Research Journal of Applied Sciences, Engineering and Technology 6(15): 2824-2829, 2013
ISSN: 2040-7459; e-ISSN: 2040-7467
© Maxwell Scientific Organization, 2013
Submitted: January 22, 2013 Accepted: March 02, 2013 Published: August 20, 2013

# The Impact of Temperature Effect on Exhaust Manifold Thermal Modal Analysis

[1, 2]Bin Zou, [1, 2]Yaqian Hu, [1, 2]Zhien Liu, [1, 2]Fuwu Yan and [1, 2]Chao Wang
[1]School of Automobile Engineering, Wuhan University of Technology,
[2]Hubei Key Laboratory of Advanced Technology of Automotive Parts, Wuhan 430070, China

**Abstract:** The impact of temperature effect on exhaust manifold modal analysis is analyzed in this study. Firstly, the temperature field is mapped from the CFD software and then heat conduction process is analyzed in FEM software with the temperature field boundary conditions. At last the modal analysis that considers temperature effect is done. The frequency and vibration mode between cold modal and thermal modal's are compared. The result shows that temperature has a great influence on the manifold mode and it is very valuable to product design.

**Keywords:** Exhaust manifold, Finite Element Method (FEM), temperature field, thermal modal analysis

## INTRODUCTION

Modal analysis is used to study the inherent dynamic characteristics of a system. Natural frequency can show that the structure can produce resonance under some certain excitation frequency. Vibration mode is able to show the structure deformation corresponding to each natural frequency. The exhaust manifold is close to the engine part in automotive exhaust system, because the cylinder discharge gas temperature can reach 800°C above, the tail gas heating effect is obvious. Because the thermal stress that tail gas heating caused can be as high as hundreds of Mpa, it can also lead to thermal fatigue and cause structural fracture. Temperature has great influence on material mechanical properties, so it is necessary to take the influence of the temperature pre-stress on exhaust manifold vibration characteristics into account.

The traditional modal analysis technique is linear modal analysis based on linear model. Linear theory ignores the actual system inherent nonlinearity, such as material nonlinearity, so sometimes it may cause qualitative theoretical errors, especially in resonance case. It can come to some other modes except the linear mode; in this way, the linear modal analysis is unable to deal with nonlinear system modal problem effectively. Therefore, approximate analysis methods are usually taken, one of the most typical methods is the pre-stressed modal analysis method which considering the influence of material nonlinearity, geometrical nonlinearity, contact nonlinearity or loading on structure analysis, to deal with the actual nonlinear engineering system simulation. A variety of researches have been working on this area. Such as Shi and Yang (2006) considering a flat plate as the object of research, the analyses of structural transient temperature field and characteristic of structural vibration are presented with the conditions of thermal load. Their calculation results show that transient heating has a serious effect on the characteristic of structural natural vibration. Yang and Guo (2009) make an engine piston thermal field simulation by ABAQUS software and take the pre-stress and load into account. The pre-stress include thermal stress, mechanical stress and the coupling stress and the mechanical loads include gas pressure, lateral force and mass inertia load. At last, piston fatigue analysis was done by stress results and the work is very valuable to product design. Yang *et al*. (2011) build an FEM model for the engine barrel tube and obtains its thermal vibration modal parameters, the result validates the design of the corrugated tubes is rationality. The calculation result show structure temperature will increase evidently so as to have a serious effect on the characteristic of structural natural vibration during the process of heating and offers some reference for the dynamical response analyses and structure design of tank gun barrels.

This study taking the exhaust manifold as the research object, the geometrical model is meshed in HYPERMESH software which is efficient in finite element grid partition and then the temperature effect on the modal result is analyzed by the couple of ABAQUS and STAR CCM+ software. The influence of temperature on structure natural vibration characteristics is studied. ABAQUS is engineering simulation of finite element software and STAR CCM+ is Computational Fluid Dynamics (CFD) analysis software. This study mainly considers the uneven

**Corresponding Author:** Yaqian Hu, School of Automobile Engineering, Wuhan University of Technology, Wuhan 430070, China

