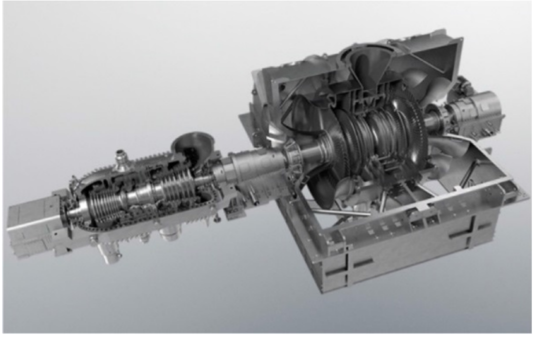
Visualization of Labyrinth Seal Force Acting on Rotating Machinery Using Pressure Sensitive Paint



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For improving the reliability of rotating machinery, it is extremely important to predict fluid force acting during the machine operation. Recently, CFD (Computational Fluid Dynamics) analysis technology has been applied to the evaluation of fluid forces. In order to verify CFD analysis and improve its accuracy, visualization and measurement technology of fluid forces are a useful tool. Regarding the verification technology, Mitsubishi Heavy Industries, Ltd. (MHI) has been working on the visualization of unsteady fluid forces using pressure sensitive paint (PSP). In this study, we improved this technology to enable measurement in narrow sections, and applied it to a seal of rotating machinery and compared the results with those of CFD analysis. As a result of the measurement, we were able to obtain a detailed pressure distribution, which led to a better understanding of the mechanism of fluid force generation. In addition, we verified the difference between the measurement using PSP and the CFD analysis, which led to the improvement of evaluation methods for the future.

1. Introduction

In order to suppress leakage of the working fluid from shafts and blade tips of rotating machinery and improve the efficiency, labyrinth seals are used. A labyrinth seal has a fin structure as shown in **Figure 1**, and the narrow section of the fin suppresses leakage from blade tips and shafts leakage. To increase the efficiency of the equipment, it is desirable to minimize the clearance at the tips of these fins, however at the same time, it is known that an increase in fluid force that causes self-induced vibration of the shaft of the rotating machinery occurs at the seal. With the increase in capacity and efficiency of rotating machinery, the working fluid has increased in pressure and the seal dimensions have also become larger in recent years. Therefore, the need for detailed evaluation of the fluid force at seals, which is the cause of self-induced vibration, has increased.

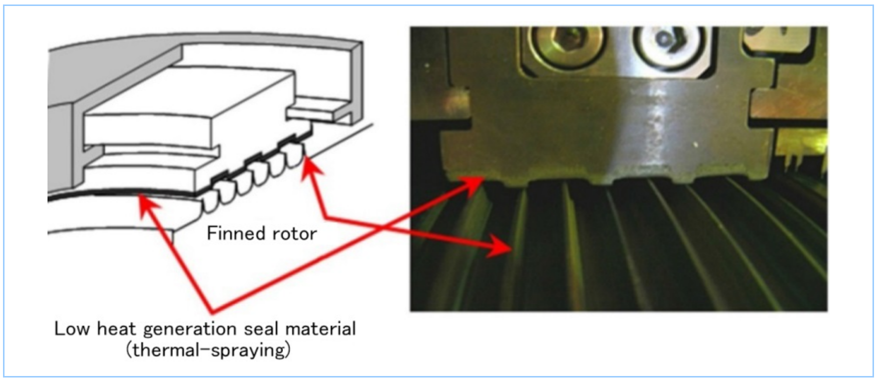

Figure 1 Example of labyrinth seal structure

Conventionally, it has been possible to evaluate the fluid force by using a theoretical formula for a simple-shape seal structure. However, as the performance of seals improves, more complex

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seal structures are being used, and there are limitations to using only theoretical formulas for evaluation. In addition, because of the complexity of the flow inside the seal, the reproducibility with CFD evaluations, which have been rapidly expanding to use in recent years, can be problematic in some cases. Therefore, in order to improve the evaluation with CFD, it is highly desirable to visualize the details of pressure fluctuation inside the seal.

