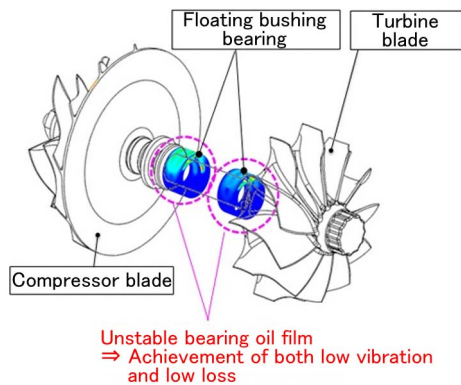


Reliability and Performance Gain Design Technique of Fluid Machinery Using Lubrication-Mechanism-Structure Coupled Analysis



TAKAYA FUTAE*1

TOSHIGAZU HAYASHI*2

HIROYUKI KANAZAWA*2 KEITARO KAMATA*1

TORU SUZUKI*1

It is difficult to make an evaluation with only a single analytical technology to improve the reliability and performance of fluid machinery, and the application of multiphysics analysis that takes into account the interaction between fluid force and structure is required. Mitsubishi Heavy Industries, Ltd. (MHI) has developed technology for the reduction of shaft vibration and noise of a turbocharger and the improvement of the efficiency and reliability of a swash plate type hydraulic piston pump by using lubrication-mechanism-structure coupled analysis. The technology introduced here is targeted at fluid machinery for which the lubrication state shows a time history change (self-excited vibration of bearings of a turbocharger and position/attitude change caused by reciprocating motion of swash plate type hydraulic piston pump). This technology enables the analysis of state changes at any given moment by coupling lubrication, mechanism and structure analysis. Furthermore, combining this analysis technology with optimization calculation facilitates the optimum design.

1. Introduction

In the field of turbochargers for automobiles and hydraulic transmissions for large vehicles, attractive products that reduce both losses of bearings and transmission devices, the soundness of bearings and sliding parts and low vibration and noise are in demand to improve performance. Evaluation in response to this demand using only a single analytical technology is difficult, and the application of multiphysics, etc., is required.

Therefore, we applied lubrication-mechanism-structure coupled analysis technology to promote efficiency enhancement through the reduction of vibration and loss of a turbocharger, which is a high-speed rotating machine, and balancing the mechanical loss and leakage loss of a hydraulic machine. This paper describes the outline and future outlook of such coupled analysis technology.

2. Coupled analytical technology for improving reliability and performance of fluid machinery

2.1 Turbocharger for automobiles

Figure 1 shows the shaft vibration measurement results of a turbocharger for automobiles. Since the turbocharger is a small high-speed rotating body, in addition to unbalanced vibration caused by an unbalance of the shaft, self-excited vibration caused by the bearing oil film can occur. Since the self-excited vibration is generated by the oil film pressure distribution determined by the relative position between the shaft and the bearing, it is necessary to accurately predict the time history change of the oil film pressure distribution to reduce the self-excited vibration. Furthermore, to improve the transient responsiveness of the engine, the reduction of loss in the bearing of the turbocharger is also needed, and a bearing design that attains low vibration and low loss is required.

*1 Machinery Research Department, Research & Innovation Center

*2 Chief Staff Manager, Machinery Research Department, Research & Innovation Center

Therefore, we developed coupled analysis technology of the multibody dynamic (MBD) model and bearing lubrication model considering the vibration characteristics of the shaft and the rigidity of the structure and now utilize the technology for product development. Such analytical technology is also being studied at university research institutes⁽¹⁾⁽²⁾⁽³⁾ and automobile manufacturers. We also couple the thermal deformation of the bearing clearance during operation, which is considered to be one of the causative factors, with the bearing and shaft vibration analysis to improve the prediction accuracy.

