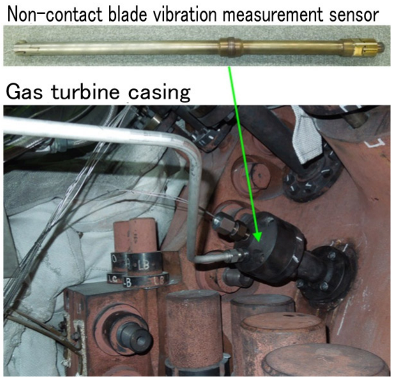
Non-contact Vibration Measurement of the Rotor Blades that Play a Pivotal Role in the Reliability of Gas Turbines



KAZUHIRO TAMURA[*1] MASAKI ONO[*2]
SHUNSUKE TORII[*3] KAZUKI MORIMOTO[*3]

The commercial gas turbines of Mitsubishi Heavy Industries Ltd. (MHI) are not only high efficiency, but also designed based on the data accumulated through component tests and field tests, placing importance also on product reliability to assure our clients the safer and securer use of our products. In particular, the first-stage rotor blades of gas turbines are used in an extremely severe environment, that is, one with high temperature, strong centrifugal force and the greatest load. Therefore, it is important to demonstrate the validity of their vibration characteristics under actual operating conditions, from the viewpoint of blade damage prevention. In order to obtain more data on vibrations of the first-stage rotor blades of gas turbines in the environment of actual use, Mitsubishi Heavy Industries, Ltd. (MHI) has developed a non-contact blade vibration measurement technology that can be applied under high temperature gas conditions.

1. Introduction

In commercial gas turbines, one of the most important components to achieve a higher thermal efficiency is the rotor blades. As these rotor blades are used under high temperature and high load conditions, the most frequently caused damage is fatigue failure or corrosion fatigue resulting from vibrations. Therefore, the requirements for gas turbine rotor blades include not only high performance but also sufficient strength against vibrations. It is crucial to accurately predict their vibration characteristics at the design stage. We have been working to develop more sophisticated blade vibration design technology for gas turbine. As a means of achieving this goal, it is essential to measure the vibration response of rotor blades under actual operating conditions and obtain blade vibration characteristics data to use it as feedback in design. Our design is based on the vibration response data of gas turbine rotor blades obtained by rotational vibration tests (air excitation) in a vacuum chamber and field tests at the demonstration combined-cycle power plant (T-point). Conventionally, the dominant method for measuring the vibrations of gas turbine rotor blades employed a telemeter system by attaching the strain gages directly to the blades. However, while use of telemeters has the advantage of very high accuracy in measurement, the obtained vibration data are only from these gage-attached blades, consequently demanding enormous cost and time if many rotor blades are to be measured. Therefore, we have improved the conventional non-contact blade vibration measurement method (which has been used to measure vibrations of gas turbine compressor rotor blades or steam turbine final-stage blades) and developed a technology that enables the measurement of minute vibrations of gas turbine rotor blades in a high-temperature combustion gas environment. Thus, more vibration data of turbine rotor blades have become obtainable.

This report presents a summary of the developed non-contact blade vibration measurement technology and the results of field tests conducted at the T-point.

*1 Takasago Research & Development Center, Technology & Innovation Headquarters
*2 Chief Staff Manager, Takasago Research & Development Center, Technology & Innovation Headquarters
*3 Takasago Gas Turbine Engineering Department, Gas Turbine Products Headquarters, Power Systems Division

2. Characteristics of the non-contact blade vibration measurement technology

The non-contact blade vibration measurement technology is a technique to analyze vibrations of turbine rotor blades by detecting the timing of a blade passing the sensors (optical, capacitance, eddy current or other) attached to the inner circumference of the casing. When a turbine rotor blade passes the tip of a sensor, it produces a blade-passing pulse signal as shown in **Figure 1**. If a turbine rotor blade does not vibrate, these pulse signals occur at a constant time interval from reference signals. However, when a turbine rotor blade vibrates, these intervals fluctuate. Therefore, a turbine rotor blade vibration can be estimated by obtaining the time difference between these two intervals with/without blade vibrations. Furthermore, because a vibrating turbine rotor blade passes the sensors being fixed on the casing (which is stationary), the vibrating direction of a rotor blade has a significant effect on the measurement accuracy. In other words, the conditions for measurement are most preferable when the vibrating direction of a rotor blade matches the direction it rotates, but these two directions do not always coincide. Before the interpretation of the results, the real amplitude has to be recalculated according to the equation given in **Figure 2**.