In this study, we measured pressure fluctuations using a fast-responding polymer-ceramic-type pressure sensitive paint (PC-PSP) to visualize pressure distribution inside seals. By illuminating the pressure sensitive paint with excitation light from the opposite side of the pressure acting surface and measuring with a high-speed camera, we succeeded in making unsteady measurements in a complex channel such as the inside of a seal. Using the detailed visualization results of unsteady pressure fluctuations obtained in this study, it was found that the pressure distribution calculated by CFD and that measured with the pressure sensitive paint differed significantly near the position where the flow separation occurs, which is an important result as a fundamental finding for improving turbulence models used in CFD.

2. Measurement of seal excitation force

2.1 Seal excitation force

The equation of the motion of shaft vibration of rotating machinery can be expressed by a two-degree-of-freedom system with respect to two directions of shaft deflection as follows:

$$\mathbf{M}\begin{bmatrix}\ddot{X}\\ \ddot{Y}\end{bmatrix}+\mathbf{C}\begin{bmatrix}\dot{X}\\ \dot{Y}\end{bmatrix}+\mathbf{K}\begin{bmatrix}X\\ Y\end{bmatrix}=\begin{bmatrix}F_X\\ F_Y\end{bmatrix} \quad (1)$$

Since the seal excitation force is a fluid force that is generated in response to the shaft vibration response, it can be represented as the added stiffness and added damping of this vibration system and can be matrixed as in the following equation.

$$\begin{bmatrix}F_X\\ F_Y\end{bmatrix}=-\begin{bmatrix}K_{XX} & K_{XY}\\ K_{YX} & K_{YY}\end{bmatrix}\begin{bmatrix}X\\ Y\end{bmatrix}-\begin{bmatrix}C_{XX} & C_{XY}\\ C_{YX} & C_{YY}\end{bmatrix}\begin{bmatrix}\dot{X}\\ \dot{Y}\end{bmatrix} \quad (2)$$

The seal excitation force is a problematic force that contributes to shaft vibration and is generated by the swirling flow entering a seal narrow section as shown in **Figure 2**. By understanding the stiffness matrix and damping matrix in equation (2) and performing a stability analysis, it is possible to calculate whether self-induced vibration occurs over the whole of the rotor system.

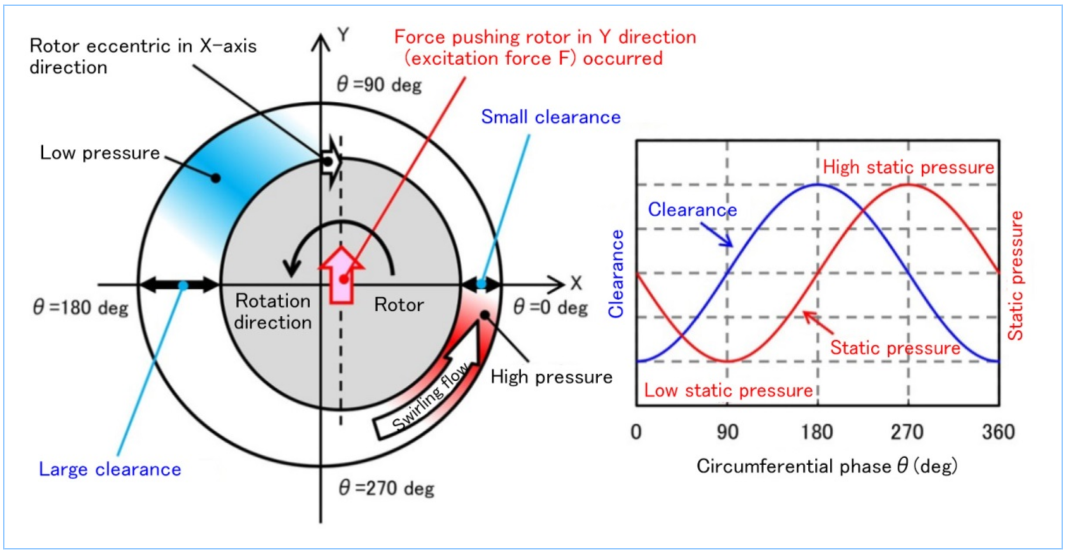

Figure 2 Mechanism of shaft vibration generated by rotor whirling

2.2 Rotational test equipment

Figure 3 shows rotational test equipment for measuring seal excitation force. This equipment has two disks on one rotor, and is equipped with seal fins to be used for measurement at the tips of the disks. Compressed air supplied from the center of the two disks passes through the left and right seal fins to balance the differential pressure in the axial direction. The rotor is supported by cage-type springs via rolling bearings. By using an electromagnetic actuator at the shaft end to vibrate the rotor in a whirling manner, an excitation force is generated at the seals, which is measured by a load cell. **Figure 4** shows the seal used in this test. The strength of the swirling flow at the inlet of the seals was measured using a three-hole pitot tube. The seal used is an interlocking seal (ILS), which has fins on the rotor side and stator side protruding alternately.

