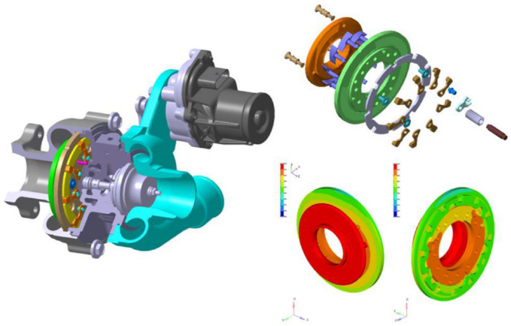
Reliability Assessment Technology of Variable Geometry (VG) Turbocharger Nozzle through MBD Analysis in Consideration of Thermal Deformation



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For passenger vehicle turbochargers, which are one of the products offered by Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. (MHIET), variable geometry turbochargers (hereinafter referred to as VG turbochargers) are widely adopted as a technology for realizing both fuel efficiency and power output. A VG turbocharger controls the flow velocity of exhaust gas to the exhaust turbine blade to enhance the turbocharging effect. The nozzle mechanism, which controls the flow rate, consists of many components and operates in a high-temperature and non-lubricated environment. Accordingly, design in consideration of both function and reliability is difficult.

For the purpose of design that improves the reliability of this mechanism, we developed a dynamic behavior evaluation technology that can take into consideration interference and sliding resistance, in which the thermal deformation of components is added to the conventional MBD analysis technology considering elastic deformation and vibration response. This paper introduces an overview of the developed technology.

1. Introduction

MHIET is trying to improve reliability and performance by making full use of all analysis techniques for designing turbochargers. In the conventional design of VG turbocharger nozzle mechanisms, a method of designing the clearance based on the component shape at normal temperature and evaluating the operability and the damage due to sliding wear to specify dimensional tolerances was used. Furthermore, a design method to predict thermal deformation in the operating temperature environment to avoid the risk of functional deterioration due to contact was also used. In actual operation, since the mechanism operates in a high-temperature environment, it is difficult to evaluate the mechanism using only one-way analysis technique like the conventional method. Therefore, multiphysics analysis that adds consideration of the influence of thermal deformation to multibody dynamics (MBD) analysis for predicting the motion and vibration of the mechanism is required.

We have developed a technology that can directly handle the effects of thermal deformation, which was previously difficult with MBD analysis, and can take into account changes in the clearance and rigidity that change from moment to moment due to thermal deformation by being coupled with the function of MBD analysis. This report introduces the developed technology.

2. Overview of MBD and thermal deformation coupled analysis technology

2.1 Issues to solve

Figure 1 depicts the mechanism and effects of a VG turbocharger, and **Figure 2** illustrates the arrangement and mechanism of a VG turbocharger nozzle. As an example of predicting the operating behavior of this mechanism, **Figure 3** gives the temperature distribution at the time of

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gas temperature rise (non-steady state) and **Figure 4** presents the temperature distribution at the time of steady gas temperature. As the exhaust gas temperature and flow change during operation, the temperature distribution changes and the thermal deformation interconnectedly changes. Considering the change in the clearance of each of the multiple nozzle mechanism components in response to this change in thermal deformation, a design that maintains the positioning performance defining the throttling amount of the variable nozzle and avoids the risk of damage due to contact sliding under any operating condition is required.