The non-contact blade vibration measurement technology is characterized by (1) there being no need for rotor modification because it is a non-contact measurement and (2) the capability of measuring the vibration response of all blades. This technology has been used for quality verification tests of our turbine rotor blades and their reliability demonstration tests under actual operating conditions.

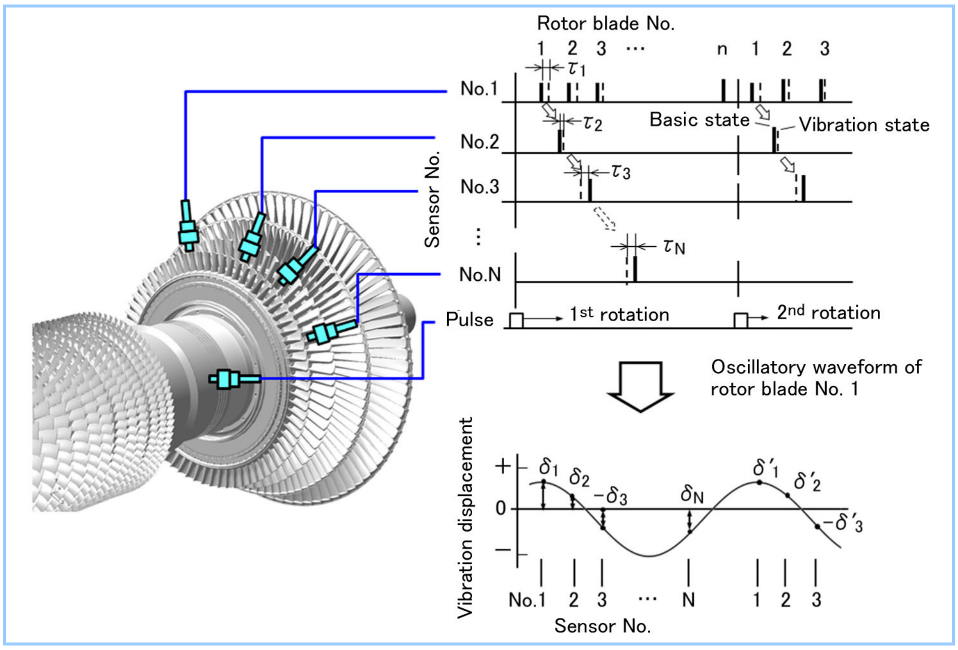


Figure 1 The principle of non-contact blade vibration measurement

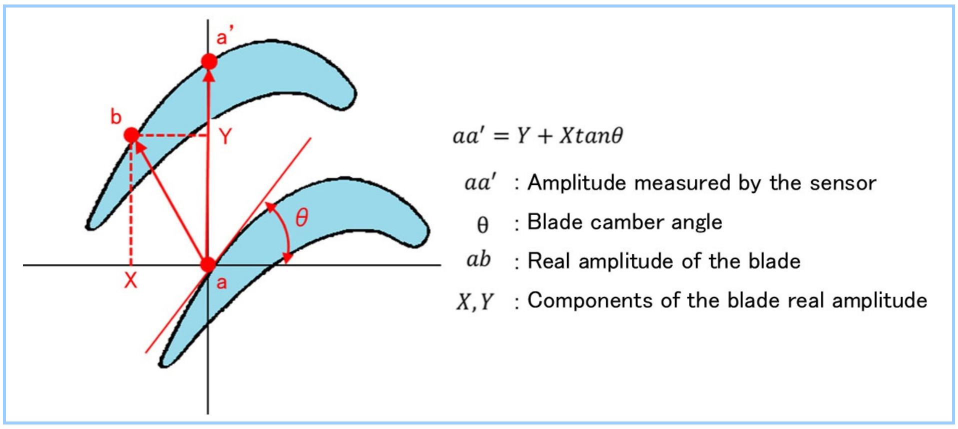


Figure 2 Amplitude obtained by the non-contact blade vibration measurement

3. History of the development of non-contact blade vibration measurement technologies

Figure 3 summarizes MHI's history of developing non-contact blade vibration measurement technologies. As our engagement in the development of this technology originated from the Moonlight Project, it started under the technical guidance of the National Aerospace Laboratory (NAL; currently, Japan Aerospace Exploration Agency or JAXA). Thereafter, we have made original improvements to realize the current standards.