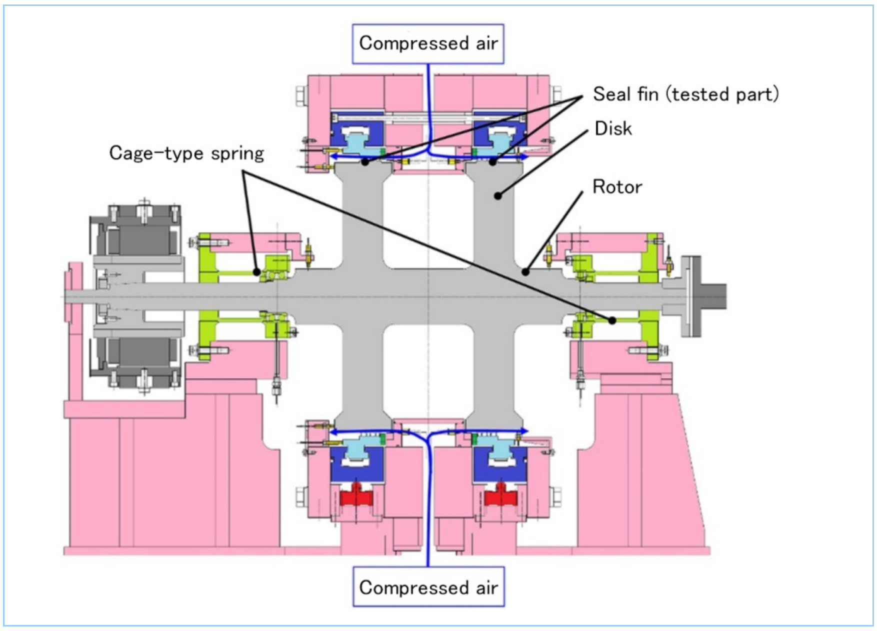

Figure 3 Rotational test equipment for measuring seal excitation force

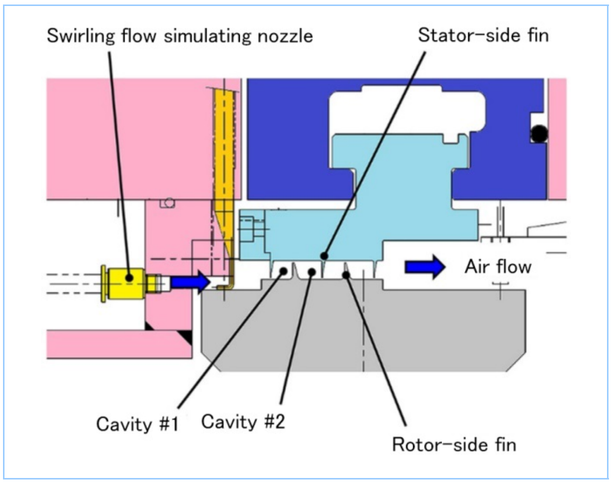

Figure 4 Structure of tested seal

2.3 Result of excitation force measurement

In this test, excitation was performed while changing the strength of the swirling flow into the seal fins. **Figure 5** shows the measurement results. It was observed that the magnitude of the off-diagonal term in the seal excitation force stiffness matrix, which is the cause of unstable vibration, increased in proportion to the strength of the swirling flow.

