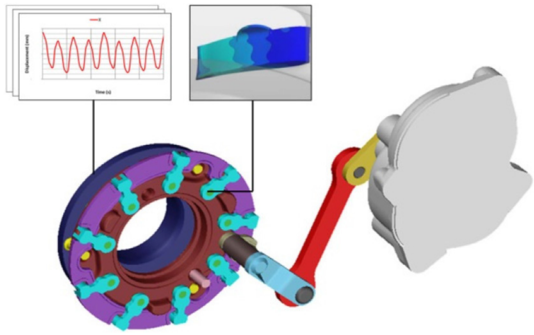
Evaluation Method of Reliability of Variable Geometry Turbocharger for Gasoline Engine by Digital Mock-up



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We have applied a simulation using 3D-CAD-based digital mockup to the behavior evaluation of variable geometry turbochargers (hereinafter referred to as VG turbochargers) developed for passenger-car gasoline engines that can comply with exhaust gas regulations (RDE : Real Driving Emission) , which regulate emissions under actual vehicle running situations in which the engine is required to generate a significant amount of torque and function at wider speed range . This method uses a combination of flow/heat transfer analysis that sets boundary conditions and structure/mechanism analysis that is used for reliability evaluation. We have established this evaluation method for matters related to the reliability of VG turbochargers used for gasoline engines, which are subject to higher temperatures than diesel engines, such as the damage and deformation due to thermal stress and the wear of mechanical parts and implemented it to product development.

1. Introduction

In recent years, development and technological innovation have been promoted for passenger-car gasoline engines that can comply with exhaust gas regulations (RDE), which regulate emissions under actual vehicle running situations in which the engine is required to generate a significant amount of torque and function at wider speed range. As part of these efforts, the adoption of VG turbochargers, which enable higher supercharging, has been promoted. Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. has developed a highly-efficient VG turbocharger with a completely redesigned compressor and turbine. The details have already been presented in the previous Technical Review(1).

In the case of gasoline engines, the exhaust gas temperature is higher in comparison to diesel engines to which the VG turbocharger has been usually applied and it is necessary to both improve the aerodynamic efficiency and ensure the operability and durability of the variable nozzle mechanism. Therefore, product development with due consideration for reliability is required. Matters that are particularly important in terms of reliability include damage due to the strength deterioration of parts caused by the increase in temperature and the wear of variable nozzle parts used in a high-temperature and non-lubricated environment. In order to ensure reliability, it is necessary to evaluate behaviors such as deformation in a high-temperature environment and response when an external force such as from fluid or engine vibration is applied. This report introduces technology that applies 3D-CAD data-based digital mockups and various simulations to the development of VG turbochargers for gasoline engines in order to predict the behavior of each part of the VG turbocharger for reliability verification at the design stage.

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2. Internal flow evaluation using flow analysis

