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Research Article

Numerical Simulation for Exhaust Manifold Based on the Serial Coupling of STAR-CCM+ and ABAQUS

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Abstract: This study aims to realize the serial coupling of STAR-CCM+6.04 and ABAQUS 6.11-1 and provide boundary conditions for the thermal fatigue analysis. To predict the thermal fatigue life of the internal combustion engine exhaust manifold effectively, the transient heat-transfer process between exhaust gases and exhaust manifolds should be reflected accurately. The transient fluid-solid-thermal coupling simulation on the exhaust manifold is carried out by using serial coupling method. The research of dealing with the problems of transient temperature loading, the mesh generating and the interface temperature interpolation of fluid and solid are conducted in the process of numerical simulation. The goal of bidirectional fluid and solid coupling simulation between the CFD software STAR-CCM+ and the FEA software ABAQUS is achieved and the transient temperature and thermal stress distribution are obtained. Comparison with the steady analysis results shows that it's a necessary and effective way of conducting transient analysis.

Keywords: Exhaust manifold, fluid-solid-thermal simulation, serial coupling, transient heat transfer

INTRODUCTION

Exhaust manifolds are the main heated parts of internal combustion engine which connect with the cylinder head directly. The phenomenon of exhaust manifold fatigue rupture often occurs when the internal engine durability tests are conducted owing to the severe work environment such as the heavy thermal load, high thermal stress, high frequency of heat cycle shock. To predict the thermal fatigue life of exhaust manifolds effectively, it's necessary to make the transient heat coupling analysis of fluid and structure, calculate the transient fluctuation situation of temperature and thermal stress, find the weak place of the structure so as to provide references for the improvement of manifolds' design and supply thermal boundary conditions for the analysis of thermal fatigue.

There's a widespread phenomenon in nature and engineering practices occurred for two or more fields' interactions in one system, which we called Multi Physics Problems (MPPS). MPPS of manifolds can mainly be classified into the following 5 aspects' coupling (Cesareo, 2006): fluid-thermal coupling, structure-thermal coupling, fluid-structure coupling (fluid-solid interaction, FSI problems), fluid-structure thermal coupling and fluid-structure-thermal coupling. The first four are two-fields coupling and the third one is three-fields coupling. The researches of fluid-thermal and structure-thermal coupling are more than the coupled heat transfer and FSI. Now, the author has realized the research of the transient strong coupling heat transfer of automotive engine piston and cylinder-liner motion contact, but the heat transfer process between combustion gas and combustion chamber components is a weak coupling (Jiang *et al*., 2007; Liu and Jiang, 2008). Other researchers mainly adopt reverse algorithm to study the coupling heat transfer of cylinder head, piston, etc.: measured several key points' temperature, adjusted the thermal boundary conditions to make the calculated value correspond with the measured value. After more than one hundred times of trials in literature, the calculated value of a few key points is closed to the measured value, but the calculation cycle is long and the cost is relatively high. Reverse algorithm is based on the temperature measurements, can only improve the existing engines, can't provide guidance for the new design.

In the study of exhaust manifold, the approach of FSI is adopted to calculate the steady temperature field and thermal stress. First, the transient flow field (in a certain crank angle range) is calculated by CFD software. The steady heat transfer coefficient and ambient temperature of inner wall are obtained by time-average method; then map them to the corresponding finite element meshes. The calculation result can't be regarded as converged until the maximum difference value of relevant nodes temperature is in a certain scope after several round iterations. The steady temperature

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field distribution of exhaust manifold is obtained accordingly (Deng and Liu, 2011). Although the FSI method based on time average can obtain relatively accurate temperature field not dependent on the actual measurement results of temperature, this kind of method has some redundant processes like through files for data transmission or the uses of extra transit software, etc. At the same time, time-average method can't reflect the transient heat transfer process's influence on thermal fatigue life because the varying thermal boundary conditions can't be applied to the solid boundaries.

Nowadays, steady calculation is a popular method for fatigue analysis, because the transient thermal boundary conditions can't be provided to the structure analysis accurately. However, in this study, we solved this problem successfully. We found a new computing method of fluid mechanics and machinery, realized the real-time coupling of fluid and structure calculation software in a new way without third-party software, acquired the transient temperature fields, provided transient thermal boundary conditions for thermal fatigue analysis and conducted thermal stress analysis of exhaust manifolds using this new method.