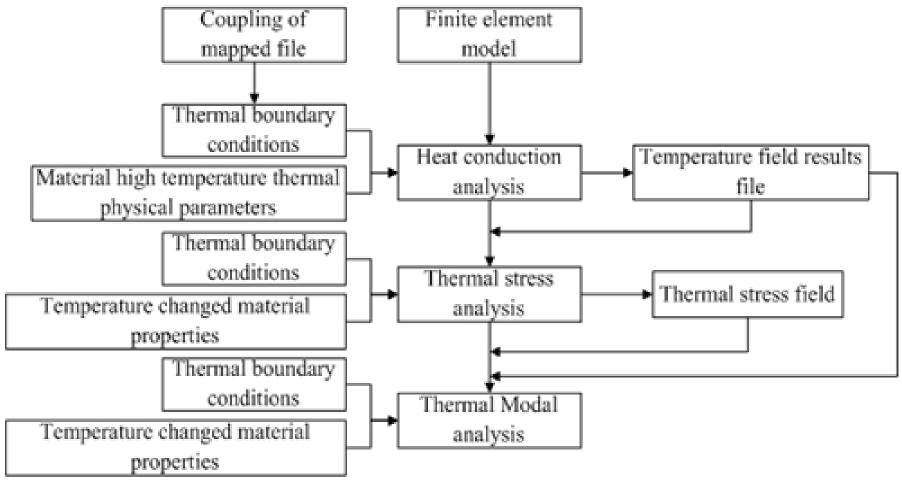


Fig. 1: Thermal modal analysis process

temperature distribution which leads to material nonlinearity, temperature pre-stress and bolt pre-tightening force impact on modal analysis.

**Basic analysis process of thermal modal analysis:** The thermal modal analysis considering the influence of the temperature and stress fields is based on thermal analysis and structure analysis (Shi and Zhou, 2006; Ji *et al*., 2010), the basic analysis process of thermal modal analysis is as follow and the flow chart is shown in Fig. 1:

- Through the fluid analysis in STAR CCM + and the coupling with ABAQUS, the wall temperature and heat transfer coefficient are mapped to ABAQUS grid.
- Take the mapping result as the analysis condition in the heat conduction analysis by ABAQUS.
- Take the temperature field result of heat conduction analysis as load and combine with the temperature changed material physical properties and mechanical performance parameters to solve structure thermal stress.
- Take the thermal stress result as initial stress condition and consider the heterogeneity of temperature field, combine with the temperature varied material physical and mechanical properties (density, elastic modulus, coefficient of linear expansion and Poisson's ratio), to solve the structure thermal mode.

## STRUCTURE THERMAL STIFFNESS AND MODAL ANALYSIS THEORY

**Structure thermal stiffness theory:** The temperature effect on structure stiffness is mainly from two aspects. On the one hand, the heating up temperature can change the material elastic modulus and lead to the initial stiffness matrix changes. Take the structure initial stiffness matrix that after heating up as Shi and Yang (2006):

$$K_T = \int_\Omega B^T D_T B d\Omega \tag{1}$$

where,

B = Geometric matrix

$D_T$ = Elastic modulus which is related to material elastic matrix E and Poisson's ratio μ

On the other hand, because the thermal stress caused by temperature gradients, additional initial stress stiffness matrix is needed besides structure stiffness matrix. The structure initial stress stiffness matrix is:

$$K_\sigma = \int_\Omega G^T \Gamma G d\Omega \tag{2}$$

where,

G = The shape function matrix

Γ = Stress matrix

In summary, the structure thermal stiffness matrix is:

$$K = K_T + K_\sigma \tag{3}$$

**Modal analysis theory of temperature effect:** The basic equation for typical un-damped modal analysis is classic eigenvalue problem. According to mode theory, the structure will typically be seen as a system constituted by the mass point, rigid body and damper and discrete it as finite number of elastic coupling rigid bodies. Therefore, an infinite multi-degree freedom system turns into limited multi-degree freedom system. When the linear time-invariant system requirements are met, the system general motion mathematical model can be expressed as:

$$M\dot{x}+C\dot{x}+Kx=f(t) \tag{4}$$

where,

M, C, K : The mass matrix, damping matrix and stiffness matrix
x : The exhaust pipe vibration displacement vector
f (t) : The exhaust pipe load vector

