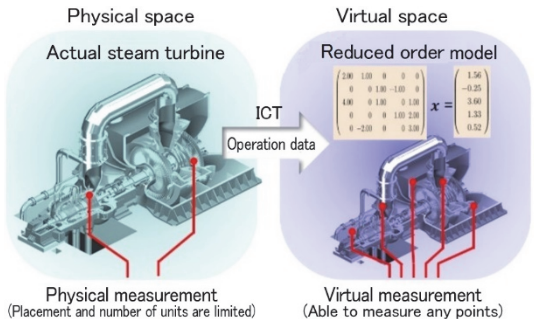
Virtual Measurement Technology for Supporting Flexible Operation of Steam Turbine



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We have been working on the development of virtual measurement technology for predicting the thermal deformation of steam turbine utilizing model order reduction (MOR) technology that enables high-speed and high-precision numerical prediction with mathematical reduction of finite element analysis (FEA) models. This report describes the application of this virtual measurement technology to actual equipment and the realization of real-time prediction of a steam turbine radial clearance with an accuracy comparable to that of FEA. This technology is useful for enhancing clearance management resulting in improvement of performance and safety and is expected to contribute to improving the flexibility of thermal power generation.

1. Introduction

Thermal power generation is now expected to play a role in adjusting the balance between supply and demand of electric power by compensating for fluctuations of variable renewable energy output in addition to supplying electric power. Therefore, rotating machines for power generation (steam turbines and gas turbines) are required to improve in terms of flexibility, such as improvement of the output change rate and shortening of start-up time. However, a change in the output (a change in the operating gas flow rate) affects the thermal deformation of the rotor and the stationary parts such as the outer casing, inner casing, blade ring, etc., as shown in **Figure 1**, so it causes a problem in that the risk of contact between the rotor and stationary parts increases. For this reason, the enhancement of clearance management becomes more important by monitoring the clearance between the rotor and stationary parts in performance and safety improvement. However, physical sensors are limited in terms of their placement and number of units, and as such cannot monitor all high-risk areas. Therefore, we have been working on the development of virtual measurement technology that estimates the radial gap (radial clearance) between the rotor and stationary parts of a steam turbine using a numerical prediction model based on the state quantity (pressure and temperature of the operating gas), which can be measured easily. The purpose of this development is to realize virtual measurement that can predict radial clearance in real time with an accuracy comparable to that of FEA by using a reduced order model, which is obtained by lowering the dimension of the thermal/structural FEA model with MOR, as this numerical prediction model.

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Steam turbine components	Thermal factors of radial displacement
Rotor	Thermal expansion of rotor, Vertical movement due to thermal expansion of bearings and bearing oil film
Internal parts such as inner casing and blade ring	Thermal expansion of internal parts, Linking to vertical movement of outer casing
Outer casing	Thermal expansion of outer casing, Warpage deformation due to temperature difference between upper and lower parts of outer casing, Vertical movement due to thermal expansion of support base

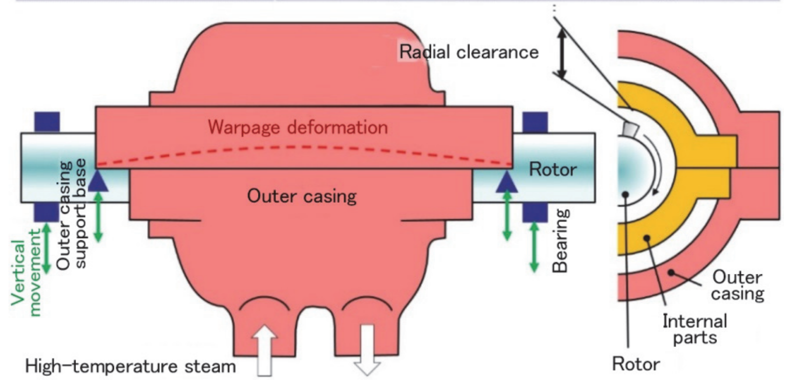

Figure 1 Outline structure of steam turbine
Thermal factors of fluctuation of radial clearance is illustrated.