The flow of gas inside a turbine not only decides the turbine performance, but is also an important factor that affects the conditions of heat input to parts subject to high temperature and the fluid force acting on the variable nozzle. Flow analysis (CFD: Computational Fluid Dynamics) is an effective means for evaluating gas flow at the design stage. **Figure 1** shows the structure of a VG turbocharger. The high-temperature exhaust gas from the engine flows in from the spiral scroll of the turbine housing, passes through the variable-geometry nozzle vane and is supplied to the turbine. **Figure 2** is the pressure (static pressure) distribution inside the scroll and around the nozzle vane obtained from the CFD analysis results. Under condition α1 where the opening angle of the nozzle vane is small, the pressure difference between the inner and outer circumferences of the vane is very large. On the other hand, however, under condition α4 where the opening angle large, the pressure difference is small. The optimization of turbine efficiency responding to the change in the flow inside the turbine with respect to the nozzle opening angle as shown in Figure 2 is investigated and the shapes of the turbine wheel, nozzle vane and scroll are determined accordingly. At the same time, the strength, driving force and wear of the variable nozzle mechanism are evaluated in consideration of the change in the fluid force generated due to the influence of the pressure distribution around the nozzle. The hysteresis and the wear of the sliding part during the operation of the variable nozzle mechanism are sensitive to the fluid force acting on the nozzle vane, especially the rotational torque. **Figure 3** illustrates the change in the rotational torque generated by fluid force with respect to the nozzle vane opening angle in the case where the shape of the nozzle vane is changed. The conventional nozzle vane design sometimes causes a decrease or reversal of the rotational torque when the nozzle opening angle is large, which leads to the risk of wear due to the unstable nozzle posture. Therefore, the design is changed such that the rotational torque of the nozzle vane is constant regardless of the opening degree. **Figure 4** gives the pressure distribution around the nozzle under the condition where the nozzle vane opening angle is large. The distribution of the pressure at the leading and trailing edges of the nozzle, which is small in the conventional product, is reconsidered and the design is changed so that the rotational torque in the opening direction can be generated stably regardless of the opening angle. When torque is applied in the opening direction, the nozzle moves to the opening side even when wear occurs. If the nozzle moves to the closing side when wear occurs, the flow velocity at the turbine rotor inlet increases, which may cause damage to the rotor due to over-rotation of the turbine. In this design, consideration is also given to avoiding such risk.

As described above, CFD is important not only for the performance design of the turbine, but also for reliable design. In addition, efforts to improve accuracy through experiments are continuously being implemented. The calculation result of the internal flow obtained from CFD is also reflected in the convective heat transfer for CHT (Conjugate Heat Transfer) analysis described below.