Modal analysis method is to replace the physical coordinates of modal coordinates that each principal mode corresponded, so that the differential equation decoupling to be independent differential equations in order to obtain the system modal parameters. The vibration of the engine exhaust pipe is a slight vibration, basically belong to linear time-invariant systems, it can be assumed that M is a constant matrix. The structural damping of exhaust pipe has little effect on the natural frequencies and therefore do not consider the external load and damping. Thus Eq. (4) simplifies to:

$$K-\omega^2 M\Phi=O \tag{5}$$

where, $M - \int_{\Omega} \rho N^T N d\Omega$ is the structure overall quality matrix.

When the order of matrix K and M is n, the $\omega^2$ in formula (5) is the n times real coefficient equation and the system degree of freedom vibration characteristics (natural frequencies and mode shapes) problem is to solve the matrix eigenvalue ω.

## FINITE ELEMENT ANALYSES

**Finite element model:** The exhaust manifold finite element model is shown in Fig. 2, use HYPERMESH to do the mesh generation work, the grids of the inner and outer wall of the exhaust manifold are corresponding with fluid analysis grids for internal and external wall temperature field boundary coupling between software. Use tetra elements with local region refined, the amount of elements was about 550000.

**Material properties:** The structure material is QTANi35Si5Cr2. It's Poisson's ratio is 0.283 and density is 7450 kg/m$^3$. The specific heat capacity, thermal conductivity, Young modulus, thermal expansion coefficient are different according to the temperatures. Build temperature changed material field in ABAQUS as material properties (Yang and Guo, 2009). The material properties are shown in Fig. 3 and 4.

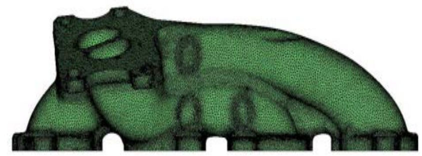

Fig. 2: Finite element model

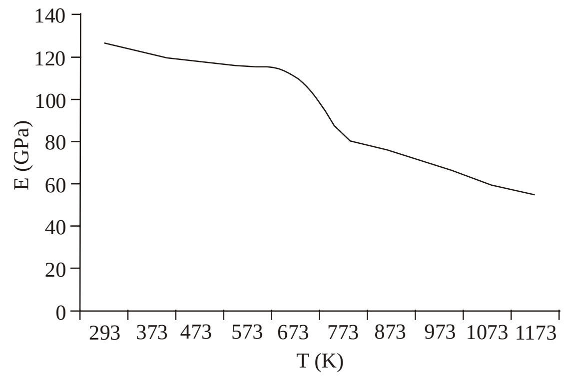


Fig. 3: Temperature varied young modulus

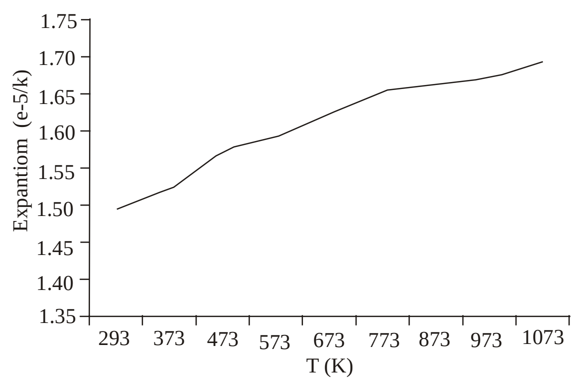


Fig. 4: Temperature varied thermal expansion coefficient

**Constraints and load description:** It is set to be normal displacement constraints (Y direction) on exhaust manifold inlet flange end face and radial displacement constraints (X, Z direction) in the inlet flange end bolt holes.

Simplify the load acting on the exhaust manifold, such as simplify the connection relationship of the bolt and the circular hole for the reference point and the distribution coupling of the hole inner surface constraint and apply bolt pre-tightening force. Temperature load is set as a predefined field through the heat conduction results.

In the thermal modal and cold modal analysis, cold modal analysis means the modal analysis with constant material properties parameters under room temperature and whereas thermal modal analysis means modal analysis with temperature pre-stress and with temperature dependent material properties parameters.

