

Study on the Unsteady Heat Transfer of Engine Exhaust Manifold Based on the Analysis Method of Serial

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ABSTRACT

In order to predict the thermal fatigue life of the internal combustion engine exhaust manifold effectively, it was necessary to accurately obtain the unsteady heat transfer process between hot streams and exhaust manifold all the time. This paper began with the establishment of unsteady coupled heat transfer model by using serial coupling method of CFD and FEA numerical simulations, then the bidirectional thermal coupling analysis between fluid and structure was realized, as a result, the difficulty that the transient thermal boundary conditions were applied to the solid boundary was solved. What's more, the specific coupling mode, the physical quantities delivery method on the coupling interface and the surface mesh match were studied. On this basis, the differences between strong coupling method and portioned treatment for solving steady thermal stress numerical analysis were compared, and a more convenient and rapid method for solving static thermal stress was found. Finally, aiming at the thermal stress analysis of steady and unsteady temperature fields, the thermal fatigue life of the exhaust manifold was estimated in application of Manson-Coffin formula, giving a general qualitative analysis.

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INTRODUCTION

The exhaust manifold is one of the most important components in the engine exhaust system, which is the first place that high temperature exhaust gases pass through. With progressively sophisticated engine technology, increasingly stringent emission regulations and rising power demand, the engine effective pressure and combustion temperature increase, and the exhaust temperature is more and more high (above 900°C), resulting in exhaust manifold heat load getting close to its limits. Cyclical changes in thermal load conditions are likely to cause thermal fatigue failure, making it appear to have the problem of exhaust manifold cracks or breaks. What's more, the vehicle may have leaks, and it will cause severe spontaneous combustion. Therefore, the study on the thermal fatigue life of the exhaust manifold has been subjected to widespread attention by scholars from various countries.

At present, the analysis of thermoplastic and thermal fatigue of solid structure is still at the initial stage, the difficulties lie not only in the solid nonlinear analysis, but in the thermal boundary conditions' application as well. Structural analysis and fluid dynamics have long been separate disciplines, and the research on the interaction between solid and fluid still occurs

at the most fundamental levels. The method of FSI (fluid-structure interaction) calculation has been pulled off the agenda because of the daunting computational time and resources involved. In the current study, Jiang, Y. and Liu, Z. et al. made the strong coupling transient heat transfer between piston and cylinder liner realizable, but the heat transfer between cylinder gas and combustion chamber was weakly coupled [1,2]. Heat transfer process of exhaust manifold was built around the basis of solid domain uniform temperature variation by other researchers [3,4]. Although non-linear property of material and complicated contact relationship of components were considered, the achievement and loading of transient coupled thermal boundary conditions were far from properly addressed. Temperature field of fluid-solid interaction was mapped to solid exhaust manifold by Dong, F. and Cai, Y. et al. through the interpolation theory of shape function [5]. The significance was to generalize the load of temperature changes; however, the writing for the given procedures of interpolating data required operator to have a fairly high level of theoretical knowledge, besides, the accuracy of the interpolation function had not yet been verified. Therefore, it is essential to find a simple and precise two-way coupling approach to simulate transient heat transfer between solid and fluid.

Fundamental Principles of Unsteady Coupled Heat Transfer

Unsteady heat transfer of engine exhaust manifold falls into fluid-solid coupled heat transfer category. It refers to a process that temperature increases (heating) or decreases (cooling) in a system. Energy, temperature, heat flux, thermal boundary conditions and other parameters are changing radically with time. According to the first law of thermodynamics, the energy expression of transient heat balance proposed in matrix form is below [6]:

$$[C]\{\dot{T}\} + [K]\{T\} = \{Q\} \quad (1)$$

In the formula (1), $[C]$ is the matrix of specific heat capacity, which has relations with internal energy alteration of a system; $[K]$ is the matrix of heat transfer, including heat conduction coefficient, heat convection coefficient and heat radiation

coefficient; $\{T\}$ is the vector matrix of node's temperature; $\dot{T}$ is the first derivative of temperature with respect to time; $\{Q\}$ is the vector matrix of nodes' heat flux rate, the generation of heat included.

A four cylinder four stroke gasoline engine exhaust manifold was regarded as the research object. In order to explore the thermal fatigue properties of exhaust manifold under the complex assembly conditions, accurate transient temperature field was required to obtain. To start with, a model based on STAR-CCM+ and ABAQUS serial coupling algorithm in two coupling regions was established. Coupling method was given in Figure 1. In the current time step, several internal iterations might run on the purpose of meeting convergence conditions; when the stopping criteria were satisfied or internal iterations reached a threshold, data interchange of two codes would be done, and close behind was the next time step. It was clear from the figure that data was exchanged only once in each time step. The great virtue of this approach was small amount of calculation and fast convergence of speed.