2. Building thermal/structural FEA reduced order model

In the integrity evaluation at the design and development stage, the radial clearance is evaluated by the following procedures (**Figure 2**(a)): (1) FEA calculation conditions (wall heat transfer coefficient, steam temperature and pressure, rotor centrifugal force, etc.) are set based on operating conditions (steam temperature and pressure at the inlet and outlet, etc.); (2) The unsteady temperature distribution of the steam turbine metal parts is calculated using thermal FEA and the result is used as the thermal load for the structural FEA model to obtain the deformation of the entire steam turbine; (3) The radial clearance at the evaluation time is calculated by adding/subtracting the radial displacement of the rotor and the stationary parts and the separately calculated displacement of the blade, bearing and outer casing support to/from the initial radial clearance value. These evaluation procedures using FEA can obtain accurate results due to precise modeling, but take more than one day per calculation of one case, so they cannot be applied to virtual measurement that requires real-time performance. Therefore, we enabled real-time evaluation to realize virtual measurement by substituting FEA with the reduced order model built using MOR (Figure 2(b)).

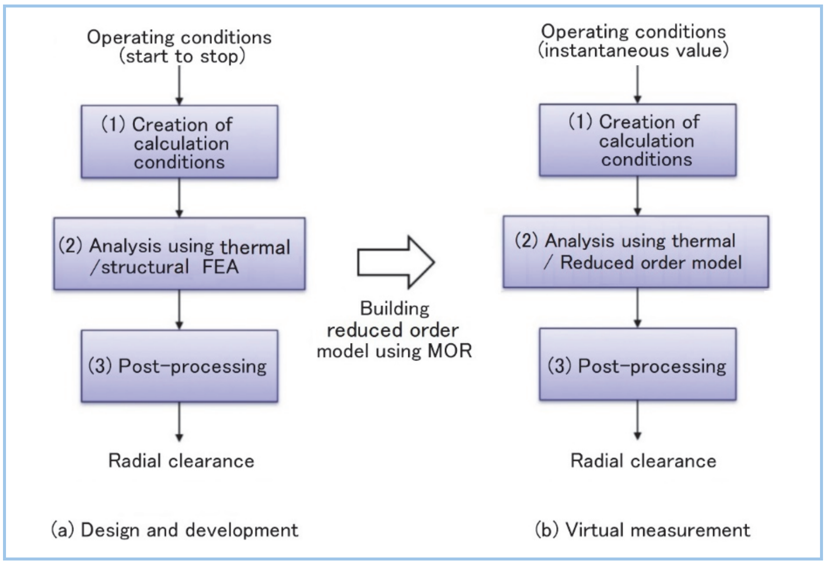

Figure 2 Evaluation method of radial clearance
Radial clearance evaluation procedures using FEA in design and development and modifications therefrom for virtual measurement are illustrated.

For structural FEA, the following descriptions explain the MOR procedure [(1)-(6)] using proper orthogonal decomposition (POD) and Galerkin projection. Galerkin projection is a mathematical method that limits the M-dimensional state space that defines the domain of the governing equation (force balance equation with the displacement as an unknown variable) to the N-dimensional subspace and transforms the problem into N-dimensional one. The solution on this state space is represented by an M-dimensional real number vector and the subspace selected is one that contains a set of actually possible solutions. The specific method for determining the subspace is described below. As shown in **Figure 3**, FEA is performed under various calculation conditions in advance to obtain the solution set (snapshots). Then, the Nth-order truncated singular value decomposition is applied to the snapshot matrix in which these solutions are arranged in columns to obtain the M × N matrix U in which the resulting left singular vectors are arranged in columns. This matrix U is also a projection matrix to the N-dimensional subspace, whereby the desired subspace can be obtained. Here, N is usually much smaller than M.