## FINITE ELEMENT ANALYSIS AND RESULTS

**Heat conduction analysis and temperature field result:** Thermal boundary conditions of heat conduction is the inside and outside wall temperature and convective heat transfer coefficient mapping file that ABAQUS and STAR CCM+ coupled. The outer wall and the air convective heat transfer coefficient are set for 13.5, ambient temperature for 360 K. Temperature field result of thermal conductivity analysis is shown in Fig. 5, unit is K.

**Thermal modal analysis and cold-modal analysis results:** The cold modal frequencies are as follows in Table 1 and heat modal frequencies are shown in Table 1.

Table 1 data shows that: the cold modal (normal temperature) and the thermal modal in a free state and the constrain state, the first order and higher order frequencies vary differently and the thermal modal frequencies with temperature effect decreased as a whole. With temperature pre-stress and bolt pre-tightening force and the same boundary condition, the exhaust manifold thermal modal frequency is lower than the cold modal frequency of the same order and with the increase of order, the reduction is larger. The influence of temperature on every modal frequency is different, but the total effect is lowering.

The first three order vibration shape diagrams of cold modal and thermal modal in free state are shown in Fig. 6:

Comparison can be seen in the vibration shape diagrams that in free state vibration shapes of cold modal (room temperature) and thermal modal are mainly torsion, as can be seen from the vibration shape that the first three orders of cold modal are mainly torsion in X direction and the first order of thermal modal is mainly torsion in X direction, the next two orders are mainly torsion in Y direction.

First three order vibration shape diagrams of cold modal and thermal modal in constrain state are shown in Fig. 7.

It can be seen from the diagrams that in constrain state, vibration shapes of cold modal (room temperature) and thermal modal are mainly bend. as can be seen from the vibration shape that the first order of cold modal is mainly bend in Z direction and the next two orders are mainly bend in X direction, the first order of thermal modal is mainly bend in Z direction, the next two orders are mainly bend in X direction.

Exhaust manifold temperature effect is mainly reflected in two aspects. On the one hand, the temperature reduce the material stiffness and uneven temperature distribution lead to material nonlinearity; on the other hand, the thermal stress that the

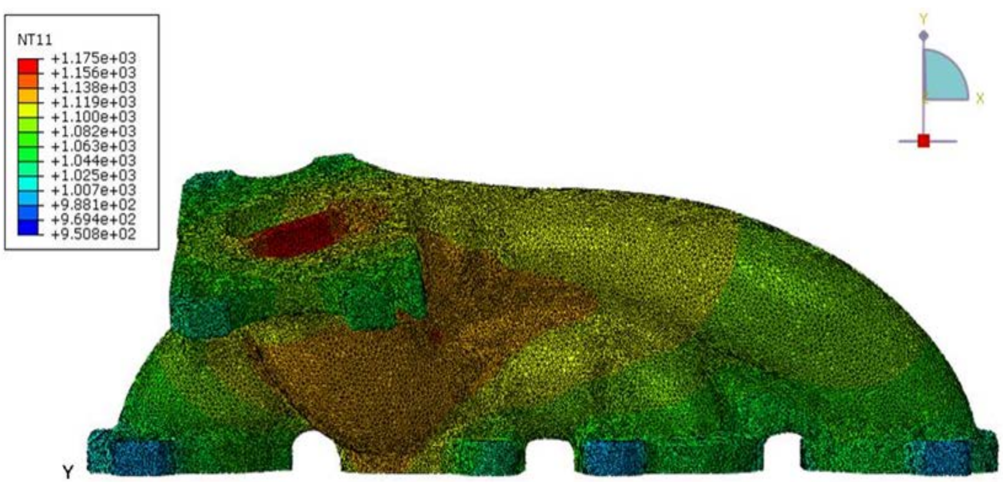


Fig. 5: Temperature field nephogram

Table 1: Cold and thermal modal frequency

| | Frequency (Hz) | | | |
|---|---|---|---|---|
| | Cold modal (normal temperature) | | Thermal modal | |
| Order | Free state | Constrain state | Free state | Constrain state |
| 1 | 1392.5 | 1985.2 | 463.73 | 1352.0 |
| 2 | 1989.4 | 3386.4 | 1053.80 | 2285.4 |
| 3 | 2277.1 | 4423.6 | 1079.00 | 3011.2 |
| 4 | 3451.1 | 4892.5 | 1517.30 | 3354.1 |
| 5 | 3794.2 | 5877.6 | 2051.50 | 4021.7 |
| 6 | 4067.4 | 6741.8 | 2262.60 | 4612.9 |