METHODOLOGY

Fundamentals and process of transient coupling heat transfer: The thermal boundary conditions of coupling heat transfer problems aren't given in advance, but are dynamically confirmed by the heat exchanging process. The temperature or heat flux of interface should be regarded as a part of calculation results, not the known conditions.

From the solving method of control equation, FSI analysis can be divided into the strong coupling of direct solution and the weak coupling of partition iteration solution (Qian and Dong, 2008; Zhang, 2004). The strong coupling method constructs the fluid domain, solid domain and the effect of coupling in the same control equation, solves the whole varies in the same time step simultaneously. The weak coupling method solves the control equations of fluid and structure respectively at each time step and exchanges the calculation data via medium to realize the coupling solution. The strong coupling method needs a relatively deep understanding of various disciplines, program development costs and hardware requirements are pretty high (Michler *et al*., 2004). However, the weak coupling method is capable of considering the interactive effects of boundaries making use of existing programs of various disciplines. Moreover, because the analysis of each physical field is relatively independent, it can solve large-scale complex engineering practical problems easily by using the computer parallel

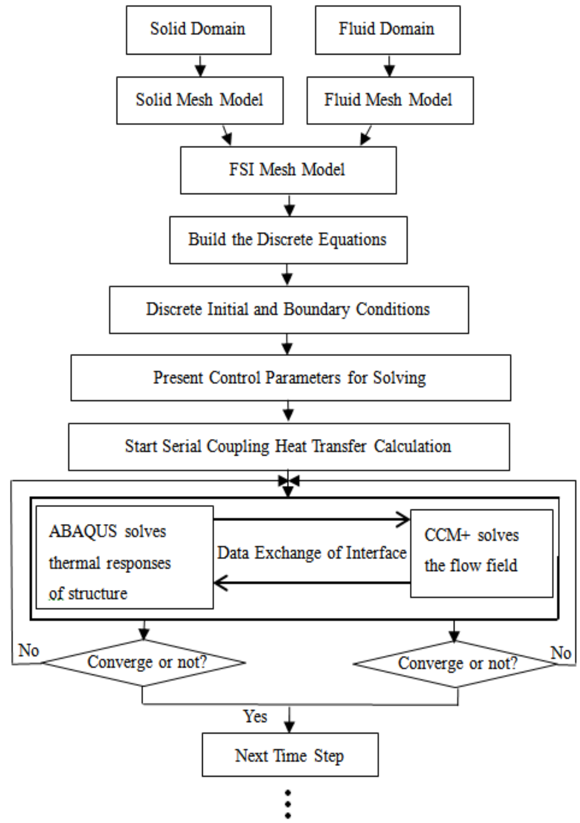
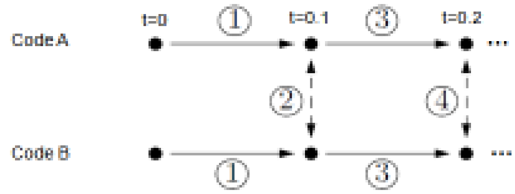


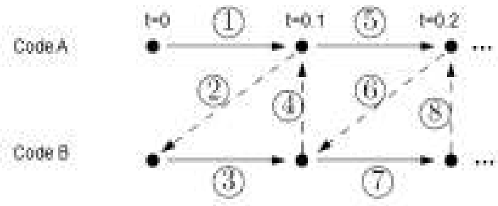
Fig. 1: Flow chart of transient heat transfer

techniques (Dong and Fan, 2009). Considering the flexible and convenient features of weak coupling solution process, many foreign scholars and research institutions in this respect conducted fruitful researches, in which the MPCCI-Mesh-based Parallel Code Coupling Interface, developed by Germany scientific computing and algorithm research institute, a multidisciplinary coupling analysis tool is the most famous. According to the weak coupling principle, powerful links are established in multi-disciplinary commercial software and the STAR-CCM+ software developed by CD-adapco company realizes the coupling with SIMULIA company's FEA software ABAQUS without using additional software, improves the calculation efficiency greatly. But there are few reports about the research of this aspect in domestic. Therefore, this study adopted the serial coupling method of STAR-CCM+ and ABAQUS to analyze the transient thermal flow field and thermal stress of exhaust manifolds and the calculation flow is shown as Fig. 1.