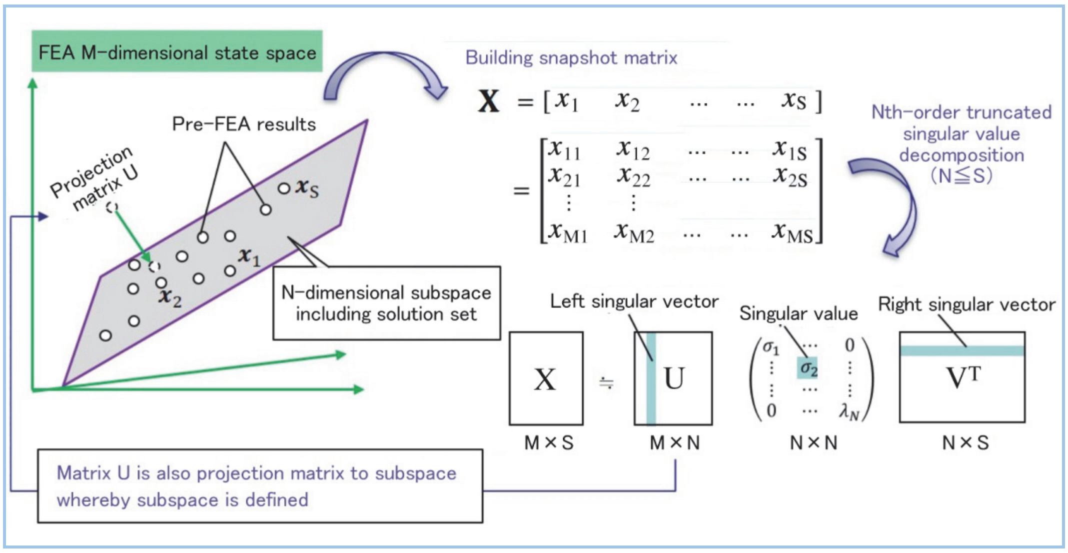

Figure 3 Definition of subspace by POD and Galerkin projection
Method to obtain the subspace used for dimension reduction using pre-FEA results and singular value decomposition is illustrated.

Once the projection matrix U is obtained, the governing equation can be converted into a reduced order model (simultaneous linear equations the number of unknown variables of which is N) by Galerkin projection shown in **Figure 4**. Empirically, a value N of about 100 is sufficient. In this case, by using the reduced order model, the solution can be obtained about 10,000 times faster than the original governing equation. Furthermore, by using the projection matrix, the original variables can be restored from the reduced order model solution.

In the above, the procedure of MOR is explained assuming linearity, but the actual thermal deformation phenomenon includes non-linear phenomena such as temperature dependence of physical properties and radiation (heat transfer problem). In this development, several reduction methods for these non-linearities are also applied to improve the accuracy of the reduced order model.

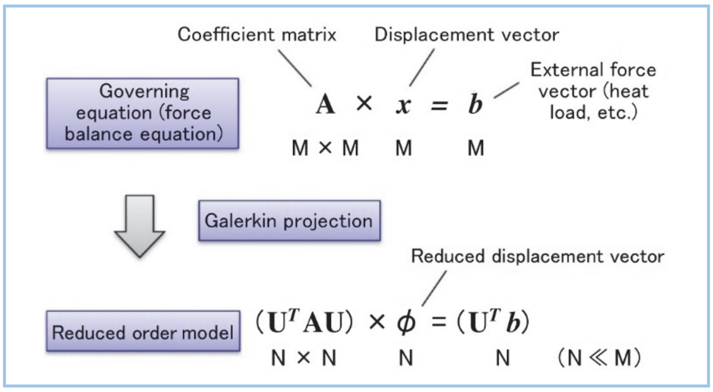

Figure 4 Derivation of reduced order model using POD and Galerkin projection
Method to degenerate force balance equation into low-dimensional model using projection matrix U

3. Mechanism of virtual measurement system

Similar to physical measurement, virtual measurement can be used for monitoring and operation control by displaying the measurement results on the monitoring screen in the power plant, or for remote monitoring using TOMONI™ (trademark of digital solution produced by Mitsubishi Power, Ltd.). In this development, in order to verify the former usage, the virtual measurement system shown in **Figure 5** was constructed in the special measurement room of the combined cycle power plant validation facility (T-Point 2).