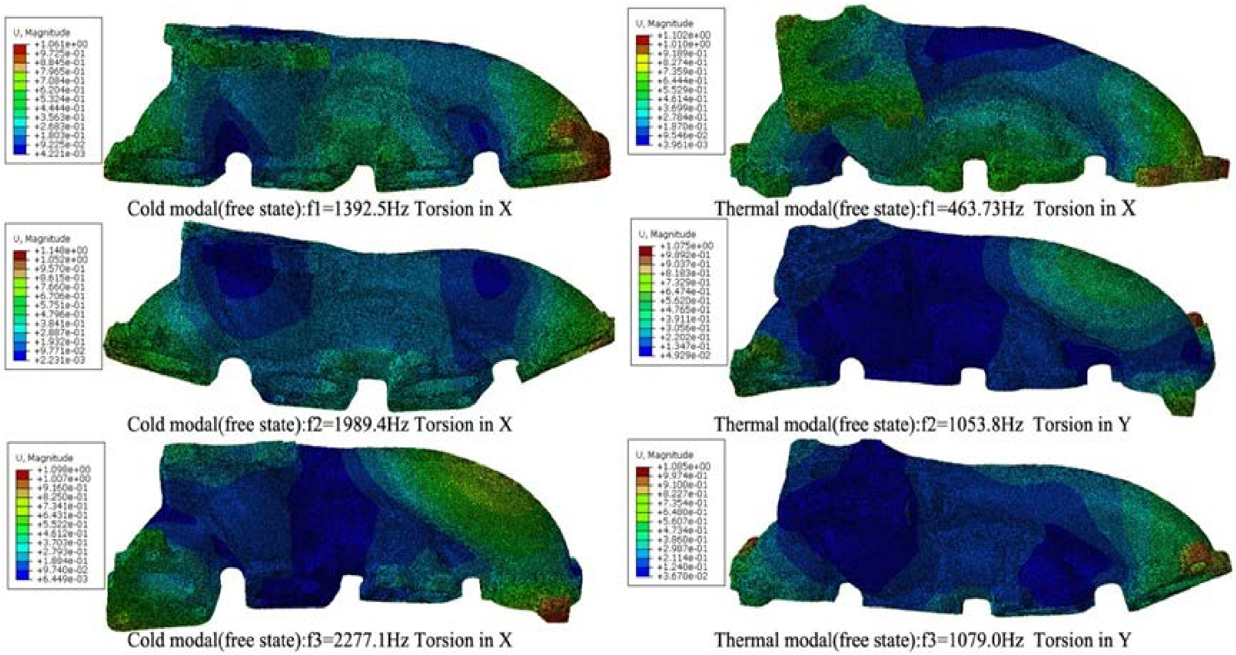


Fig. 6: The first three order vibration shape diagrams of cold modal and thermal modal in Free State