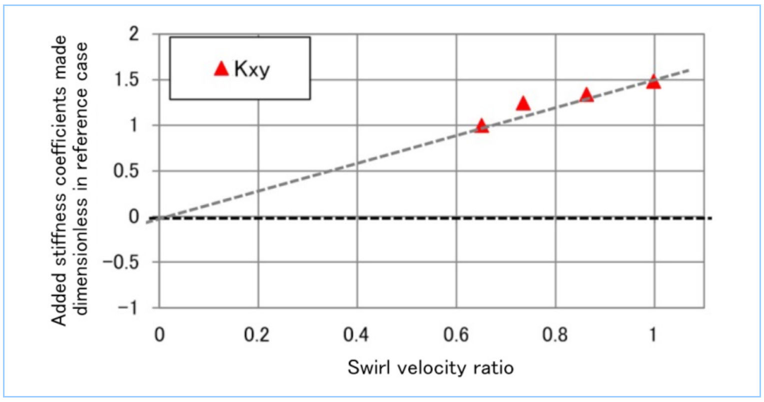

Figure 5 Measurement result of seal excitation force added stiffness coefficient

3. Measurement using pressure sensitive paint

3.1 Pressure sensitive paint

Pressure sensitive paint consists of a dye, the luminescence intensity of which changes according to oxygen concentration, indicating changes in the partial pressure of oxygen due to changes in the static pressure of the air. Pressure sensitive paint, with which static pressure can be measured as a change in its luminescence intensity, is applied to pressure measurement. For this test, a polymer-ceramic-type pressure sensitive paint containing a platinum porphyrin dye and mixed with ceramic powder to increase the response speed was used. This paint was provided by the Japan Aerospace Exploration Agency (JAXA). **Figure 6** shows a schematic diagram of the measurement using pressure sensitive paint. When a pressure sensitive paint is applied to the surface of an object to be measured and then irradiated with excitation light such as ultraviolet light, luminescence is produced at a wavelength according to the characteristics of each dye and at an intensity corresponding to the oxygen concentration. By measuring this with a high-speed camera, unsteady pressure can be visualized and measured.

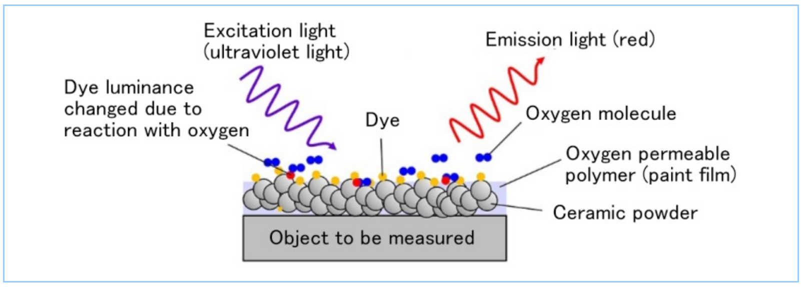

Figure 6 Principle of measurement using pressure sensitive paint

3.2 Measurement setup

Figure 7 shows the measurement part of pressure sensitive paint. The measurement of pressure sensitive paint requires evaluation of the change in luminance from a reference image, and it is therefore more advantageous that the object to be measured remains stationary from the standpoint of measurement accuracy. For this reason, the wall surface of the seal cavity on the casing side was used as the object to be measured. However, the conventional measurement method requires that the pressure acting surface coated with the pressure sensitive paint (the surface to be measured) and the directions of the excitation light irradiation and camera installation coincide, which makes it impractical to measure the narrow inner surface of the seal cavity. Therefore, in this test, we made a modification by optimizing the composition of the pressure sensitive paint and irradiating the excitation light from the opposite side of the pressure receiving surface (i.e., outside of the test equipment) so that measurement with a camera can be performed. The tested seal has five seal cavities: cavity #1 to cavity #5 from the upstream side. Among them, we used cavities #1 and #2, which are strongly affected by the swirling flow and prone to relatively large destabilizing forces, as the cavities to be visualized and measured using pressure sensitive paint.