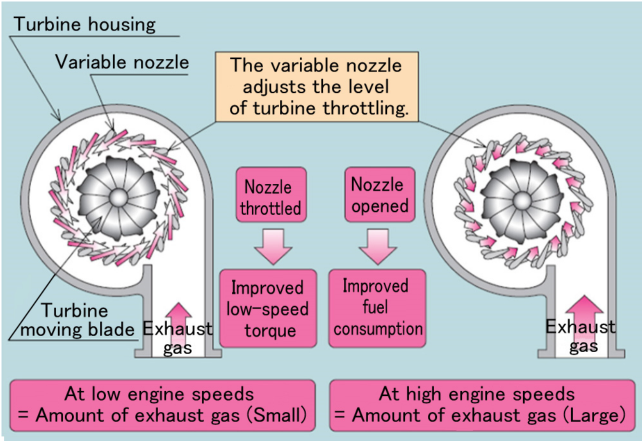

Figure 1 Mechanism and effect of the VG turbocharger

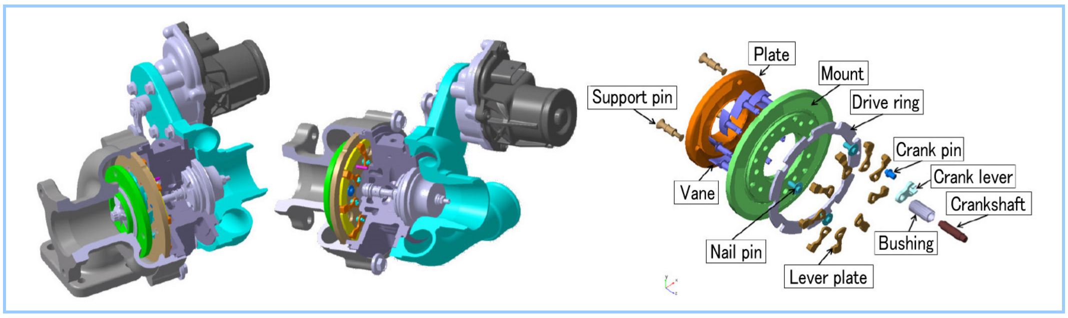

Figure 2 VG turbocharger nozzle mechanism

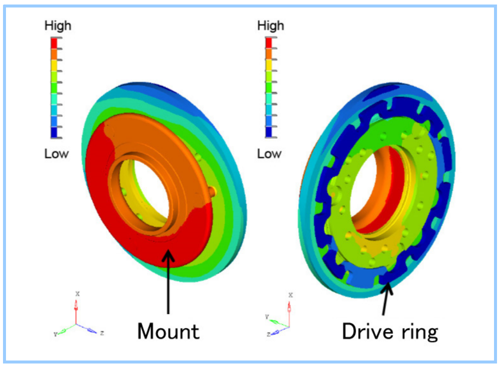

Figure 3 Temperature distribution at the time of gas temperature rise

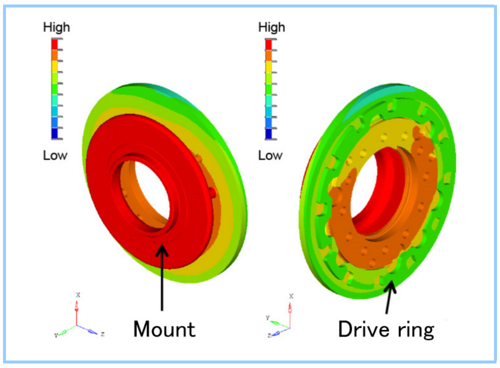

Figure 4 Temperature distribution at the time of steady gas temperature

2.2 Development of MBD analysis technology considering thermal deformation

Currently, the mainstream method of predicting thermal deformation is FEM analysis. It is difficult to couple this method with MBD analysis, which solves an equation of motion configured by defining constraints between product components, so there were difficulties in considering thermal deformation in MBD analysis. Responding to this situation, focusing on a method(1) of mode-decomposing an equation of heat conduction as a differential equation, we developed a method to analyze and evaluate the thermal deformation and motion of the mechanism simultaneously by coupling this method with the equation of motion of MBD analysis in joint research with The University of Iowa(2)(3).

In general, the characteristic equation for the temperature distribution described above can be expressed as **Equation 1** by coupling it with the equation of motion of the object. In addition, **Figure 5** shows the mode (eigen value analysis result) of the temperature distribution of the drive ring. By superposing these modes, the deformation caused by the temperature distribution shown in Figure 3 and Figure 4 is reproduced.

Figure 6 is the estimation result of the thermal deformation of the drive ring and mount using MBD analysis. The difference in relative deformation between components due to the temperature distribution causes a contact form distribution. In this way, MBD analysis can predict changes in clearances and contact conditions between components due to the rotational behavior of the drive ring using the deformation and contact conditions as boundary conditions.

Heat stress effect term

$$\begin{bmatrix} \mathbf{M}_{ff} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}}_f \\ \ddot{\mathbf{q}}_T \end{bmatrix} + \begin{bmatrix} \mathbf{D}_{ff} & \mathbf{0} \\ \mathbf{0} & \mathbf{D}_{TT} \end{bmatrix} \begin{bmatrix} \dot{\mathbf{q}}_f \\ \dot{\mathbf{q}}_T \end{bmatrix} + \begin{bmatrix} \mathbf{K}_{ff} & \mathbf{K}_{fT} \\ \mathbf{0} & \mathbf{K}_{TT} \end{bmatrix} \begin{bmatrix} \mathbf{q}_f \\ \mathbf{q}_T \end{bmatrix} = \begin{bmatrix} \mathbf{Q}_f \\ \mathbf{Q}_T \end{bmatrix}$$

