

Cracking Failure Analysis and Optimization on Exhaust Manifold of Engine with CFD-FEA Coupling

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ABSTRACT

For fracture cracks that occurred in the tight coupling exhaust manifold durability test of a four-cylinder gasoline engine with EGR channel, causes and solutions for fracture failure were found with the help of CFD and FEA numerical simulations. Wall temperature and heat transfer coefficient of the exhaust manifold inside wall were first accurately obtained through the thermal-fluid coupling analysis, then thermal modal and thermoplastic analysis were acquired by using the finite element method, on account of the bolt pretightening force and the contact relationship between flange face and cylinder head. Results showed that the first-order natural frequency did not meet the design requirements, which was the main reason of fatigue fracture. However, when the first-order natural frequency was rising, the delta equivalent plastic strain was increasing quickly as well. Ultimately, to solve the problem, the semi-shell was strengthened and some dents of critical areas were added so as to absorb some energy, consequently, the plastic strain decreased in the process of thermal expansion and cooling contraction. Meanwhile, the optimum model was verified effective by test. It can be concluded that this study was of certain value for engineering application.

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INTRODUCTION

Tight coupling exhaust manifold, the multi-orifice structural component with its thin-wall curved surface, is the main heated part in the exhaust system, responsible for better transmitting the high temperature exhaust gas to the subsequent tail gas treatment system in time, working in an extremely poor environment [1]. Developments in modern internal combustion engine are proceeding along high-power and lightweight [2, 3] tendency. Further, its enhancement degree continues to improve and the exhaust temperature is also rising. These problems will cause heat load aggravation of several certain parts, resulting in exhaust manifold stress concentration [4], therefore, more and more cracking failures would happen, and it could seriously affect the security and durability of engine [5]. In a word, the crack diagnosis and optimization design for exhaust manifold are indispensable.

It is the alternating temperature that leads to the alternating variation of stress, which will accelerate the speed of plastic strain accumulation. Once thermal cracks form and spread quickly along boundaries, plastic fractures are very easy to occur in the exhaust manifold. In addition, the resonance between engine and exhaust manifold could make strain energy of some parts highly concentrated, and vibration stress also brings in fracture problems. In order to make sure the natural frequency of exhaust manifold is not within the excitation frequency range, it is necessary to validate the well performance of exhaust manifold by simulation analysis and comparison with experiments in the field of product design and

development. In existent researches relative to fatigue failure of exhaust manifold, Yuanfu, C. et al. [6] made full use of temperature field data measured by the bench test, and the fluid-solid coupling model of exhaust manifold was established based on the accurate heat transfer model. Results of the thermal load simulation showed that the largest plastic strain positions were consistent with the fracture zones of actual occurrence; Santacreu, P. et al. [7] put forward a low cycle fatigue life prediction on elasto-viscoplastic behavior and damage model with the aid of a number of thermal-mechanical experiments, what's more, the thermal-mechanical fatigue properties of stainless steel exhaust manifold were assessed successfully; Mamiya, N. et al. [8] computed the complicated finite element model by considering the bolt pre-tightening force and nonlinear contact, and the plastic strain increment was applied to evaluate the thermal fatigue, besides, the accuracy of the numerical results were authenticated compared with experiments.

The tight coupling exhaust manifold used for a four-cylinder gasoline engine with EGR channel was concerned in the study. There would be cracks in the side of the upper shell if it ran 400 cycles during the durability test. These cracks expanded completely after 700 cycles, giving rise to fractures around the bolt hole of the mounting bracket, thus causing leakage. Undoubtedly, the structure of the exhaust manifold needed to be optimized.

To explore the fundamental reasons and specific solutions for failures which happened in the exhaust manifold, first of all, with considerations for the thermal radiation between exhaust manifold and heat shield as well as nonlinear characteristics of materials, the exhaust manifold temperature distribution was obtained correctly through the analysis of fluid-solid coupling heat transfer. Afterwards, contact relationships between flange face and cylinder head, and between fixed bracket and base plate were taken into account, besides, the bolt pre-tightening force was applied, and after that the thermal shock process was simulated. Numerical analysis results and bench test results, in comparison, were in relatively agreement, which manifested that the method and step of modeling proposed in this study were practical. According to the calculations of thermal load and thermal modal, it was believed that fatigue fractures originated from the fact that the first-order natural frequency of exhaust manifold was very close to the engine's excitation frequency. For the purpose of increasing the first-order natural frequency, the structure of fixed bracket was designed to improve its rigidity, but the delta equivalent plastic strain was in such a high value that the exhaust manifold was out of the design maximum. Indeed, making a delicate balance between increase of first-order natural frequency and enhancement of plastic strain levels was needed. Finally, aiming at a relatively high first-order natural frequency and appropriately low plastic strain, several measures were taken, for example, the structure of semi-shell was optimized by making it wider and higher while the fixed bracket was retained its original state. On the whole, it was proved that the modification of the existing exhaust manifold sufficed requirements and offered a certain reference value for practical engineering application.