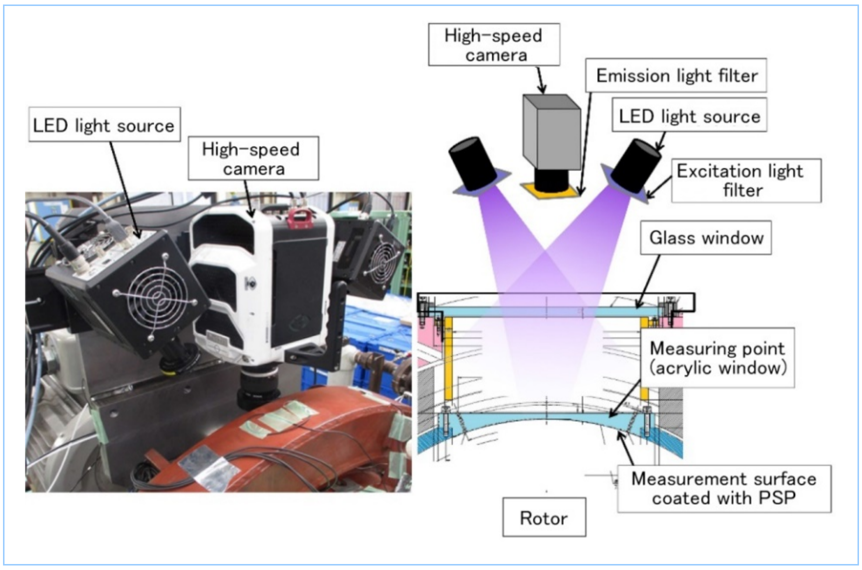

Figure 7 Setup of measurement using PSP

3.3 Measurement result

We installed a small pressure sensor inside the seal cavity to verify the measurement accuracy of the pressure sensitive paint. **Figure 8** compares the result of measurement using the pressure sensitive paint and the result of measurement using the pressure sensor in the excitation test. It is indicated that the level of pressure fluctuation with respect to the vibration frequency is in good agreement between the two. We averaged the result of measurement using the pressure sensitive paint with the rotor displacement phase in order to clarify the relationship between the rotor eccentricity position and the pressure fluctuation due to excitation. In addition, for the purpose of averaging the uneven dispersion of the pressure sensitive paint dye, etc., we averaged and evaluated the measurement results at each measurement position, taking into account the change in rotor phase. **Figure 9** shows the averaging method schematically. **Figure 10** shows the averaged measurement results. The measurement result clearly indicates the mechanism that a high-pressure part of the seal excitation force exists in a phase relationship that contributes to rotor whirling excitation with respect to the rotor eccentric phase, thereby contributing to rotor instability vibration. In addition, highly detailed pressure distributions inside the seal cavity and near the seal fins were obtained, which are data that can be used for comparison with the results of CFD analysis.