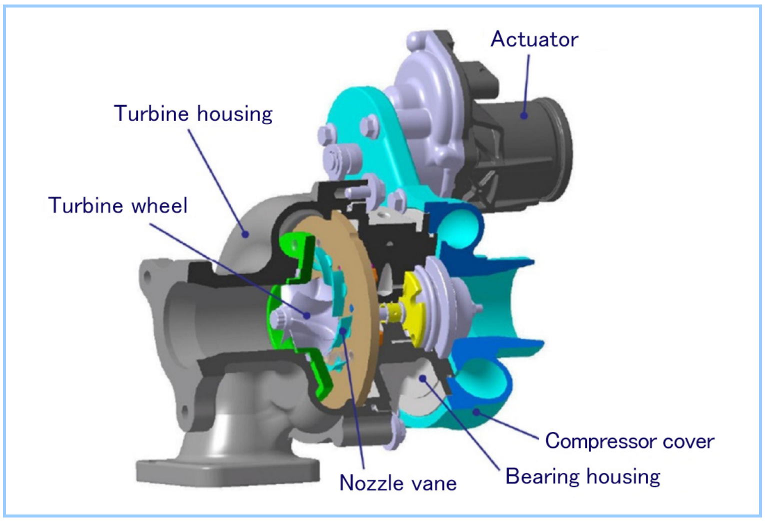

Figure 1 Structure of VG turbocharger

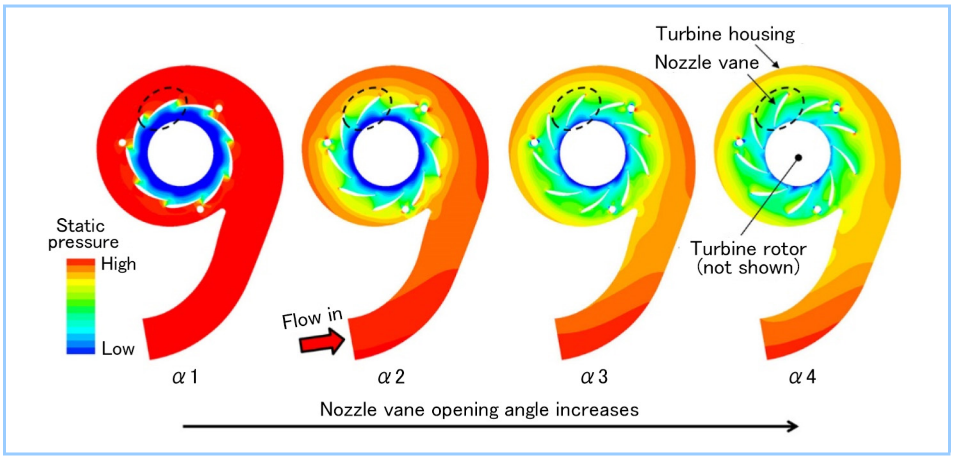

Figure 2 Pressure distribution inside scroll and around nozzle

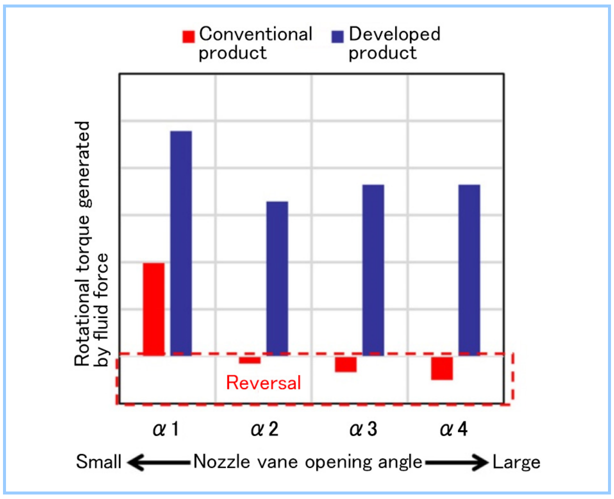

Figure 3 Rotational torque applied to nozzle vane

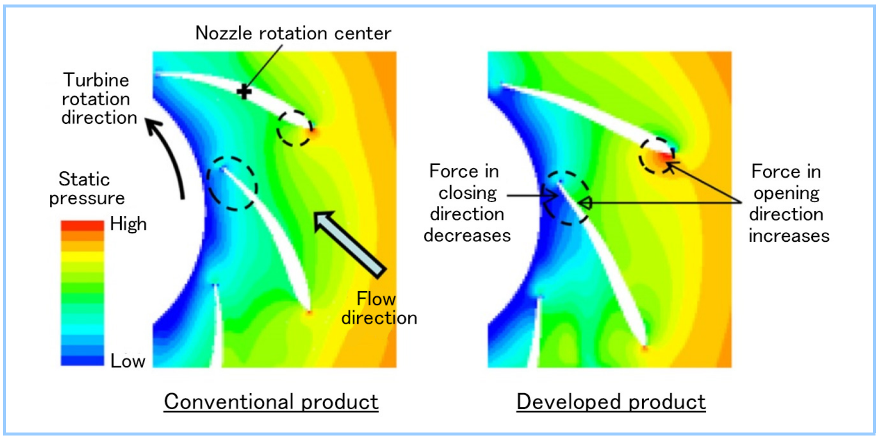

Figure 4 Pressure distribution around nozzle vane (opening angle α3)

3. Evaluation of thermal and flow field with CHT analysis

In VG turbochargers, thermal and flow field with thermal energy loss of high-temperature gas causes circumferential temperature distribution of the turbine section, resulting in the significant influence on the temperature field, strength and durability of various parts including the variable nozzle vane structure.

CHT analysis can simulate heat transfer from high-temperature fluid to various structures and simultaneously evaluate the temperature variation of fluid due to thermal energy loss. So far, CHT analysis has been conducted on detailed structure models of VG turbochargers for diesel engines and its advantage has been confirmed[(2)]. Furthermore, this analytical method is applied for the development of VG turbochargers for gasoline engines, in which operating temperature is higher.