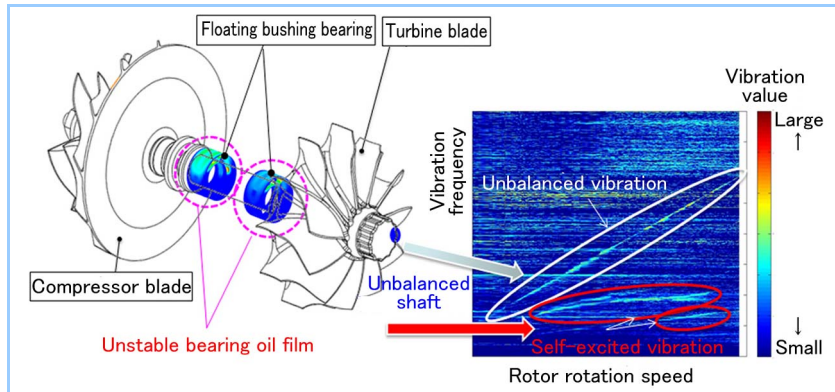


Figure 1 Shaft vibration measurement results of turbocharger for automobiles

2.2 Swash plate type hydraulic piston pump

Figure 2 shows the structure of the swash plate type hydraulic piston pump. Components of a swash plate type hydraulic piston pump behave in a complicated manner owing to mutual influence between multiple sliding parts such as the piston and the cylinder, the shoe and the swash plate, the valve plate and the cylinder block, etc., occurs, and the components. For this reason, product development progresses while design and verification are repeated, which leads to a prolonged development period. Therefore, we combined lubrication-mechanism-coupled analysis capable of simultaneous evaluation of multiple sliding parts with an optimization algorithm⁽⁴⁾ based on the Kriging response surface method developed by our company to construct an optimum design method to realize reliability and performance simultaneously to promote the shortening of the product development period.

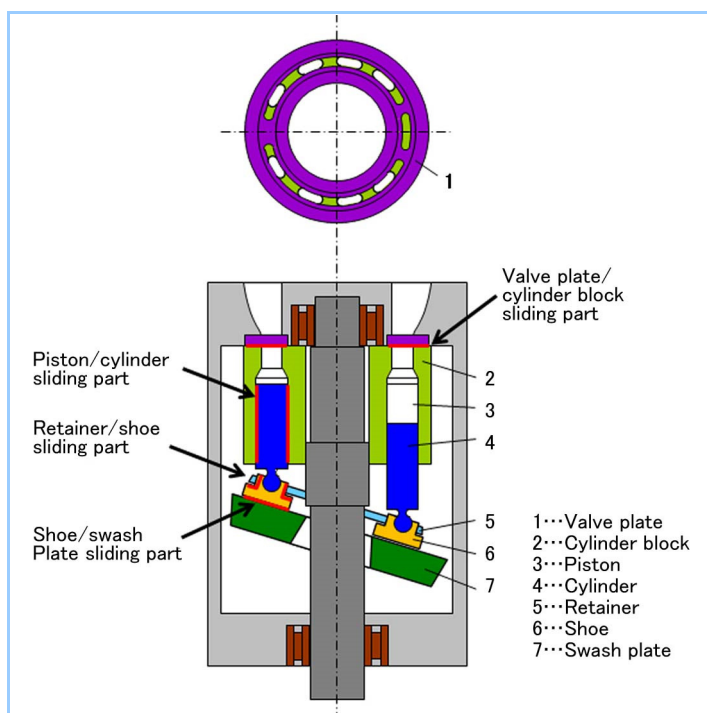


Figure 2 Swash plate type hydraulic piston pump

The next section describes an overview of the lubrication-mechanism-structure coupled analysis technology developed by our company.

3. Outline of design technology with coupled analysis

3.1 Low vibration and low loss bearing design technology of turbocharger

To predict self-excited vibration amplitude, the vibration displacement of the shaft and the oil film reaction force that change at any given moment are coupled-analyzed. **Figure 3** gives a calculation flowchart. This calculation can reproduce the occurrence of self-excited vibration by coupling shaft vibration analysis and bearing analysis as shown in the flow. By using the coupled analysis method, the behavior of the shaft and the bearing in the case of the occurrence of self-excited vibration can be estimated, and the creation of a bearing shape plan for reducing self-excited vibration is possible.