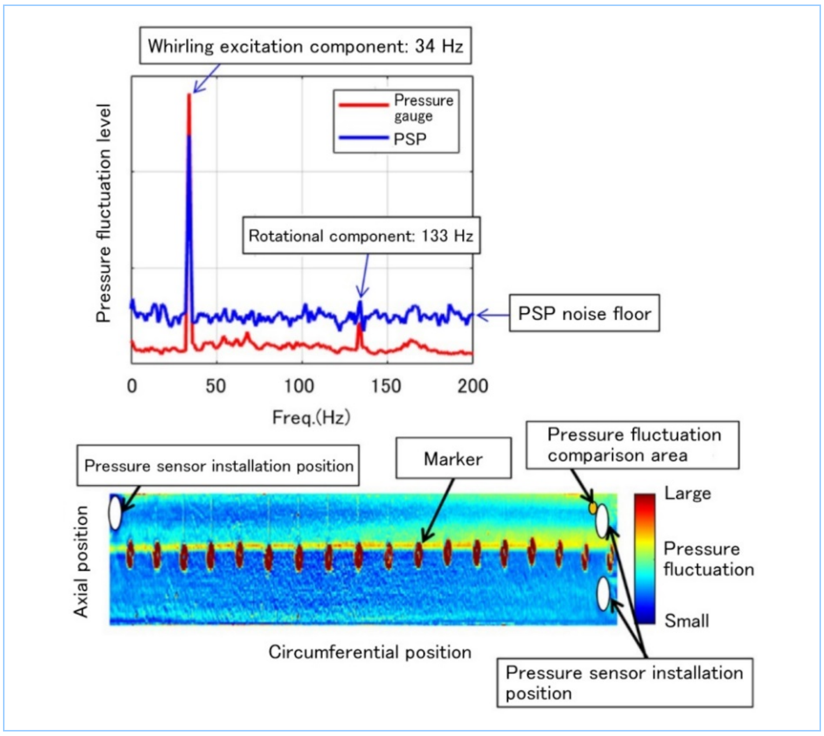

Figure 8 Comparison of pressure sensitive paint and pressure sensor

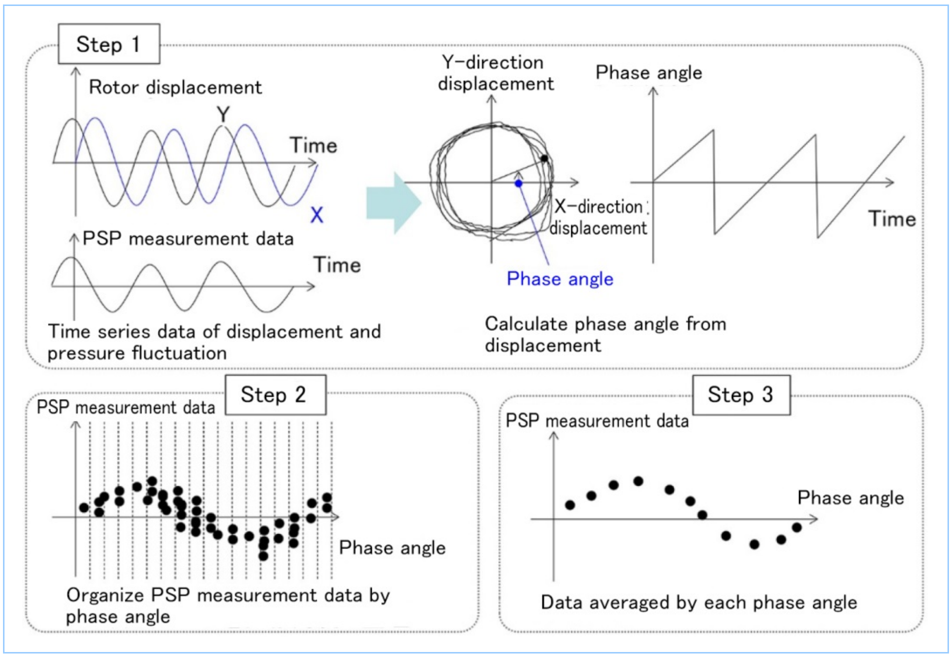

Figure 9 Phase averaging method

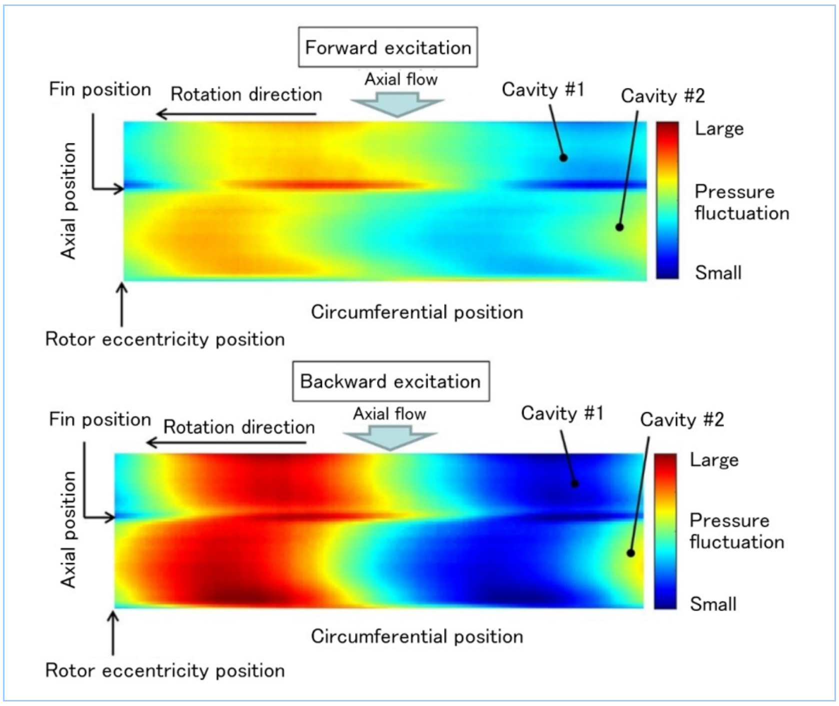

Figure 10 Measurement result after phase averaging

4. CFD analysis and consideration

4.1 CFD analysis

To verify the accuracy of CFD analysis, which is used as a prediction method for seal excitation force, a CFD analysis was used to reproduce and analyze the excitation force measurement test. For the CFD analysis, a steady-state analysis method called the whirling rotor method was used, in which the SST k-ω RANS model was used as the turbulence model, the eccentricity of the rotor was given as the steady eccentricity, and the relative velocity due to rotor rotation speed and whirling excitation was given as the wall surface velocity. **Figure 11** shows the analysis domain. The analysis domain simulates only the rotor disk on one side of the rotational test equipment. The cavities between the disks, the nozzle to simulate swirling flow, and the exhaust channel are modeled with the same dimensions as those of the test equipment. **Table 1** shows the CFD analysis setting.

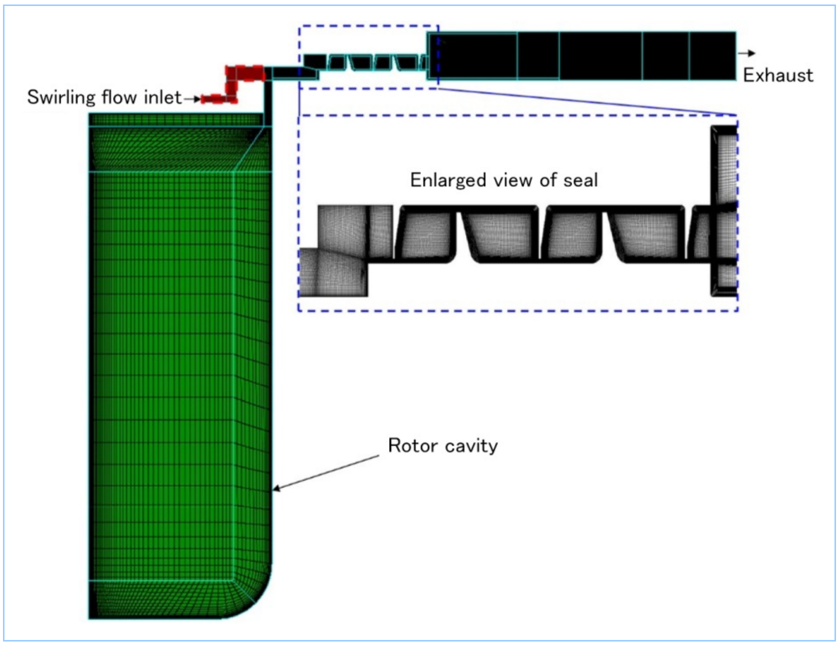

Figure 11 CFD analysis domain

Table 1 CFD analysis setting

		Analysis setting
Calculation method	Solution type	Steady-state calculation (Whirling rotor method)
	Analysis solver	Three-dimensional pressure-velocity coupling
Fluid	Physical property	Air
	Density change	Ideal gas
	Specific heat, viscosity, heat transfer coefficient	Set as a function of temperature
Turbulent condition	Turbulence model	RANS SST k-ω
	Inlet turbulence condition	5%