Figure 5 shows the temperature distribution under high load condition. Radiation heat transfer model is applied to the CHT analysis in addition to convective heat transfer based on CFD of the exhaust gas passage, the water-cooling channel and the closed fluid cavity between the variable nozzle vane structure and the bearing housing. As a result, detailed thermal and flow field evaluation of the VG turbocharger is realized. The steep temperature gradient from the turbine housing to the bearing housing was formed. The temperature field of the variable nozzle vane structure was influenced by the temperature reduction of exhaust gas from the inlet to the outlet of the turbine scroll passage. It was then confirmed that the temperature field resulted from the CHT analysis was consistent with experimental temperature distribution in a gas stand test.

Figure 6 compares the measured temperatures under cooling/heating cycle condition with those of the transient CHT analysis. The CHT analysis was capable of simulating the measured transient temperature behavior. Applying the temperature field to structural analysis, the reliability for the structure design with thermal deformation is attained.

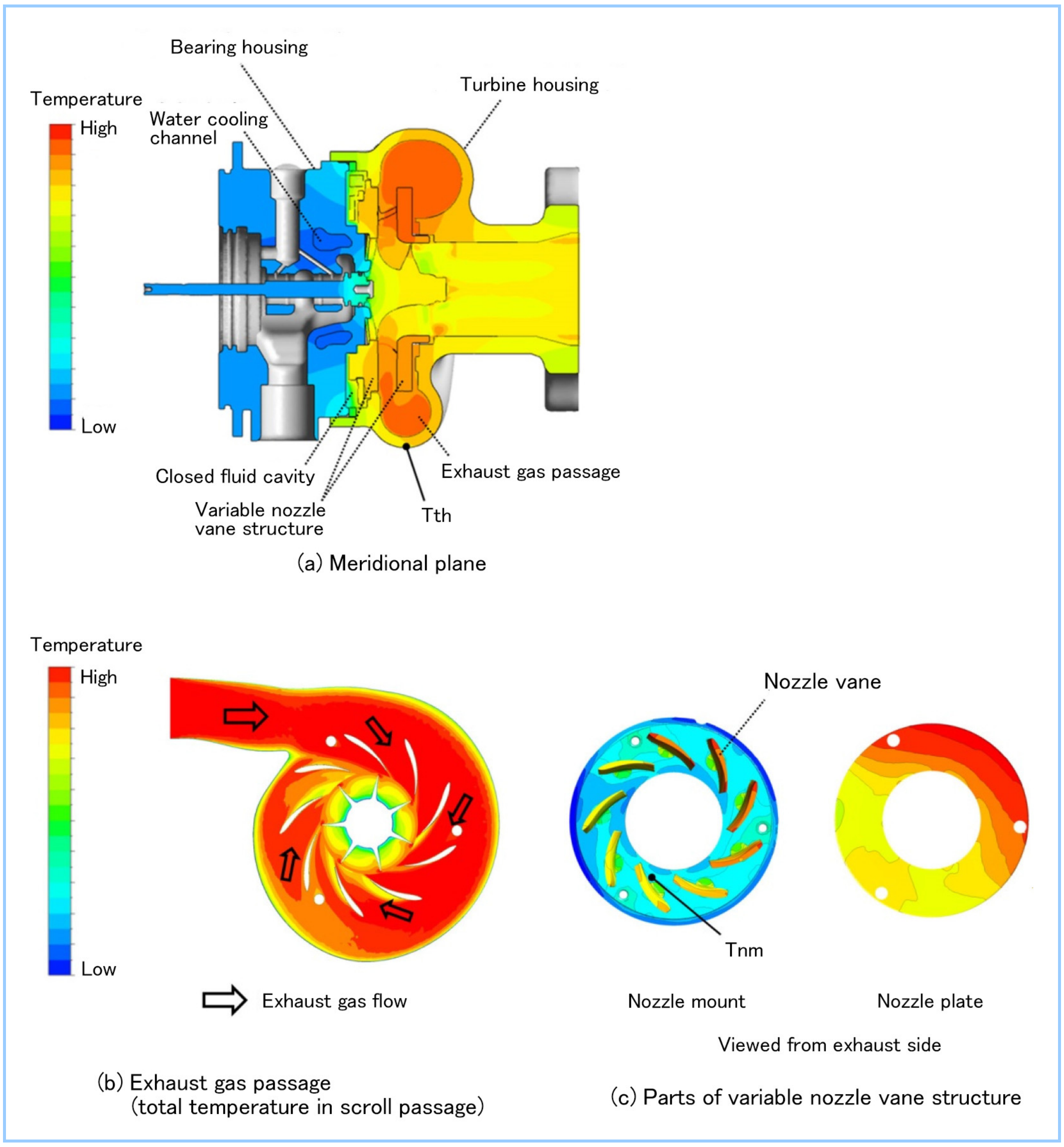

Figure 5　Temperature field of VG turbocharger

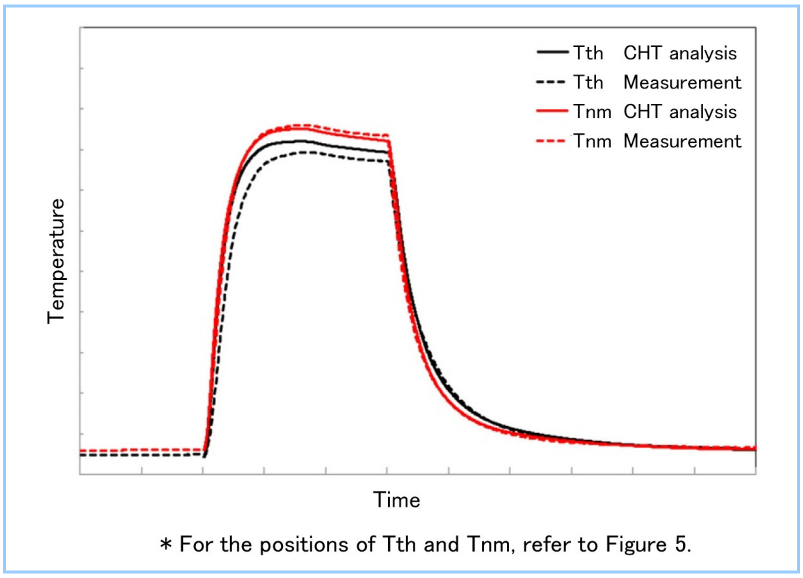

Figure 6 Transient temperature behavior in cooling/heating cycle condition

4. Reliability evaluation using structural analysis