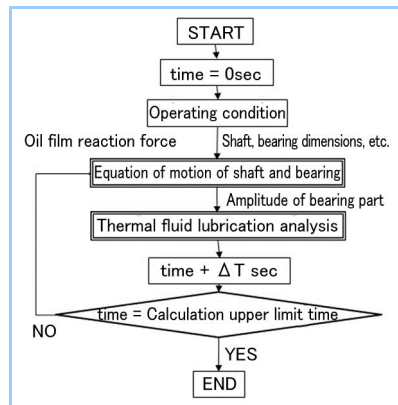


Figure 3 Calculation flow of turbocharger vibration characteristics

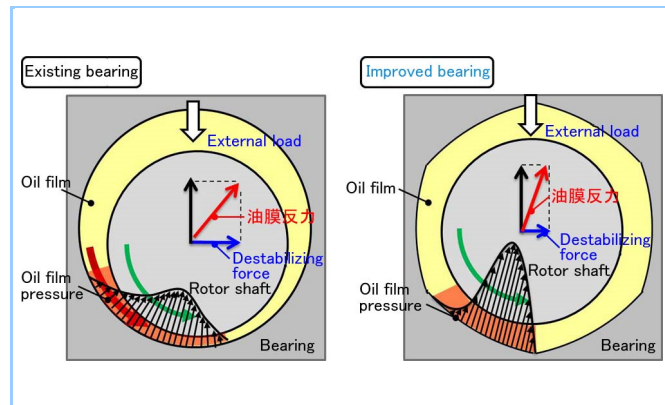


Figure 4 Conceptual diagram of oil film pressure distribution of existing bearing and improved bearing

Figure 4 illustrates a conceptual diagram of the oil film pressure distribution of existing bearings and improved bearings. In the case of existing bearings, for example, when an external load acts in the vertical direction, an oil film reaction force is generated in a direction tilted with respect to the external load due to the oil film pressure distribution, and a destabilizing force which causes self-excited vibration occurs. On the other hand, it is known that the oil film pressure distribution can change when the bearing surface is multilobe, so the destabilizing force can be reduced by changing the direction of the oil film reaction force. Based on this concept, we have devised an improved bearing for the turbocharger with a multilobe inner peripheral surface. **Figure 5** presents the calculation results of the vibration characteristics of the improved bearing. As can be seen in this figure, in the case of the improved bearing, the self-excited vibration amplitude was reduced. **Figure 6** shows the bearing loss measurement results of the improved bearing. The bearing loss of the improved bearing is equivalent to that of existing bearings, and it was also confirmed on actual equipment that the bearing loss is equivalent and self-excited vibration can be suppressed. Therefore, the improved bearing is currently being applied to products.