The data of coupling interface are transferred automatically through the SIMULIA Co-Simulation Engine (CSE) which is a software component responsible for communication between Abaqus and STAR-CCM+ and is distributed and installed with the



(a) Parallel coupling



(b) Serial coupling

Fig. 2: Coupling mode of STAR-CCM+ and ABAQUS

ABAQUS software as dynamic link libraries, namely the fluid domain outputs film temperature and heat transfer coefficient to solid domain, the solid domain inputs temperature variables to fluid domain. The data transfer of coupling interface is divided into two methods-parallel coupling and serial coupling. Parallel coupling refers to both codes advancing simultaneously and completely synchronously. In each time step exchange data, in the new time accept the old time data of boundary conditions, as shown in Fig. 2 (a); serial coupling causes the two applications to run sequentially, namely one code is waiting while the other code is calculating, as shown in Fig. 2 (b). Generally speaking, the reliability of parallel coupling is not as well as serial coupling and there is a time deadlock phenomenon caused by two codes waiting for the other one's data, so neither of them can continue to calculate. Thus, the serial coupling method is adopted in this study to accomplish the data transfer of coupling interface.

Mathematical models: Fourier heat conduction equation connecting the entity and heat convection equation of fluid are used to describe the heat transfer of the interface between solid and fluid (Luo, 2008):

$$K_{cond}\frac{\partial T}{\partial n}|_{wf}=q^{conv}=h_{conv}(T_f-T_w) \tag{1}$$

In formula (1):

K_{cond} = Thermal conductivity of solid
h_{conv} = Local heat transfer coefficient
T_f = Fluid temperature
T_w = Wall temperature

The transient control equations of exhaust manifolds internal flow field are compressible Navier-Strokes equations, standard *k-ε* turbulence model and standard wall functions are employed in the calculation.

In solid side, it's assumed that the parts have constant physical properties with no inner heat source, the control function of exhaust manifolds temperature field is shown as formula (2):

$$\frac{\partial}{\partial x}(k_x\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(k_y\frac{\partial T}{\partial y})+\frac{\partial}{\partial z}(k_z\frac{\partial T}{\partial z})=0 \tag{2}$$

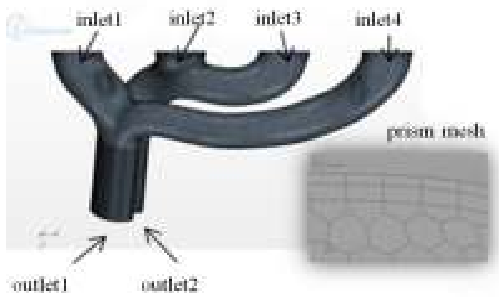
In formula (2): k_x, k_y, k_z represent the coefficients of heat conduction in x, y, z directions respectively.

In the transient thermal stress calculation, the temperature and heat transfer coefficients of each moment from the result of transient thermal fluid calculation are loaded to the FEA models served as the first and third boundary conditions to provide transient thermal boundary conditions for the structure intensity calculation and thermal fatigue analysis of exhaust manifolds.

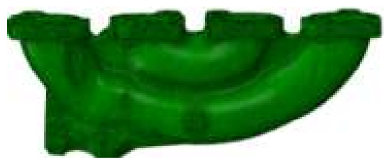
Calculations models:

Geometric modeling and meshing: Take the four-stroke gasoline engine exhaust manifold as the research object, fluid and solid domain surface mesh was generated by the proceeding function of STAR-CCM+ and polyhedron grid was utilized in fluid domain, 2 layer relatively tight boundary layer mesh was generated in the fluid near wall place. In order to reduce the boundary's influence on calculation results, the fluid outlet surface along the normal direction was extended a distance, as shown in Fig. 3 (a). Export the surface mesh of solid from CCM+ in the format of .nas and generate the volume mesh in HYPERMESH. Solid domain only contains the tetrahedral mesh, as shown in Fig. 3 (b). The material attribution of manifold is shown in Fig. 4.