VG turbocharger for an automotive engine is received temperature changes in a short time, because they are used in a driving mode repeated acceleration and deceleration. Furthermore, the VG turbocharger for the gasoline engine is operated under severe high temperature condition, it is necessary to design the clearance between each part and the thermal resistant stress in consideration of the time history change of the temperature distribution. Therefore, for a large-scale FEM (Finite Element Method) analysis model of the entire VG turbocharger, a structural analysis model that reflects the precise metal temperature distribution obtained by the aforementioned CHT analysis was constructed.

In order to combine CHT analysis used for heat transfer/temperature distribution evaluation and FEM analysis used for deformation/stress evaluation and to perform the thermal stress analysis in small time increments considering a transient operation mode that requires the processing of huge amounts of data, an unsteady metal temperature mapping program for large 3D models was created. As a result, it has become possible to quickly evaluate the strength using more accurate temperature distribution under transient conditions. **Figure 7** provides an example of the thermal stress distribution evaluated by FEM analysis reflecting the large-scale 3D-FEM model and CHT analysis result. Using this large-scale 3D-FEM model, we evaluated a wide range of strengths such as the clearance of each part of the variable nozzle mechanism, thermal fatigue life, tightening force of bolt fastening points, reaction force of back plates, etc., and optimized the design. As a result, for the latest VG turbochargers, while ensuring reliability in a high temperature environment, we have realized the reduction of the diameters of the variable nozzle and turbine housing, as well as lighter weight and lower cost in comparison to the conventional models.