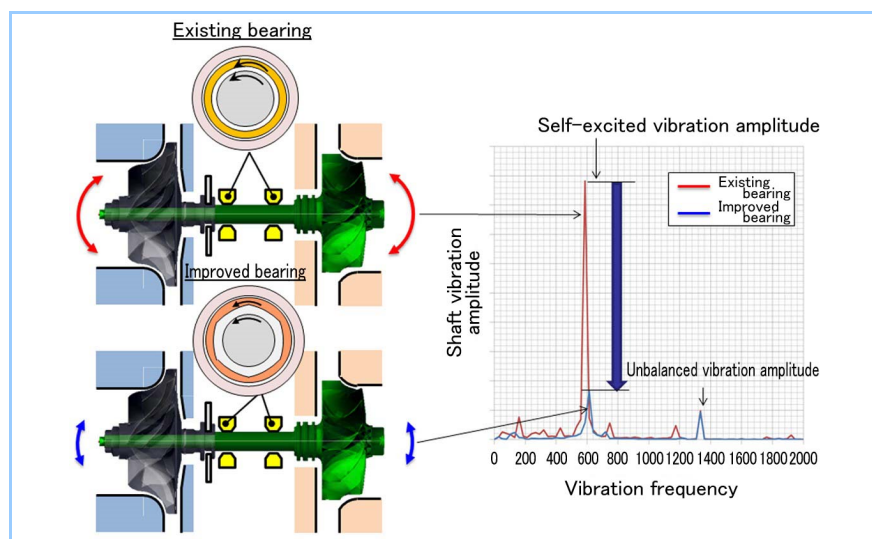


Figure 5 Calculation results of vibration characteristics of multilobe bearing

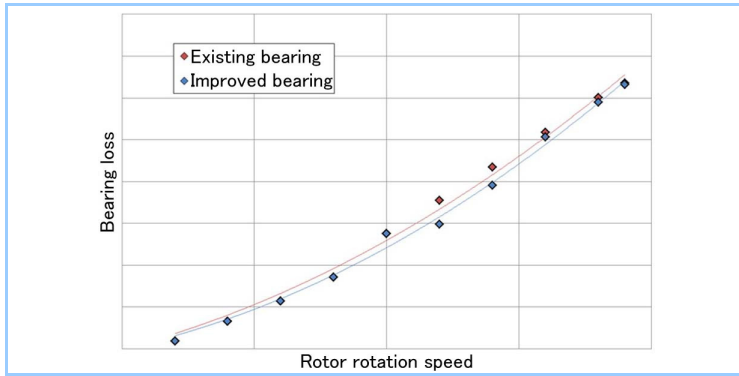


Figure 6 Bearing loss measurement results of improved bearing

To further improve the accuracy of the analysis technology, coupled analysis of thermal deformation of bearing clearance was established. Figure 7 shows a conceptual diagram of bearing-axis vibration-thermal deformation coupled analysis. As can be seen in this figure, using the bearing loss (heat generation) obtained by the bearing-shaft vibration coupled analysis, the temperature increase of the bearing surface was predicted and the thermal deformation around the bearing was estimated. Figure 8 depicts the element test apparatus which was the object of calculation. This device has less disturbance such as heat influence from the outside than the actual turbocharger, drives the rotor with a motor to rotate it at a high speed and measures the shaft vibration and the ambient temperature around the bearing.

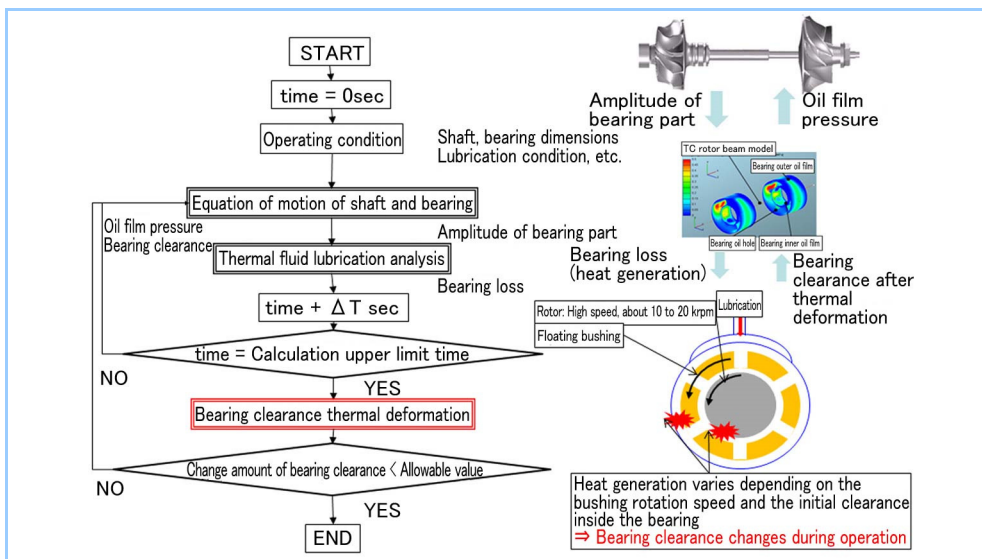


Figure 7 Flow chart of bearing-axis vibration-thermal deformation coupled analysis