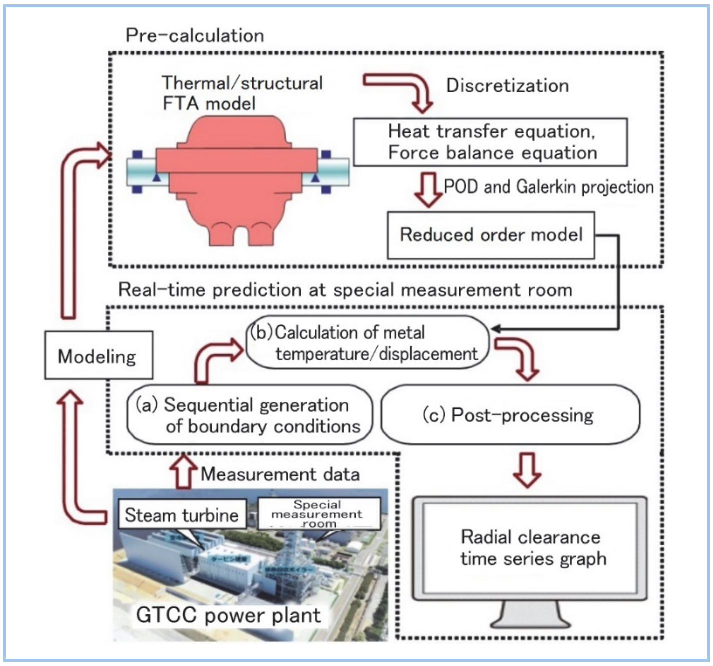

Figure 5 Overview of virtual measurement system
Outline configuration of virtual measurement system installed in special measurement room at T-Point 2 is illustrated

3.1 System configuration and real-time calculation method

This system consists of, corresponding to the FEA evaluation procedures (1), (2) and (3) described in the previous chapter, the following three main modules: (a) Calculation condition creation module that reads operating conditions from the measurement file and creates FEA calculation conditions; (b) Temperature/displacement calculation module that calculates the temperature and displacement of the steam turbine using the thermal/structural reduced order model; (c) Post processing module that processes the calculation results in the same way as the procedure (3) to obtain the radial clearance. This system executes modules (a) and (b) in sequence to update the temperature and displacement state quantities to the latest values when the measurement file is updated and then outputs the clearance results obtained by executing module (c) to the monitor. This is one cycle of virtual measurement processing. The update interval of the measurement file is 1 second and if one processing cycle takes 1 second or more, the measurement file during that period is skipped. Therefore, the output interval of the virtual measurement value is a multiple of 1 second.

3.2 Method for training reduced order model

It is considered desirable to use the FEA results (snapshots) that reflect actual operation as training data of the reduced order model. Therefore, based on the operational data in each start mode of cold, warm and hot specified by the inlet metal temperature at start-up, we created the calculation conditions in module (b) and performed FEA. Using these results, we constructed a thermal and a structural reduced order model which have 80 unknown variables each.

4. Virtual measurement results

At T-Point 2, we verified the real-time property of virtual measurement and its prediction accuracy with respect to that of FEA.

4.1 Real-time property verification results

Figure 6 shows the results of aggregating the number of virtual measurements for each processing time of one virtual measurement cycle. As for one cycle of processing time, 1 second and 2 seconds accounted for 97% of the total (94% in terms of operating time), so it is indicated that virtual measurement results can be obtained with a delay of about 2 seconds with respect to the measured value. Since the change in radial clearance for 2 seconds is small and therefore the time resolution is sufficient, it was confirmed that real-time virtual measurement can be realized.

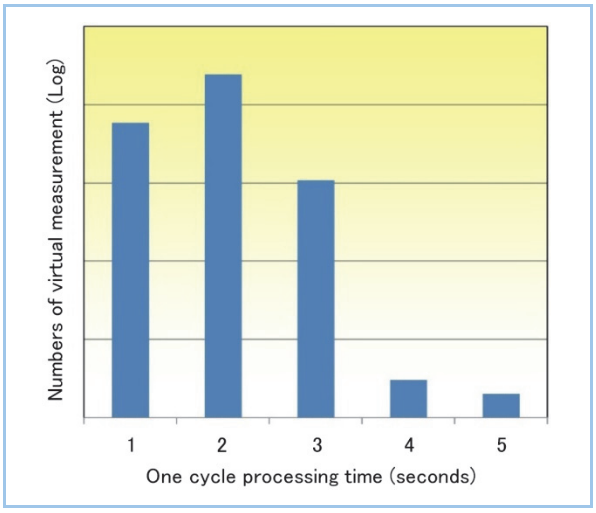

Figure 6 Measurement results of virtual measurement speed
Aggregation results of the numbers of virtual measurement for each processing time of one virtual measurement cycle are illustrated. One second and two seconds account for 97% of the total (94% in terms of operating time).