Next, this paragraph introduces the strength design technique of a turbine wheel. The operating temperature of VG turbochargers for gasoline engines tends to rise and the high-temperature strength of turbine wheels has become extremely demanding, so detailed creep strength design is required. Therefore, we constructed a creep analysis system for turbine wheels that enables quick creep strength evaluation at the time of design. **Figure 8** depicts the turbine wheel creep analysis model and an example of the analysis result[3]. It is indicated that the metal temperature was estimated accurately by modeling the shaft in addition to the turbine wheel to be evaluated and considering cooling due to lubricating oil. In the creep damage diagram, the stress time history is obtained by creep analysis and the creep damage according to the time consumption law is displayed as a contour diagram. When constructing the system, we verified the metal temperature estimation accuracy by a temperature measurement test using a thermography camera and the creep life prediction accuracy by a creep rupture test.

In this way, the reliability of gasoline engines under severe high temperature environment has been ensured by strength design using large-scale 3D-FEM analysis technique and the creep analysis system.

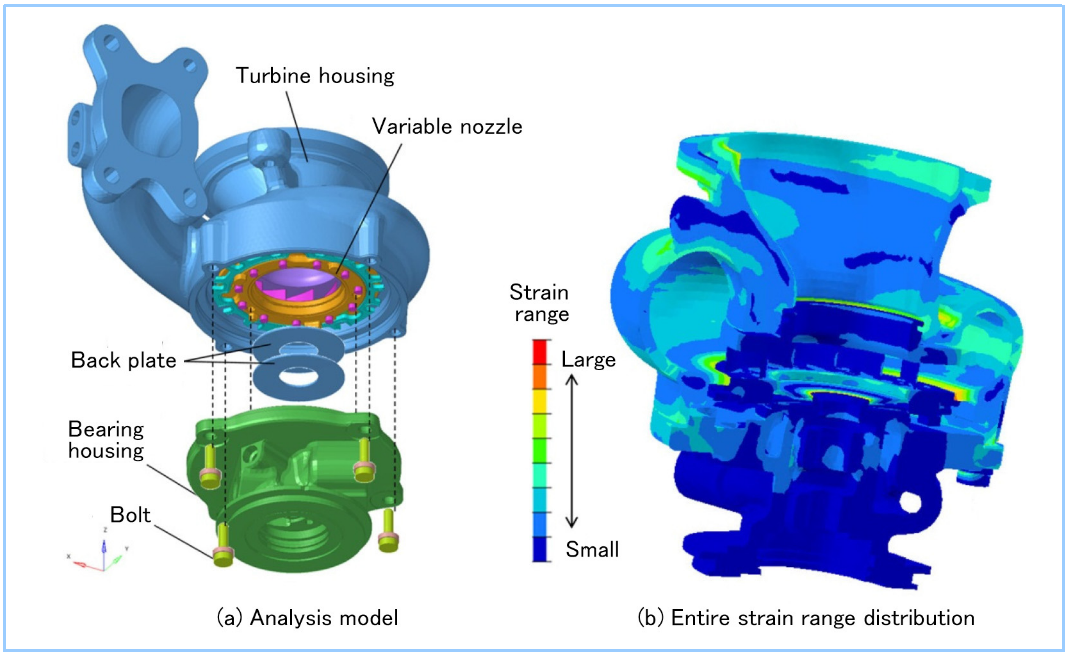

Figure 7　Structural analysis using large-scale 3D-FEM model

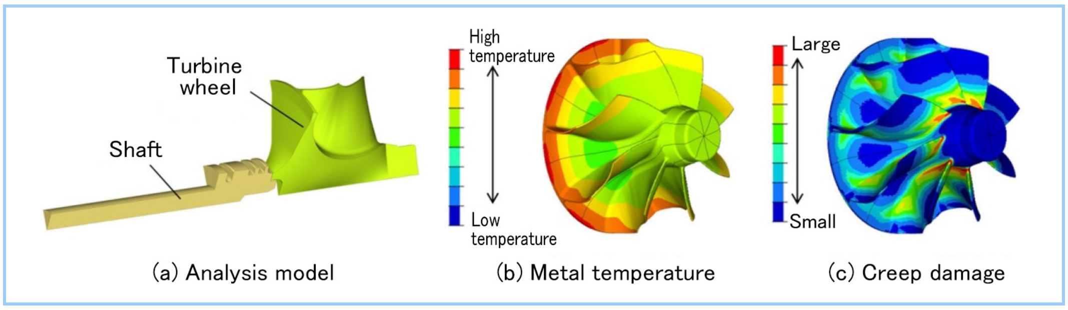

Figure 8　Creep analysis of turbine wheel

5. Behavior evaluation of variable nozzle mechanism using mechanism analysis

The variable nozzle mechanism of a VG turbocharger is required to operate so as to reach the target nozzle vane opening angle under a high-temperature and unlubricated environment while being subject to external forces such as fluid force, engine vibration, etc. For this reason, it is necessary to secure the driving force required for operation and suppress the deterioration of positioning accuracy due