EXHAUST MANIFOLD MODEL

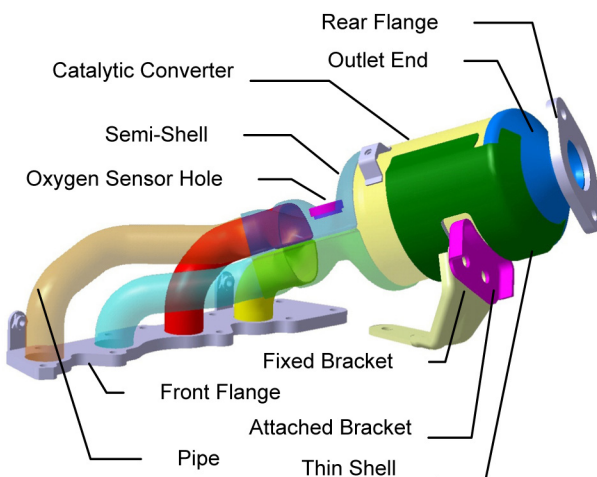


Figure 1. The main structural components of exhaust manifold

The exhaust manifold is mainly composed of flanges, branch pipes, semi-shells, brackets and a catalytic converter, as shown in Figure 1. Front flange and cylinder head were closely linked by 10 fastening screws. The exhaust gases leaving the outlet passed through branch pipes, semi-shells, catalytic converter, entering the following treatment system and finally

discharging to atmosphere. The oxygen sensor was located in the middle of the upper semi-shell, also had the ability to feed back the signals of gas temperature and velocity into ECU (Electronic Control Unit), so the power, economy and emission performance would become better. Owing to the installation of EGR (Exhaust Gas Recirculation), NO_x emissions would be minimizing and at the same time the fuel efficiency would be improved [11].

Analysis Process

The flow chart for fatigue cracking analysis of exhaust manifold was illustrated in Figure 2. The flow field of exhaust manifold fluid domain was calculated through three-dimensional CFD software STAR-CCM+, and the convective heat transfer coefficient and temperature of the fluid external surface were obtained. Next, these data were mapped into the solid internal surface of the analysis model established by finite element software ABAQUS. Additional effects should be thought about, such as thermal conduction, thermal convection, thermal radiation and thermal-related material nonlinearity, so the temperature field of exhaust manifold solid domain was computed. Bolt preload, nonlinear contact and structural-related material nonlinearity were taken into account, furthermore, the existing temperature field was adopted as thermal load, subsequently, the process of heat shock was simulated. Later, the first-order natural frequency and potential failure regions of exhaust manifold were calculated with the high temperature field as thermal modal predefined field. The comparative bench test verified the validity of simulation results at last.

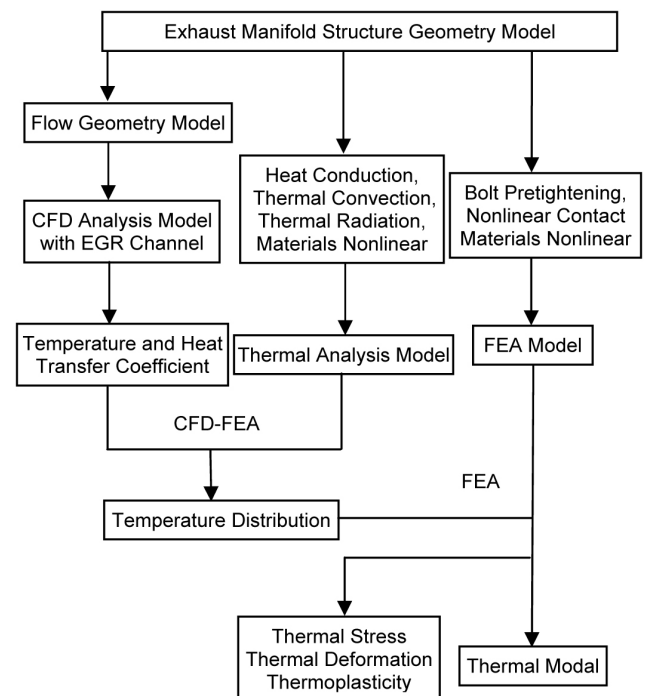


Figure 2. The flow chart of fatigue cracking simulation

Exhaust Manifold Flow Field CFD Model

The exhaust manifold fluid domain was meshed by STAR-CCM+ pre-processing module, which consisted of polyhedral and hexahedral mesh configurations, and there were three denser boundary layers in the near-wall. In order to prevent the backflow of outlet and ensure the fast convergence speed, extrusion layers were adopted. CFD mesh model was shown in Figure 3.