4.2 Results of verifying prediction accuracy of virtual measurement with respect to that of FEA

In the high-pressure steam turbine of T-Point 2, virtual measurement of the radial clearance during a cold start in the approximate position shown in **Figure 7**(a) was performed with the reduced order model. The same analysis was also performed with FEA and the difference between the two results was calculated. Figure 7(b) shows this difference nondimensionalized by an initial clearance value. From these results, it was confirmed that the difference between the virtual measurement and the FEA is less than 10% and that the reduced order model closely approximated the FEA. Note that the difference tends to be larger after turbine startup, but this difference can be reduced by building the ROM with larger degrees of freedom using more snapshots.

From the above, it has been clarified that virtual measurement can predict the radial clearance in real time with an accuracy comparable to that of FEA.

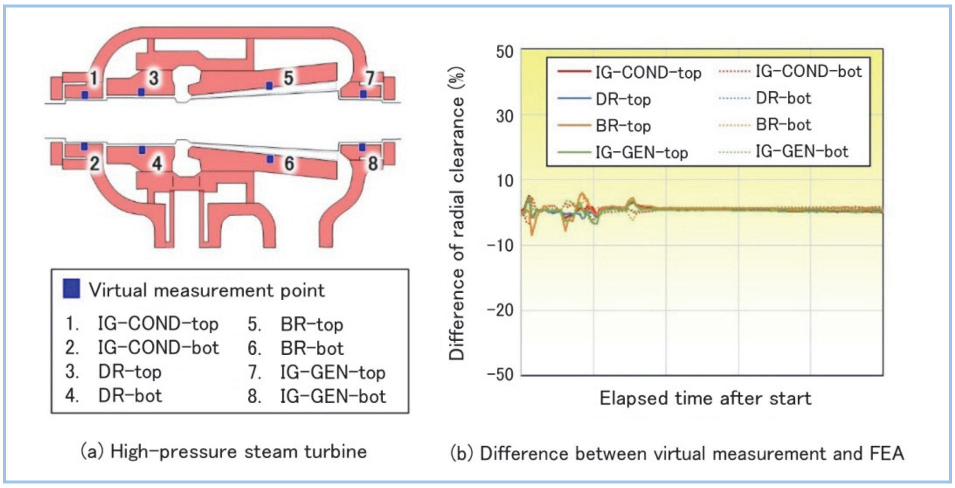

Figure 7 Virtual measurement results of radial clearance
The figure on the right shows the difference of the virtual measurement and FEA results of the radial clearances between the rotor and the internal parts for which the approximate positions are shown in the figure on the left. The difference is nondimensionalized by an initial clearance value. This figure indicates the difference with FEA is less than 10%.

5. Conclusion

In order to support the safe implementation of the flexible operation of steam turbines, we developed a technology for virtual measurement of the radial clearance using the thermal/structural reduced order model using MOR based on POD-Galerkin projection. By performing virtual measurement in the high-pressure steam turbine of T-Point 2, we clarified that the virtual measurement could predict the radial clearance in real time with an accuracy comparable to that of FEA. This technology contributes to the improvement of flexibility such as the improvement of output change rate and shortening of start-up time, and can be applied to the thermal deformation problem of rotating machines such as steam turbines and gas turbines.

In considering future development, it is important for the virtual measurement to improve the prediction accuracy with respect to the actual value in order to use it for operation control. Therefore, we will work on improving thermal deformation modeling and reducing prediction errors. Flexible operation tends to increase rotor stress, resulting in a shorter rotor life, so stricter rotor life management is required to inspect and replace the rotor efficiently. Therefore, we will also work on the development of technologies for virtual measurement of rotor stress and fatigue.

References

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