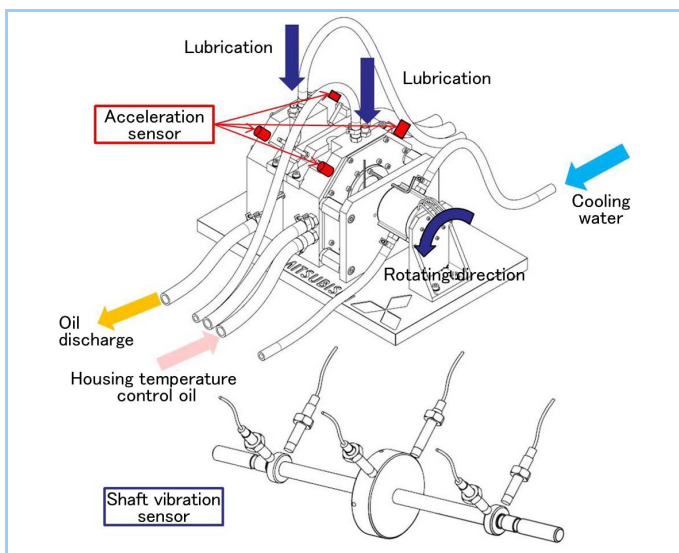


Figure 8 Element test apparatus

Self-excited vibration amplitude was calculated using the calculation model where the boundary condition around the bearing was reasonable. It was verified from the calculation results that the calculation accuracy of the amplitude and frequency of asynchronous vibration improved by approximately 10% due to consideration of thermal deformation.

3.2 Performance and reliability optimum design technology of swash plate type hydraulic piston pump

Figure 9 gives the performance and reliability optimum design flow. **Figure 10** depicts an example of lubrication-mechanism-structure coupled analysis considering multiple sliding parts simultaneously (oil film pressure distribution). This design method performs optimization calculation using the leakage loss, friction loss and PV value (product of the contact surface pressure and slip velocity) as evaluation indices. Each evaluation index was calculated from the leakage flow rate, axial power, contact force, inclination angle and sliding velocity obtained by lubrication-mechanism-structure coupled analysis. From the viewpoint of calculation cost, a calculation mesh with coarse density was used to represent local contacts in the coupled analysis. Therefore, the contact surface pressure was separately calculated using the contact force and inclination angle obtained by the coupled analysis using three-dimensional elastic contact analysis (detailed analysis of the contact area). Regarding the optimization calculation, the calculation of the next calculation condition used an optimization algorithm (EGO: Efficient Global Optimization) combining functions for sequentially updating the response surface, and the creation of the response surface used the Kriging method. The response surface was repeatedly updated until the EIF converged to derive the optimal solution.