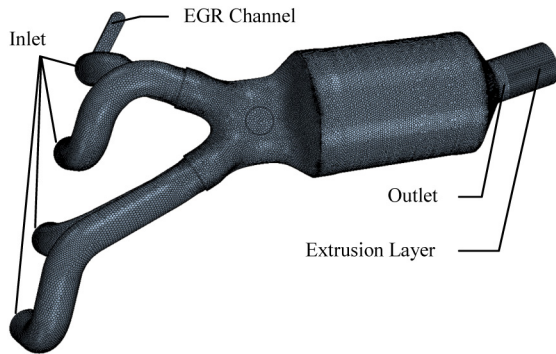


Figure 3. CFD mesh model

Because the discharge time was short, working fluid in the exhaust manifold was analyzed under the steady state. Analysis conditions were determined, including compressible N-S equation, standard κ - ϵ model, high y^+ wall function and porous media model used for catalytic effect. Flow control equation [12] was:

$$\frac{\partial(\rho\phi)}{\partial t} + \text{div}(\rho\vec{u}\phi) = \text{div}(\Gamma \text{grad}\phi) + S \quad (1)$$

Where ρ = density, ϕ = universal variables, t = time, $\vec{u}$ spatial velocity vector, Γ = generalized diffusion coefficient, S = generalized source term.

Mass flow of each inlet was measured under the full load condition and treated as a entrance boundary condition; pressure outlet type was given to the outlet and EGR port; appropriate resistance characteristics of porous region were set; interface was arranged to link the porous region and the rest of fluid domain, so it would make mass and energy smoothly transfer; the boundary condition of wall surface was defined for non-slip type.

Exhaust Manifold Thermal Analysis Model

The schematic diagram of exhaust manifold thermal analysis was depicted in Figure 4. Cylinder head and front flange were connected closely, and there was mainly heat conduction between them. On account of the motion of high temperature and high speed fluids, there was forced convection heat transfer between hot gases and the inside wall of exhaust manifold. It was found that the natural convective heat transfer occurred between the exterior surface of exhaust manifold and its surroundings; in addition, thermal radiation took place

between the exterior surface and the heat shield. In a word, the exhaust manifold heat transfer was a very complex process, which was established under the common action of pre-processing software HYPERMESH and professional finite element solver ABAQUS in this paper.

Since there was a friendly interface between STAR-CCM+ and ABAQUS, local heat transfer coefficient and local heat transfer reference temperature of fluid outer surface which were treated as the first and third thermal boundary conditions could be mapped to the inner surface of solid domain. Meanwhile, reasonable ambient temperature, convective heat transfer coefficient and thermal emissivity of solid exterior were carried out. As picked from Figure 4, temperature of zone 1, zone 2 and zone 3 was descending in sequence. During the process, the thermal conductivity coefficient of materials was varying with temperature, which can be manifested in Figure 5.

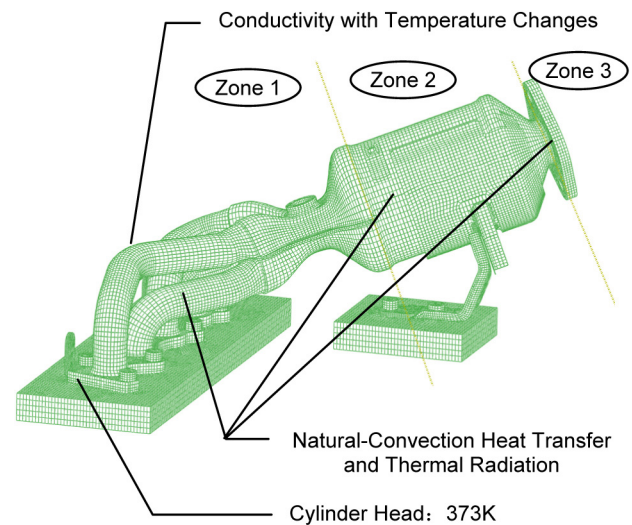


Figure 4. Thermal analysis model of exhaust manifold

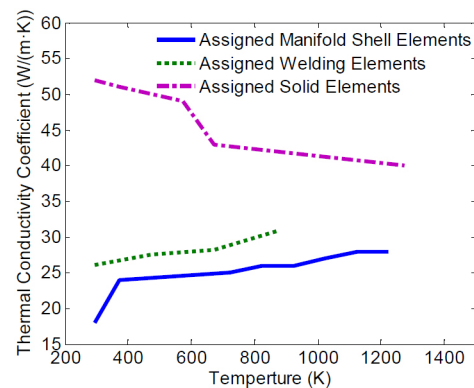


Figure 5. Thermal conductivity coefficient of materials that changed over temperature

Exhaust Manifold Finite Element Model

In the exhaust manifold thermal analysis, the mechanical load caused by internal gas pressure was much smaller than the thermal load, so it shall be negligible. The finite element model for exhaust manifold cracking analysis was seen in Figure 6.