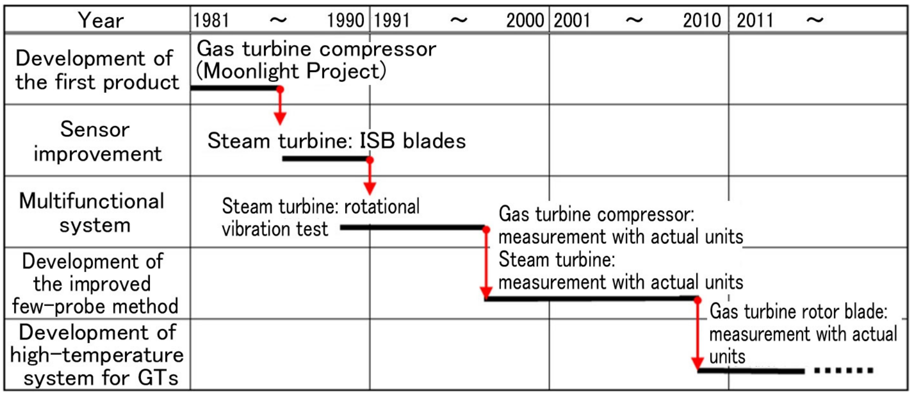


Figure 3 History of the development of non-contact blade vibration measurement technologies

Initially, the non-contact blade vibration measurement technology was adopted for vibration measurement of compressor blades in gas turbines, and optical sensors were employed for the blade sensing. The improvements such as the development of a laser sensor to achieve better optical sensitivity allowed the non-contact measurement technology to be used for rotational vibration tests of integral shroud blades at the final stage of steam turbines. To enable the measurement with actual units, we also developed analytic algorithms such as the improved few-probe method in which fewer sensors are required to measure the vibrations of turbine rotor blades, thus making it also applicable to demonstration tests of steam turbines under actual load conditions (**Figures 4** and **5**). At present, various blade vibration analysis technologies are available, including the multi-probe method, the few-probe method (with single or two probes) and the improved few-probe method. We select an analysis technology that agrees with the measurement purpose, what is measured, and the restrictions such as the number of attachable sensors.

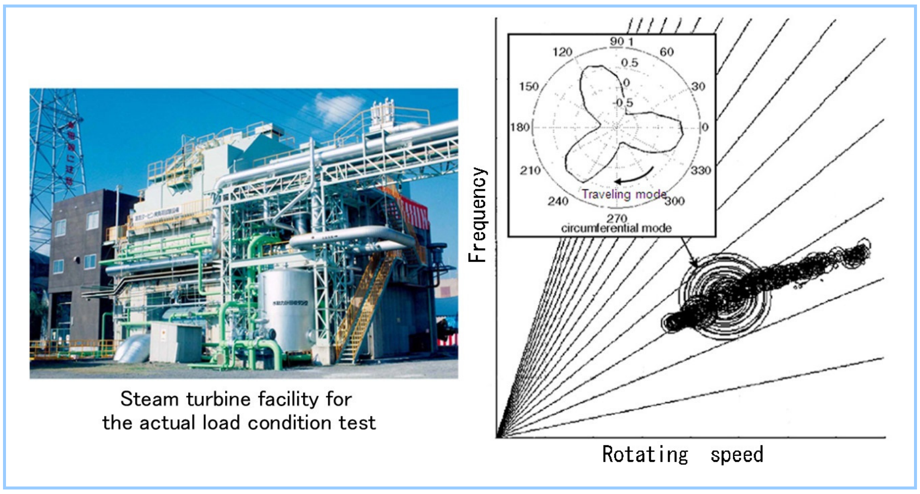


Figure 4 An example of non-contact blade vibration measurements in the actual load condition test on steam turbines

The turbine blades, which have been the target for measurement, exhibit large vibration amplitudes and the sensors used are placed in a relatively low-temperature environment. However, when applying the non-contact measurement technology to the on-site vibration measurement of rotor blades in gas turbines, the following issues have to be addressed:

(1) Requirement of better measurement resolution because of small vibration amplitudes and high rigidity of gas turbine rotor blades;
(2) Measurement in the combustion gas environment
(3) Establishment of a sensor cooling method.