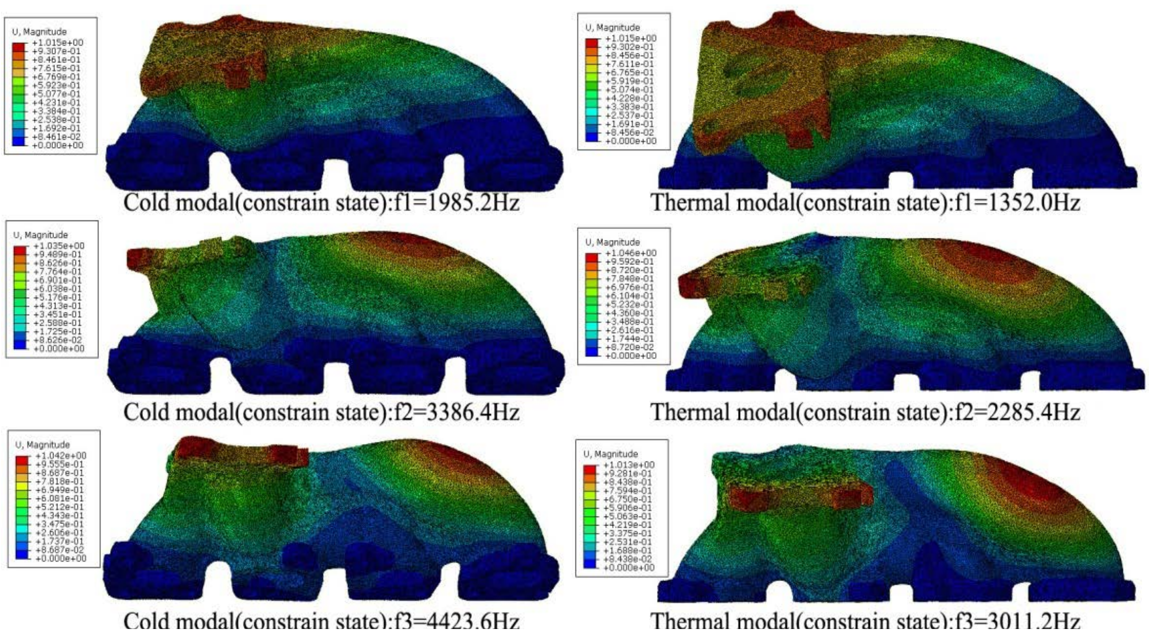


Fig. 7: The first three order vibration shape diagrams of cold modal and thermal modal in constrain state

temperature generated can be seen as pre-stress and will reduce structure's bending and torsional stiffness, therefore, the structure natural frequency will be lower under the temperature pre-stress (Yang *et al*., 2011).

The exhaust manifold mainly motivated by the road and engine, generally the road incentive is about 30 Hz and the engine inventive is more than 200 Hz, so the design frequency of exhaust manifold should be greater than 270 Hz. It can be seen by analyzing the results that the lowest order natural frequency of thermal modal analysis is 473.73 Hz and the cold modal's lowest natural frequency is 1392.5 Hz, both meet the requirements to avoid the resonance between exhaust manifold and the engine or other parts.

## CONCLUSION

In this study, a basic analysis process of the exhaust manifold thermal modal analysis is built. And the temperature pre-stress is applied on the exhaust manifold modal by the coupling of ABAQUS and STAR CCM+, then the exhaust manifold thermal mode is analyzed with bolt pre-tightening force by ABAQUS and comes to the conclusion that:

- Heating cause the nonlinear change of material physical property and generate thermal stress, the combined effects of both make the structure's natural frequency decline after heating.
- By comparing the cold modal (room temperature) with thermal modal frequencies and vibration shapes, the results show that the temperature pre-stress has different effect on the exhaust manifold structural modes, it lowers the frequency and the effect on the torsional rigidity is bigger than on bending rigidity with the temperature increasing.

Thus, in the exhaust manifold design and evaluation, the effect of temperature on material mechanical properties should be taken into account.

## REFERENCES

Ji, K.X., H.W. Song and C.H. Huang, 2010. The influence of temperature field and stress field on active cooling engine vibration modal. Proceeding of the 3rd Hypersonic Technology Academic Conference on CSTAM-2010-0039, Wuxi.

Shi, X.M. and B.Y. Yang, 2006. Temperature field and mode analysis of flat plate with thermal environment of transient heating. Comput. Aided Eng., 15(4): 15-18.

Shi, Y.P. and Y.R. Zhou, 2006. ABAQUS FEA Examples and Explanation: Mechanical Engineering Press, Beijing.

Yang, H.G. and L. Guo, 2009. Simulate study for piston heat-mechanical strength. Proceeding of the China Internal Combustion Engine Combustion Energy-Saving and Purification Branch Academic Conference (CSICE2009-013).

Yang, Z.B., H. Yang and D. Zhou, 2011. Thermal modal analysis of engine inlet. Aeronaut. Comput. Tech., 4(15): 65-71.