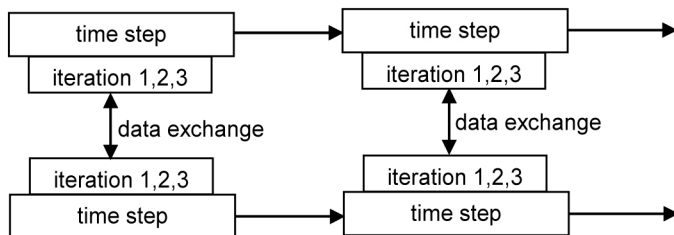


Figure 1. Coupling method used in this research

In each time step, detailed implementation of data exchange was called serial coupling mode, as seen in Figure 2. ABAQUS calculated first in this research. ABAQUS worked while STAR-CCM+ was waiting. $t=0$, ABAQUS began to calculate and carried its process to $t=0.1$, then ABAQUS would pass

the results to STAR-CCM+; newly received data at $t=0$ of STAR-CCM+ intended to push the calculation into $t=0.1$, and then transmitted the results to ABAQUS so as to update the figures of $t=0.1$. If cycles continued, data was transmitted between the two codes in sequence. The essence of serial coupling was a mode that when one code calculated, another code had to wait. If two codes were waiting for the results of the opposition, the phenomenon of time deadlock would occur and calculation of two sides were no longer viable. In addition, boundary conditions used in each code were provided by data transfer of new moment, which possessed fairly good numerical stability. On a separate note, $t=0, 0.1, 0.2$ above referred to different time point rather than concrete time point.

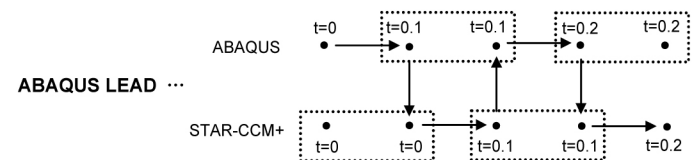


Figure 2. Serial coupling mode used in this research

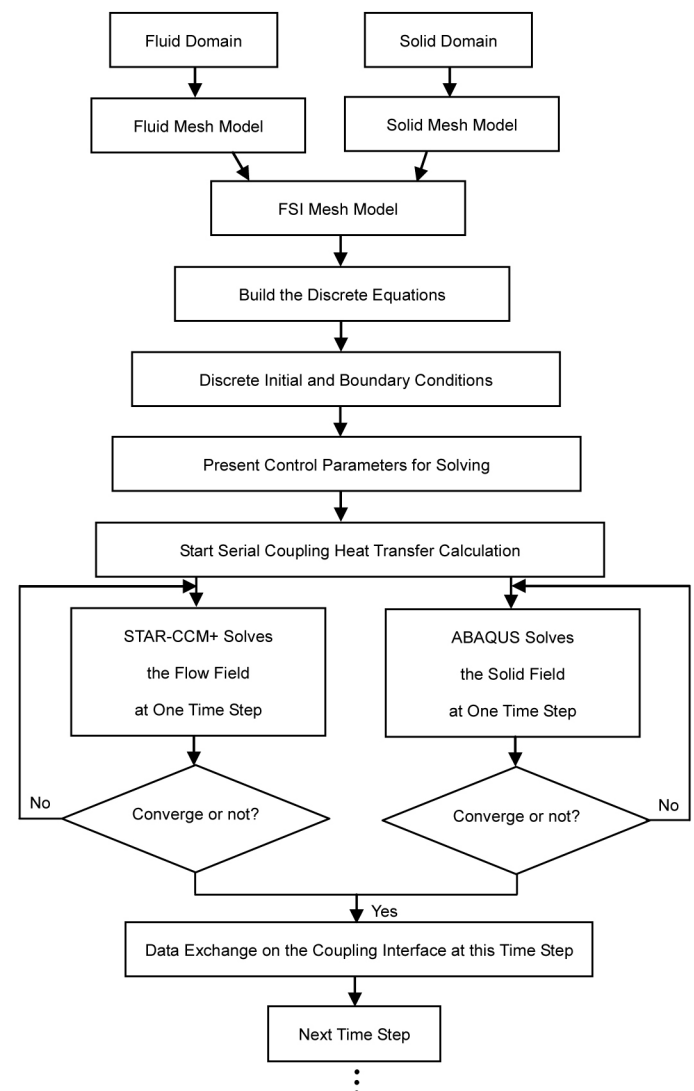


Figure 3. Flowchart of unsteady heat transfer process of engine exhaust manifold

After the heat transfer model based on STAR-CCM+ and ABAQUS serial coupling method was in operation, the transient thermal boundary conditions were gotten and were converted to the solid wall through data exchange, next the temperature field of solid was calculated by ABAQUS, finally the solid stress was analyzed. Detailed calculation process was shown in Figure 3 [7]. Data delivery of both sides was enforced in the same time step. What's more, coupling negotiation method was "export", in other words, time step arrangement of STAR-CCM+ was passed to that of ABAQUS. A data exchange was conducted every time step, as tracked from Figure 3.