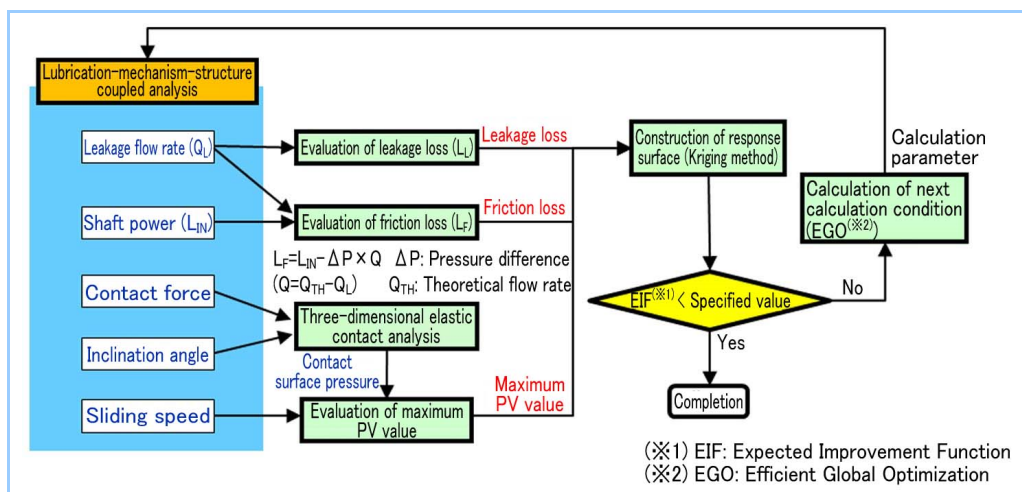


Figure 9 Performance and reliability optimum design flow

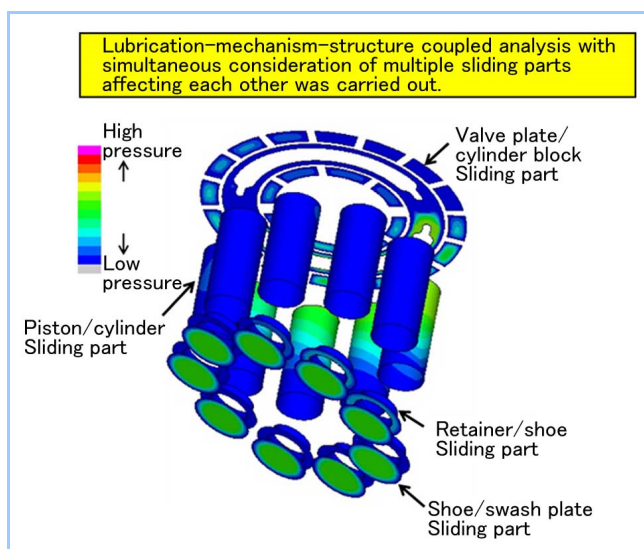


Figure 10 Example of lubrication-mechanism-structure coupled analysis considering multiple sliding parts simultaneously (oil film pressure distribution)

Figure 11 shows an example of a response surface finally obtained by the optimization calculation. Optimization calculation was performed using the clearance of each sliding part as a parameter with the constraint condition where the seizure limit value PV* of the components should not be exceeded, and it was confirmed that the minimum loss point exists outside the design range so far. It is also expected that this method can improve the efficiency by 4% and the output density by about 30% in comparison with the conventional design with the condition that the contact PV value of the sliding parts does not exceed the seizure limit.

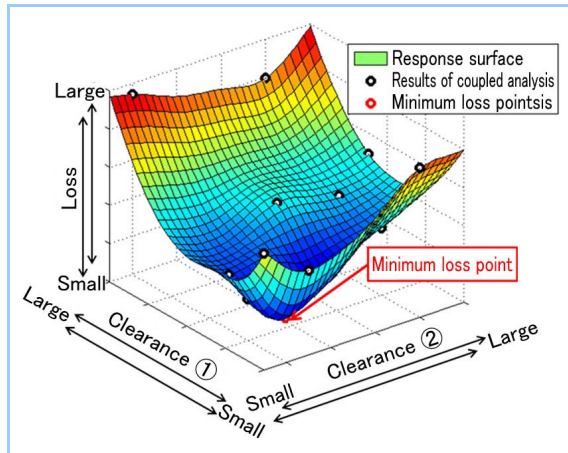


Figure 11 Example of response surface finally obtained by optimization calculation

4. Conclusion

MHI now utilizes the lubrication-mechanism-structure coupled analysis technology to improve the reliability and performance of fluid machinery. This paper presented the coupled analysis technology using the optimum design of self-excited vibration of the bearing of a turbocharger and multiple sliding parts of a swash plate type hydraulic piston pump as examples. Using this method, it is possible to develop products that can achieve both efficiency and reliability. In the future, we will continue to develop highly-efficient products while maintaining reliability.

References

1. Smolik, L. et al., Investigation of bearing clearance effects in dynamics of turbochargers, *International journal of Mechanical Sciences*, Vol. 127, (2017), Pages 62-72
2. Bernhauser, L. et al., The Effect of Non-Circular Bearing Shapes in. *Hydrodynamic Journal Bearings on the Vibration. Behavior of Turbocharger Structures, Lubricants* 2017, 5(1), 6
3. Ioannis, C. et al., Experimental and Numerical Investigations of Turbocharger Rotors on Full-floating Ring Bearings with Circumferential Oil-Groove, *Proceedings of ASME Turbo Expo, GT2017-64628*
4. Aror, R. et al., Design Technique for Mechanism Analysis Using Nonlinear Response Surface by Applying High-speed, High-precision Optimisation Method, *Mitsubishi Heavy Industries Technical Review* Vol. 53 No. 4 (2016)