Working conditions and boundary conditions: Based on the test norm of exhaust manifold thermal fatigue, confirm the variation regularity of temperature changing over time, as shown in Fig. 5, one thermal fatigue cycle is 1210s (neglecting the preheating time). Four cylinders intake gas simultaneously, taking the average mass flow rate, the value is 0.03475 kg/s. The outlet pressure is 400 kPa, the temperature difference between inlet and outlet is not preceding 5°C. The external wall heat transfer coefficient of manifold is 13.5 W/ (m^2/K) and the ambient temperature is 300 K. The others are wall boundary conditions. Initial condition: the pressure is 400 kPa, the temperature is 1218 K.



(a) Fluid mesh



(b) Solid mesh

Fig. 3: Meshes of fluid and solid domains

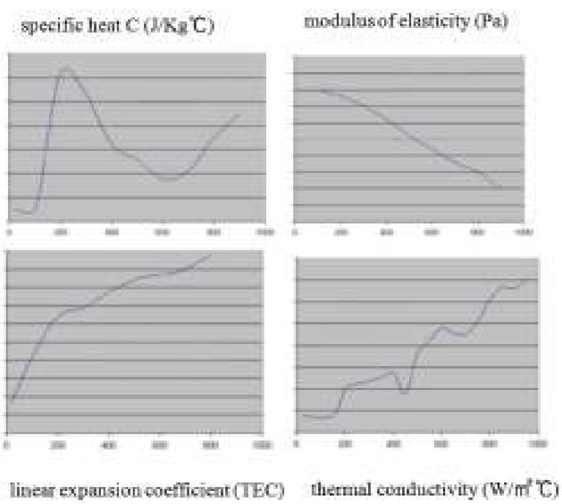


Fig. 4: Material attribution of exhaust manifold

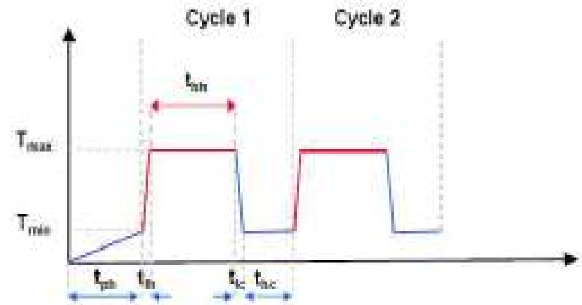


Fig. 5: Exhaust manifold temperature variation curve
T_{max}: The maximum exhaust gas temperature of inlet; T_{max} = 950°C; T_{min}: The minimum exhaust gas temperature of outlet; T_{min} = 200°C; t_{lh}, t_{lc}: Time of loading (heating/cooling); t_{hh}, t_{hc}: The lasting time of heating or cooling; t_{ph}: Preheating time

Transient temperature transfer of weak coupling analysis: To calculate the transient thermal stress accurately, solid temperature in each time of the transient coupling heat transfer calculation should be loaded into the FE model as the first boundary condition. The mapping method is used in Abaqus Co-Simulation Engine to complete the proceeding of the transient temperature loads. Using the meshes of fluid to analyze the thermal flow field, the Heat Transfer Coefficient (HTC) and reference of temperature of interface (T_{ref}) in fluid domain is interpolated to the nodes of solid domain inner surface. Temperature field in solid domain is obtained by using the thermal boundary conditions; thermal stress analysis can be conducted correspondingly. It is called surface mapping method. Figure 6 is the schematic diagram of surface mapping method; the characteristics of it are that fluid and solid domain are computed separately without the computation of solid temperature field in the step of CFD analysis, so only the fluid meshes are needed in the step of CFD analysis, only the solid meshes are needed in the step of thermal stress analysis. Thus, the less meshes are needed in the two phases