SIMULIA Co-Simulation Engine (CSE) is a dynamic link library which can automatically transmit data on the coupled interface. Both film temperature and heat flux of fluid surface were continuously mapped to the corresponding solid surface; temperature variables of solid surface were transmitted to the relevant fluid surface simultaneously. Because the unit size, type, density and grid discretization approach used by fluid and structural analysis were dissimilar, a mapping method between non-matching meshes was needed [8]. As Figure 4 suggested, the three dimensional surface mapping method was used to acquire boundary heat flux and local heat transfer reference temperature (T_{ref}) of solid inner surface. In the meantime, temperature of fluid outer surface was renewed [9]. Heat transfer results combined with other thermal boundary conditions were necessary to solve the temperature field of solid domain. Finally the calculation of solid stress was accomplished.

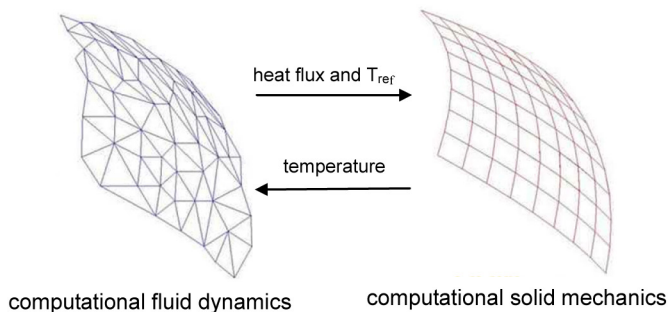


Figure 4. Schematic diagram of 3D surface mapping method

Mesh Generation

Figure 5 was the geometric model diagram of this exhaust manifold. At the export, each pair of branch pipes were combined, dividing into two branches, so there were two outlets. The design of it could help to decrease the low-speed torque output, which was suitable for the daily driving use.

The grids of fluid domain were divided by using the pre-treatment function of STAR-CCM+. The fluid domain was mainly composed of polyhedral meshes, and near-wall surface of fluid was divided into two thick prism layers so as to avoid boundary effect on calculation results. The grids of outlet were stretched along the normal direction by a discrete distance,

which was shown in Figure 6. Polyhedral mesh was peculiar to STAR-CCM+. A polyhedral grid represented the best way to divide a surface into regions of equal area with the least total perimeter. In contrast with tetrahedral mesh, convergence of polyhedral mesh was much better. Most of the time, it needed a fewer iterations to satisfy optimum results. Besides, dependence on the number of grid was relatively smaller.

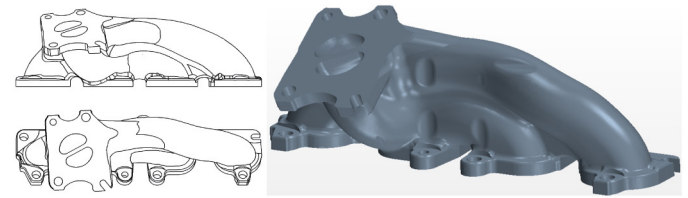


Figure 5. Geometry model of exhaust manifold

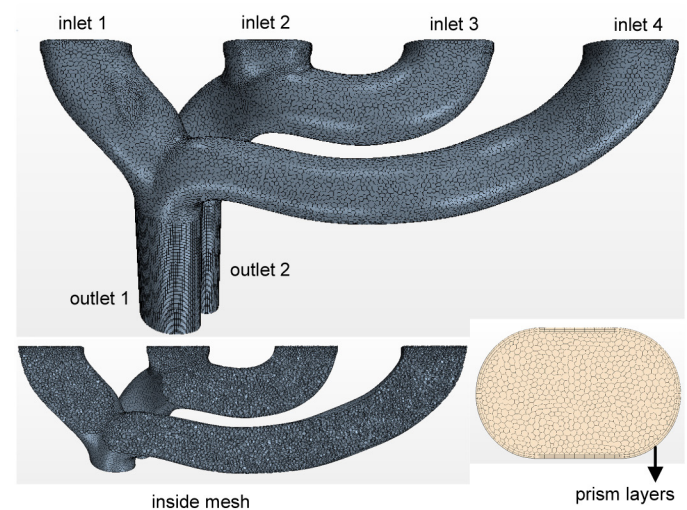


Figure 6. Mesh generation diagram of fluid domain

The volume mesh of solid domain would be generated in HYPERMESH, which was only comprised tetrahedral grids, as depicted in Figure 7.



Figure 7. Mesh generation diagram of solid domain

Calculation Parameters Set Up

Initial Conditions

In particular, in transient analysis, initial conditions must be set and those values would usually affect the results substantially. The Initial conditions of flow field were as follows: $P_{initial}=400\text{KPa}$; $T_{initial}=1248\text{K}$. The initial condition of heat analysis was: $T_{initial}=300\text{K}$.