to wear. In order to evaluate the driving force and wear at the design stage, it is necessary to evaluate the contact force and slight movement between parts in consideration of the effects of fluid force and engine vibration. MBD (Multi-Body Dynamics) analysis is effective as a method for that purpose. The following paragraph describes an example of the wear evaluation of nozzle drive parts using MBD analysis.

Figure 9 is an overview of the MBD analysis model. The model is created based on 3D-CAD data, and the vane fluid force and engine vibration calculated by CFD analysis are input as the external force. Since the clearance between the parts is also taken into account, the behavior of the parts sliding while coming into contact with each other due to external force is expressed therein. **Figure 10** gives an example of calculating the contact force and sliding velocity between linkage parts. Figure 10 also presents the fluid force acting on the nozzle vane, and the contact force synchronized with the fluctuation of the fluid force and the sliding velocity that changes depending on the contact state are obtained as the calculation result.

The amount of wear is predicted by the specific wear rate, which is determined by material combination and other sliding conditions, the contact load and the sliding distance. The FV value, which is the product of contact load F and sliding velocity V and expresses the severity of wear, is obtained by MBD analysis. **Figure 11** depicts the relationship between the FV value obtained by MBD analysis and the amount of wear obtained in an engine durability test for the internal parts of the variable nozzle mechanism. It is verified therein that the amount of wear gets small as the FV value is reduced. Therefore, the shapes of nozzle vanes and turbine housings are designed so as to optimize the fluid force, which has a significant effect on the contact force, in order to achieve both performance and reliability.