We have enabled blade vibrations in actual gas turbines to be measured, by selecting the sensors suitable for the on-site vibration measurement of gas turbine rotor blades and establishing a sensor cooling method and a signal processing technology. Figure 5 outlines our non-contact blade vibration measurement system.

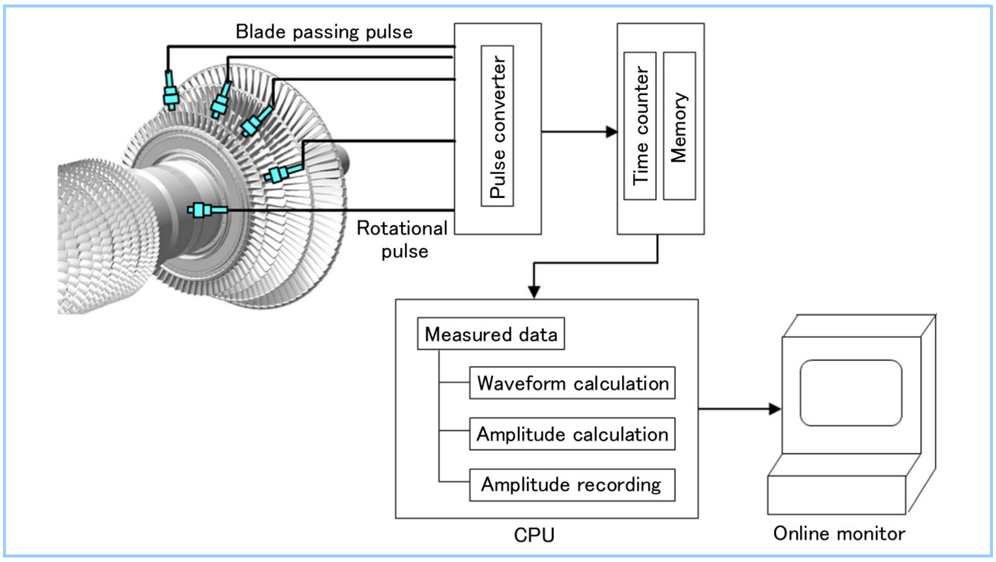


Figure 5 Non-contact blade vibration measurement system

4. Non-contact blade vibration measurement of gas turbine rotor blades under actual operating conditions

Figure 6 is the exterior view of the demonstration combined-cycle power plant (T-point) located within the MHI Takasago Machinery Works. At T-point, the first prototype of our latest gas turbine M501J has been test-operated since February 2011 with the ongoing technical research to realize higher performance in M501J.

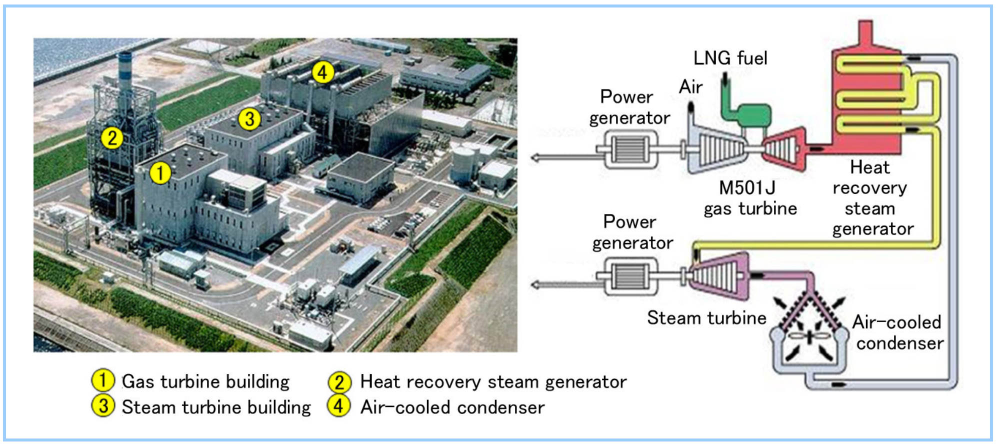


Figure 6 Demonstration combined-cycle power plant at the MHI Takasago Machinery Works (T-point)

In order to improve the design technology for gas turbine rotor blades, we needed vibration characteristics data of rotor blades in gas turbines under actual operating conditions, which were used as feedback in the design. By employing the non-contact blade vibration measurement technology, we have succeeded in measuring the vibrations of first-stage rotor blades of a gas turbine. The use of this technology for on-site measurement can result in cost reductions and a considerably shortened preparation period for measurement, compared with the telemeter measurement with strain gages.