Wall model		Adiabatic boundary, smooth surface
Eccentricity		10% of seal clearance
Inlet boundary condition		Mass flow rate
Bypass flow boundary condition		Static pressure condition
Outlet boundary condition		Static pressure condition (open to atmosphere)

4.2 Comparison of CFD analysis result and test result

Figure 12 shows the result of CFD analysis and the result of measurement using pressure sensitive paint. First, the trends of the pressure distribution inside the seal cavity are in good agreement between the two. In the result of CFD analysis, the isobars of the pressure distribution tend to bend strongly at the flow separation points, but in the result of measurement using pressure sensitive paint, this tendency is not noticeable. This is thought to reflect the fact that the actual separation is different from that of CFD given that the measurement using pressure sensitive paint also has sufficient spatial resolution. **Figure 13** compares the values of the added stiffness and added damping coefficient values of the seal excitation force calculated from the result of measurement using pressure sensitive paint and those calculated from the result of CFD analysis. Although the trends of the two results are consistent, differences are observed when the levels of added stiffness and added damping coefficient for each seal cavity are compared. The difference between the result of CFD analysis and the result of measurement using pressure sensitive paint is considered to be caused by the reproduction accuracy for flow separation as described above, and it is considered that the accuracy can be improved by optimizing the turbulence model to be used.