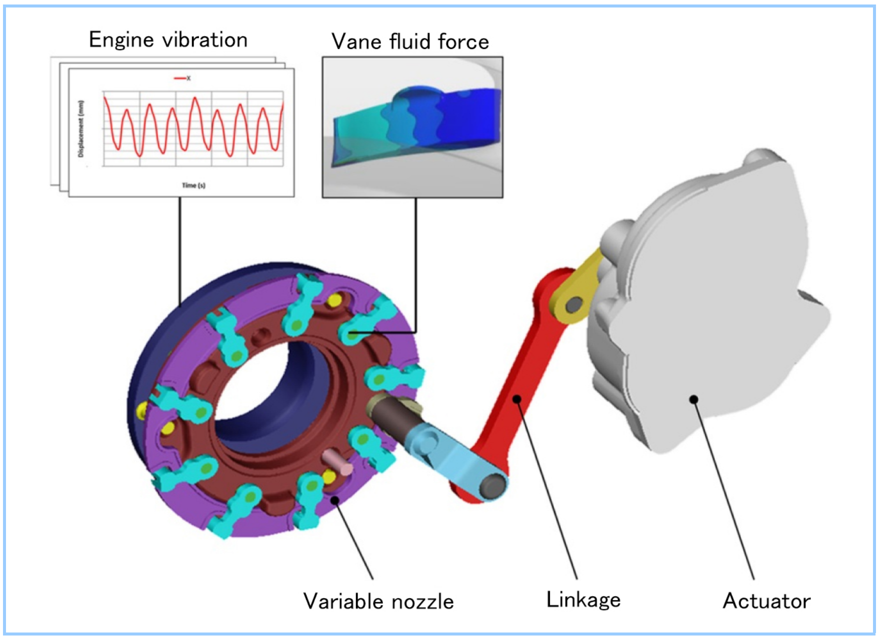

Figure 9 MBD analysis model

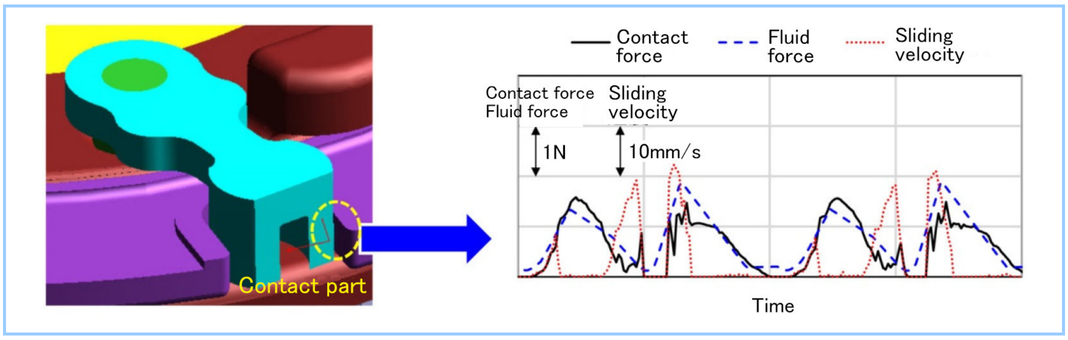

Figure 10 Example calculation of contact force between parts and sliding velocity using MBD

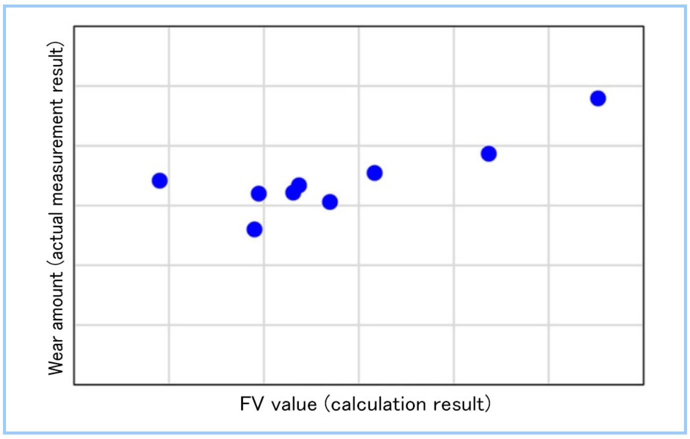

Figure 11 Comparison between MBD analysis result and wear amount

6. Conclusion

This report described that we are developing highly-reliable turbochargers by utilizing a method to evaluate the behavior of VG turbochargers for gasoline engines by combining various simulations such as CFD, CHT, FEM, MBD, etc., based on digital mockups. VG turbochargers developed using this method have already begun to be used for passenger cars. We will continue to contribute to the realization of a low-carbon society by promoting the development of high-performance, high-reliability turbochargers that can be combined with a variety of engines.

References

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