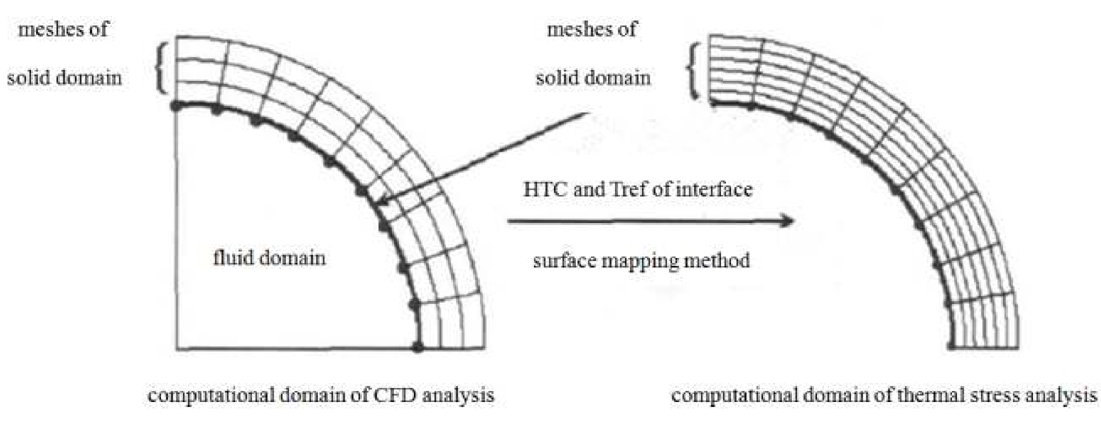


Fig. 6: Schematic diagram of surface mapping method

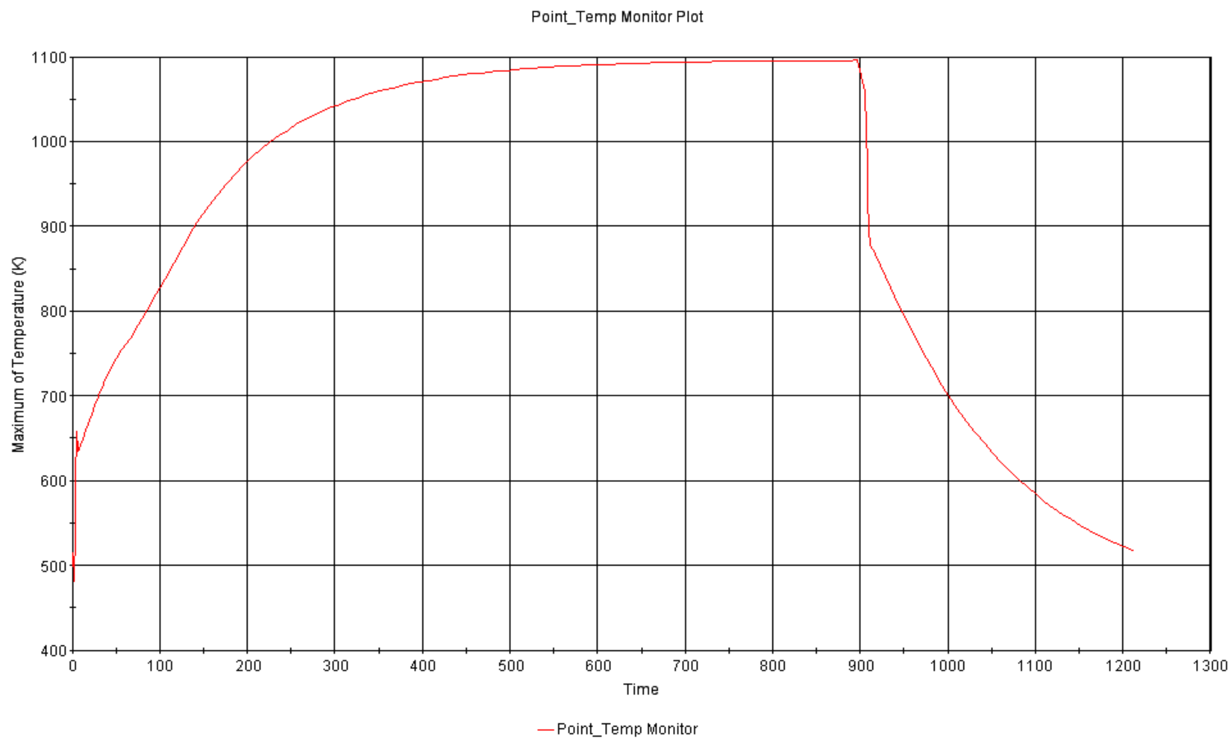


Fig. 7: Temperature variation curve of node in coupling interface

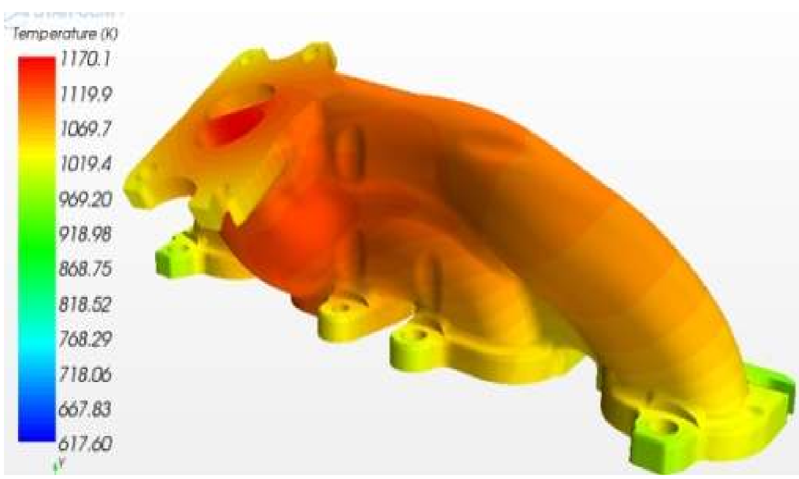


Fig. 8: Steady temperature calculation result

to obtain the results. The computing resources are utilized efficiently.

CALCULATION RESULT ANALYSIS

Based on the above-mentioned transient temperature transfer principle of weak coupling analysis, the calculation results of exhaust manifold temperature field and thermal stress are obtained.

Result of temperature field: As the thermal cycle in Figure 5 shows, the engine starts up from the cold boot

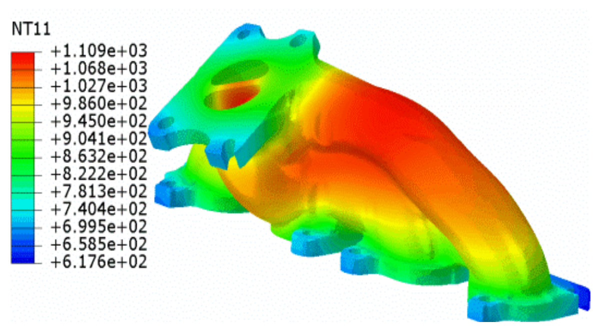


Fig. 9: Transient temperature calculation result (t = 905s)