Heat capacity effect term　　Heat conductivity effect term

Equation 1　Coupling of equation of motion and equation of heat conduction

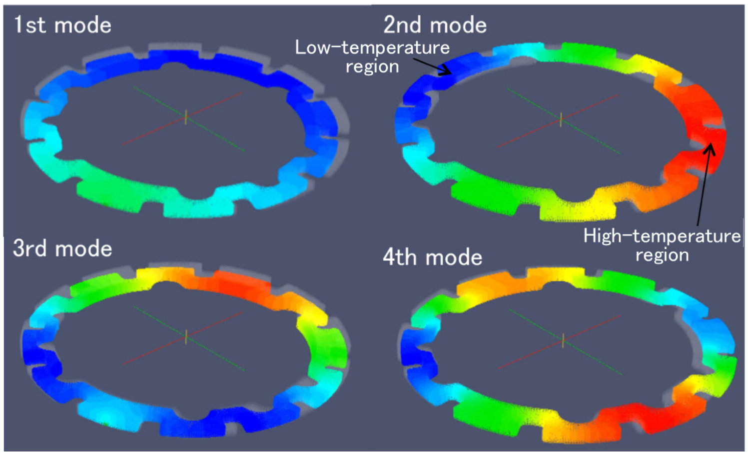

Figure 5　Drive ring temperature distribution mode (eigen value analysis result)

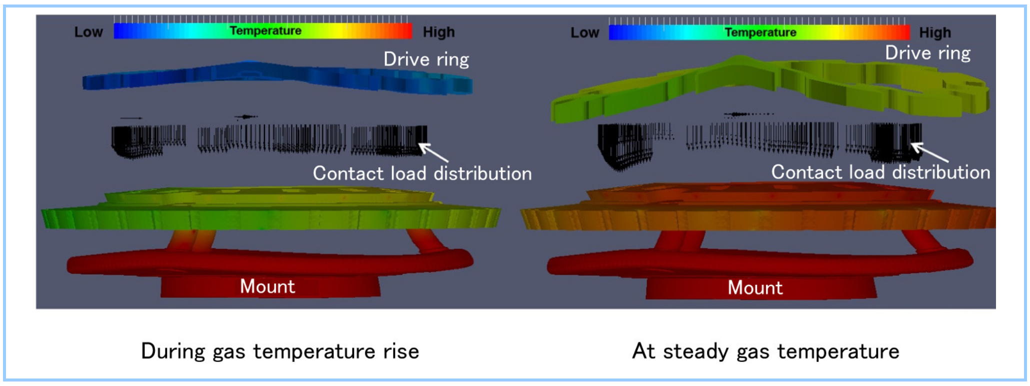

Figure 6　Contact load distribution due to thermal deformation of lower surface of drive ring and upper surface of mount

3. Prediction of behavior and event occurrence using coupled analysis

3.1 Prediction of behavior responding to thermal deformation of temperature distribution at steady gas temperature

The behavior of the nozzle mechanism opening and closing operation was analyzed with the component clearance and the contact state having thermal deformation using the temperature distribution as the boundary condition shown in Figure 3. **Figure 7** presents the result of extracting the contact load between the drive ring and the mount. The prediction result indicates that the contact point and load change depending on the drive ring rotation angle (vane opening degree).

