variations. The mechanical and fatigue parameters of most metallic materials are temperature dependent, such as those of elastic module, expansion ratio, yield strength, fatigue cyclic life. It is known that temperature elevation imposes significant adverse impact on plastic deformation and fatigue.

The purpose of the present thermal analysis is to calculate the transient temperature fields under the thermal shock cycles, during which the exhaust manifold alternatively experiences different thermal loads at rated speed full load, rated speed motored and idle speed conditions. Figure 3 shows the simulation procedure. The 1-D engine performance analysis is used to provide boundary conditions for 3-D CFD analysis, which include gas flow-rate, pressure and temperature over a complete engine cycle. Then calculated mean values of local heat transfer coefficients and near-wall gas temperatures from Equation (3) and Equation (4) are input into a Finite Element (FE) model to run a transient analysis to obtain time-dependant skin temperatures distribution. At location $\mathbf{x}$, the time averaged heat transfer coefficient $\bar{h}(\mathbf{x})$ and the time averaged gas temperature are as followings [8]:

$$\bar{h}(\mathbf{x}) = \frac{1}{720} \int_0^{720} h(\varphi, \mathbf{x}) d\varphi \quad (3)$$

$$\bar{T}_g(\mathbf{x}) = \frac{1}{720 \bar{h}(\mathbf{x})} \int_0^{720} h(\varphi, \mathbf{x}) T_g(\varphi, \mathbf{x}) d\varphi \quad (4)$$

Here $h(\varphi, \mathbf{x})$ and $T_g(\varphi, \mathbf{x})$ are transient local heat transfer coefficient and gas temperature respectively. is crank angle.

Figure 4 and Figure 5 show the 3-D CFD model and the FE model of the exhaust system, respectively. The CFD model consists of internal passage of exhaust port, exhaust manifold

and inlet part of turbo housing, while the FE model includes a part of cylinder head, exhaust manifold, gaskets, turbo charger housing, catalytic converter, brackets, bolts and nuts. The mean gas film temperature and heat transfer coefficients are mapped from CFD mesh to FE mesh. In addition, heat transfer coefficient at the coolant side of cylinder head and heat transfer coefficient at the external air side, which are calculated from steady CFD analysis, are also input into the FE model.

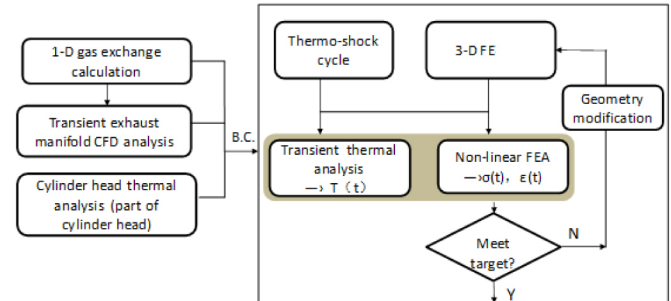


Figure 3. Calculation procedure

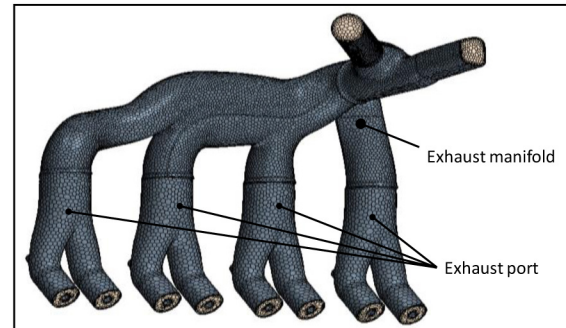


Figure 4. 3-D CFD model of exhaust manifold interior domain

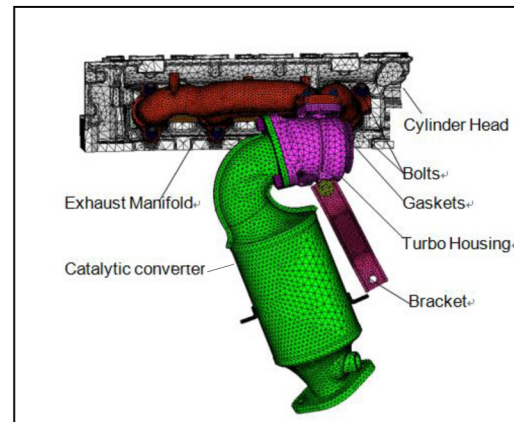


Figure 5. FE model of the hot end of exhaust system

At peak power condition, the interior wall of exhaust manifold is exposed to exhaust gas with temperature up to 950°C. Figure 6 shows the contour of mean value of local gas temperature at the interior wall, at peak power condition. The CFD results indicate that the internal baffle and the runner junction are heated by exhaust gas, resulting in higher temperature in these areas.