The vibration measurement of gas turbine rotor blades in an environment with a gas temperature of 1,600°C has been enabled by the adoption of air cooling and high-temperature laser sensors with excellent frequency characteristics for detection of the timings of turbine rotor blade passage (**Figure 7**). The smallest possible high-temperature laser sensors were selected to attain better cooling efficiency with use of less air. The axial relative positioning of a sensor and a turbine rotor blade was determined based on the pre-conducted analysis on the vibration modes of turbine rotor blades to allow multiple mode measurements. As an example, **Figure 8** gives the non-contact blade vibration measurement results of the first-stage rotor blades in the M501J gas turbine under actual operating conditions. Such on-site measurements of vibration response of gas turbine rotor blades make it possible to identify the natural frequency of each blade, whereby it becomes possible to assess the blade vibration design while taking dispersed vibration characteristics of each gas turbine rotor blade into consideration.

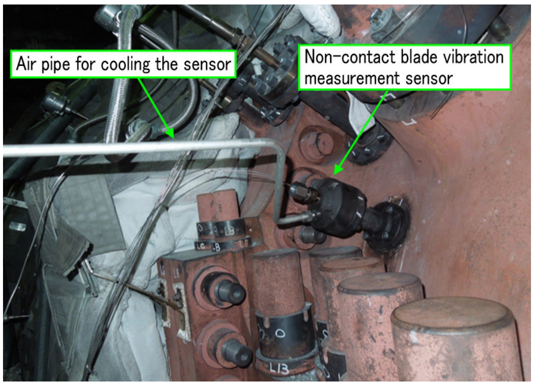


Figure 7 Non-contact blade vibration measurement of gas turbine blade under actual operating condition

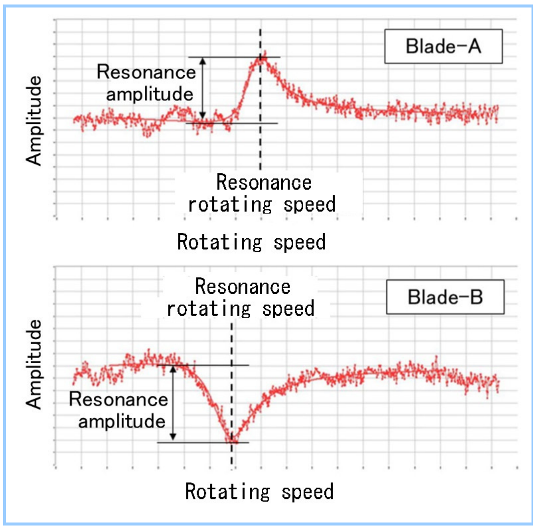


Figure 8 An example of the non-contact blade vibration measurement results of first-stage rotor blades in the M501J gas turbine

5. Conclusion

Rotor blades in gas turbines have a considerable impact on the reliability of gas turbines. We, therefore, examine the vibration characteristics of gas turbine rotor blades of actual units in operation, thereby, improving the blade vibration design technology for gas turbines. In order to obtain more vibration data on rotor blades in gas turbines, MHI worked on the development of non-contact blade vibration measurement technology and successfully conducted turbine rotor blade measurements of actual units in operation. We will further improve the reliability of non-contact blade vibration measurement technology to increase its applications, contributing to even better reliability of our rotary machinery products.

References

1. Hohenberg, R., Detection and Study of Compressor-blade Vibration, Experimental Mechanics, Vol. 7 Issue 6 (1967) pp. 19-24
2. Endoh, M. et al., Noncontact Measurement of Rotating Blade Vibration, (1983), 1, Tokyo, IGTC
3. Umemura, S. et al., Vibration Monitoring by Optical Method for the High Pressure Compressor of GT, 18th Int. Congress on Combustion Engines, (1989), 199
4. Shibata, M. et al., Development of Noncontact Blade Vibration Measuring System, Mitsubishi Heavy Industries Technical Review Vol. 37 No. 2 (2000) pp. 106-109
5. Kaneko, Y. et al., Development of Non-contact Measurement Method of Turbomachinery Blade Vibration: Improved Few-probe Method, Transactions of the Japan Society of Mechanical Engineers Vol. 67 No. 658 (2001-6) pp. 150-156
6. Kaneko, Y. et al., Measurement and analysis of random vibration of steam turbine low pressure end blade, IFToMM (2002)