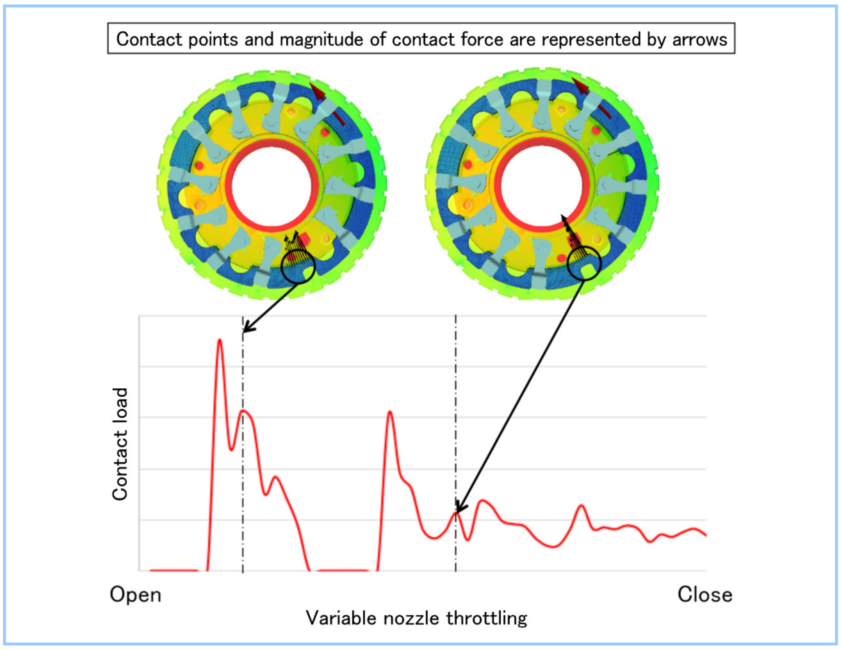

Figure 7 Change in contact load between drive ring inner diameter and mount outer diameter (during gas temperature rise)

3.2 Prediction of behavior responding to thermal deformation of temperature distribution during gas temperature rise

Next, the behavior of the nozzle mechanism opening and closing operation was analyzed using the temperature distribution during gas temperature rise as the boundary condition shown in Figure 4. As shown in **Figure 8**, the prediction result indicates that the strong contact point and the magnitude of load during operation are different compared with the results at steady gas temperature.

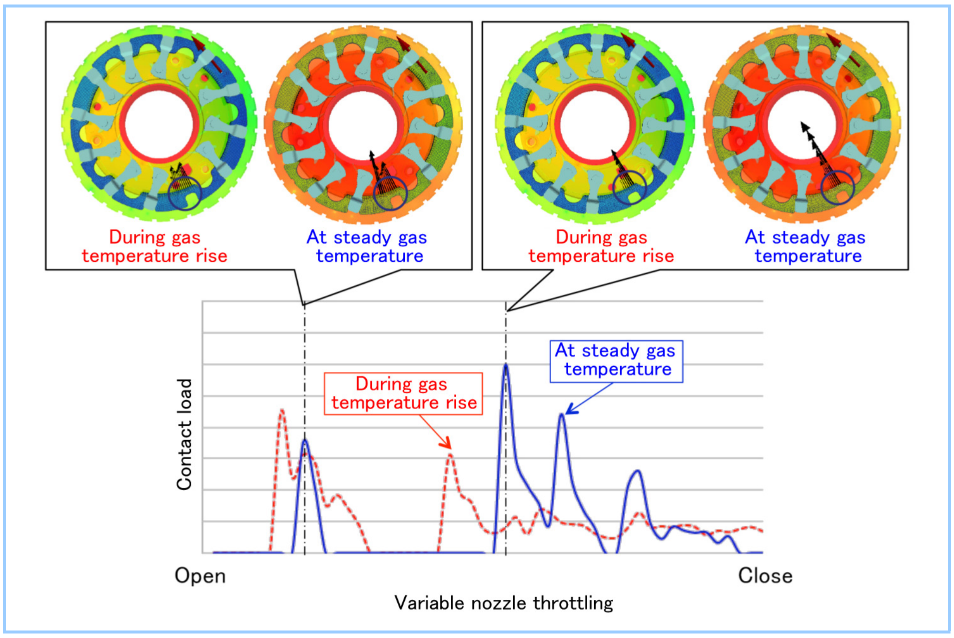

Figure 8 Change in contact load between drive ring and mount (comparison of loads during gas temperature rise and at steady gas temperature)

3.3 Expected effects of developed analysis method

The influence of temperature distribution on the opening and closing operation of a VG turbocharger nozzle mechanism is predicted using the developed MBD and thermal deformation coupled analysis technology. As given in Figure 7 and Figure 8, the prediction result indicated that the contact point between components and the magnitude of load change depending on the temperature distribution and the vane opening degree. Such a response is an event that is difficult to measure in testing. An optimal clearance that reduces the risk of damage can be designed by understanding the contact points and loads of components under all operating conditions.

4. Conclusion

This report presents examples towards the application of thermal deformation and MBD coupled analysis technology, which was conventionally difficult, to the design of VG turbocharger nozzle mechanisms.

By introducing this analysis method that enables the prediction of product performance under a high-temperature environment where the measurement and understanding of actual machine conditions are difficult, highly-reliable product design can be achieved and a reduction in the number of prototypes and tests, as well as the prevention of rework, can be expected.

References

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