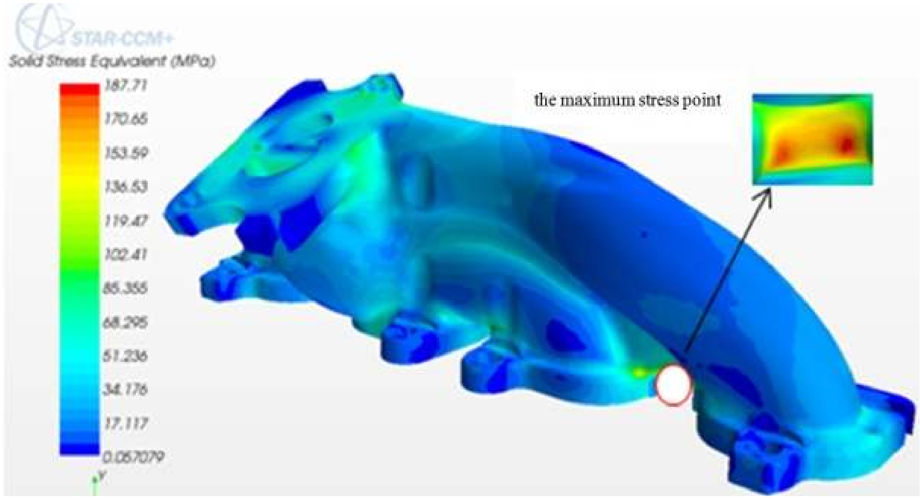


Fig. 10: Steady thermal stress calculation result

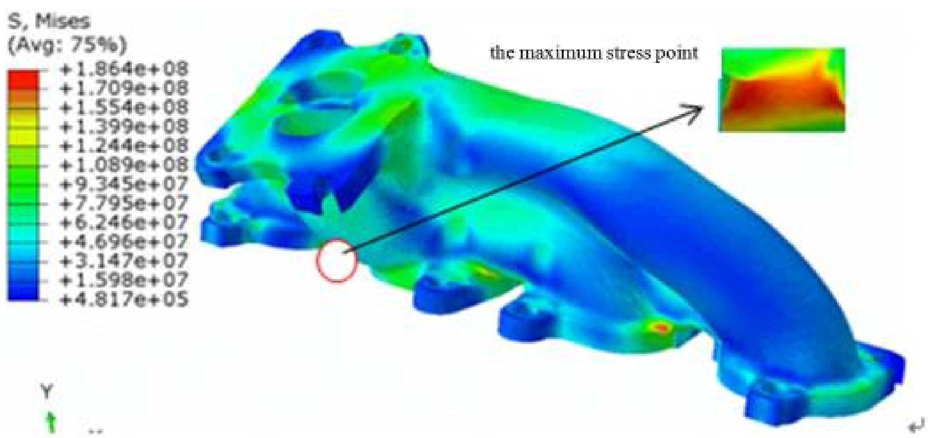


Fig. 11: Transient thermal stress calculation result (t = 905s)

state; the temperature reaches a certain value after the preheating process. Then the engine ascends to the rated power in a short time, holding for some time, turns into the low idle state in a short time and maintains a period of time, ascends to the rated power again. From the second cycle, the variation of engine temperature tends to be stable, considering the calculation time economy, take the temperature result of cycle 2 as the input temperature of structure calculation. An observation point in the coupling interface is selected to monitor the temperature variation process of manifold in real time. Figure 7 gives the instantaneous change curve of the node and the temperature variation trend is similar to Fig. 5.

Figure 8 and 9 give the steady and transient temperature distribution of exhaust manifold. In the steady state calculation, four cylinders intake gas simultaneously, taking the average mass flow rate, the value is 0.03475 kg/s and maintain the temperature in 950°C. The time corresponding to the transient temperature distribution shown in Fig. 9 is the second cycle summit point, namely in the time of t = 905s. The transient temperature result has a relatively large difference with the steady calculation for the influence of thermal inertial. In the steady calculation result, most flange surfaces temperature is above 960°C, but in the transient result, the regions temperature above 960°C reduce a lot, mainly distributing at the exhaust gas junction places.

Result of thermal stress: Figure 10 and 11 show the steady and transient thermal stress distributions of exhaust manifold. The maximum stress value of steady state is 187.1 MPa, closed to the transient calculation result. But the position of maximum stress point is different; the maximum value of transient appears in the junction of cylinder 1 and 2. As for steady calculation, it appears in the junction of cylinder 3 and 4. Meanwhile, the stress distribution of transient calculation is finer. Contrasting with the temperature field, high stress area appears in the place of high temperature gradient, further shows the thermal stress is mainly controlled by temperature gradient. Considering from the accuracy, the transient thermal fluid-stress analysis method should be used for subsequent fatigue reliability analysis.

CONCLUSION

- By means of Co-Simulation Engine, the transient coupling heat transfer analysis model is established, the volume mapping method is used to study transient temperature loading in the process of numerical simulation, the grid division and temperature interpolation methods of FSI coupling interface.
- Realized the CFD software STAR-CCM+ and FEA software ABAQUS bidirectional FSI simulation, completed conjugate heat transfer and thermal stress analysis of exhaust manifold and provided transient thermal boundary conditions for low cycle thermal fatigue calculation.
- Compared the thermal fluid-thermal stress difference between transient and steady state calculation: the difference of temperature distribution is bigger; the difference of maximum stress value is small but the position of maximum stress is different. To sum up, the transient analysis method is more effective for thermal fatigue and it's necessary and effective to conduct the transient analysis of exhaust manifold.

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