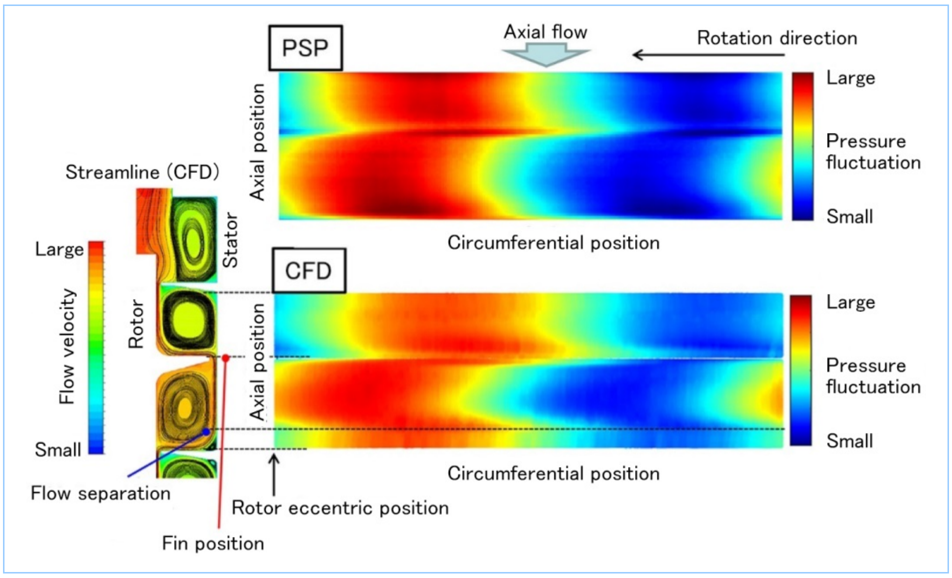

Figure 12　Comparison of result of measurement using PSP (upper) and result of CFD analysis (lower)

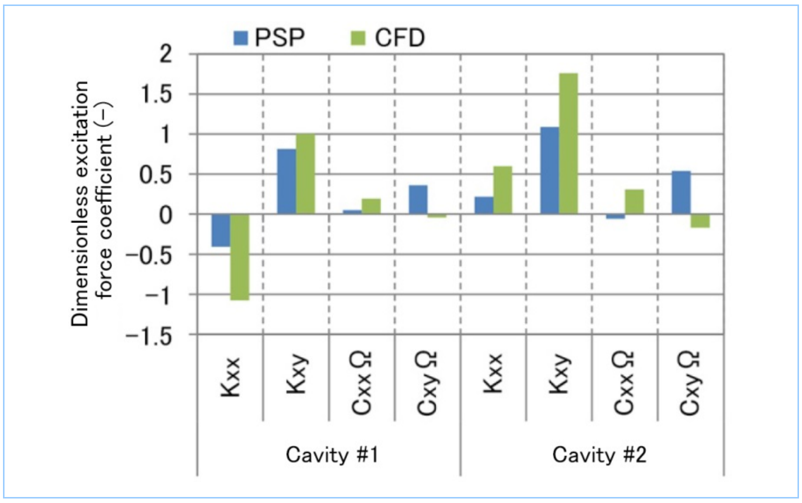

Figure 13　Comparison of excitation force coefficients between result of measurement using PSP and result of CFD analysis

5. Conclusion

To visualize unsteady pressure in narrow sections of rotating machinery, we developed a method of measurement from the back surface using unsteady pressure sensitive paint, and succeeded in measuring unsteady pressure distribution with high accuracy and high definition. Comparing the measurement result with the CFD analysis result, it was found that the global pressure distribution characteristics of the two were in agreement, but the aspects of flow separation points were not. Based on these detailed measurement results, it is possible to realize more accurate CFD analysis, which will be useful for further improving the reliability of rotating machinery in the future. This method can be applied to the visualization of unsteady pressure in other rotating machinery and internal flows, and is expected to contribute to the elucidation of the generation mechanism of fluid excitation forces in various products and to the enhancement of CFD analysis methods.

References

(1) Nishida, S. et al., Visualization of Destabilization Force of Labyrinth Gas Seal Using Fast-Responding Pressure Sensitive Paint, ASME Turbo Expo, GT2021-58893