Development of Reliability Verification Technology for Gas Turbine Rotor Blades Using an Actual Unit

(High-temperature Non-contact Blade Vibration Measurement Technology)

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As an economical and clean thermal power generating facility, gas turbine combined cycle power generation is attracting attention, and the market is expected to expand across the world on a long-term basis. While developing the world's first 1,600°C-class Type-J gas turbine for better performance, Mitsubishi Hitachi Power Systems, Ltd. (MHPS) also proceeded with research for the development of high-temperature special measurement technology that can be applied under actual operating conditions, with a view to obtaining technological evaluation data on newly-developed components and using it as feedback in design. This report introduces our high-temperature non-contact blade vibration measurement technology, which enables the examination of the turbine's first-stage rotor blade vibrations. This technology is applicable to the high-temperature (max. 1,600°C) environment of actual gas turbines.

1. Introduction

Attaining higher temperatures in gas turbines is the key to realizing better performance and efficiency of gas turbines. In the course of improving gas turbine efficiency, MHPS released the large-capacity 1,150°C-class gas turbine (M701D) in the 1980s, and one with a turbine inlet temperature of 1,350°C (M501F) in 1989. In 1997, the applicable turbine inlet temperature was increased to 1,500°C (M501G). In the latest gas turbines (M501J and M701J) that were developed recently, the turbine inlet temperature reached 1,600°C. Such elevation in the temperature can lead to increased thermal stress and lowered fatigue strength of the first-stage rotor blades of turbines, thus resulting in increased vibration intensity. Moreover, recent designs of turbine rotor blades tend to have a high aspect ratio for the realization of better turbine performance, resulting in lower rigidity and as a result, increasing the vibration intensity even more. Therefore, through testing at a power generation demonstration facility, MHPS conducted special vibration measurements of turbine rotor blades under actual operating conditions (high temperature and high pressure) and verified their reliability.

Conventionally, the dominant method for measuring the vibrations of gas turbine rotor blades employed a telemeter system by attaching the strain gauges directly to the blades. However, while the use of telemeters has the advantage of very high accuracy in measurement, the measurement cost is high. Furthermore, as the obtained vibration data are only from these gauge-attached blades, it is impossible to take the variability caused by turbine blades into consideration for design. Therefore, an adequate margin for vibration intensity is included in the design. To design turbine blades with higher efficiency, we have developed a high-temperature non-contact blade vibration measurement technology that enables the measurement of the vibration characteristics of all turbine blades under actual operating conditions at a measurement cost lower than the telemeter system. It is therefore a variation data-based assessment and realizes measurement at a turbine inlet temperature of 1,600°C.

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This report summarizes this newly-developed non-contact blade vibration measurement technology and presents the measurement results when it is applied to an actual gas turbine.

2. Measurement technology for gas turbine rotor blade vibrations under actual operating conditions

The first-stage rotor blades of turbines, which are the critical component to convert fluid energy into mechanical energy, are used in an extremely severe operating environment of high temperature and high load to produce better thermal efficiency. Damage to turbine rotor blades is mostly caused by vibration-related factors such as high-cycle fatigue and corrosion fatigue. Therefore, when developing a new turbine rotor blade, MHPS conducts verification testing through which vibration data on turbine rotor blades are collected to confirm the soundness of turbine blades and design validity.

2.1 Measurement principle of non-contact blade vibration measurement technology

Non-contact blade vibration measurement technology is a technique to analyze the vibrations of turbine rotor blades by detecting the timing of a blade passing by the sensors (optical, capacitance, eddy current, etc.) 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, turbine rotor blade vibrations can be estimated by obtaining the time difference between these two intervals with/without blade vibrations. 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 capacity to measure 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 operation conditions.

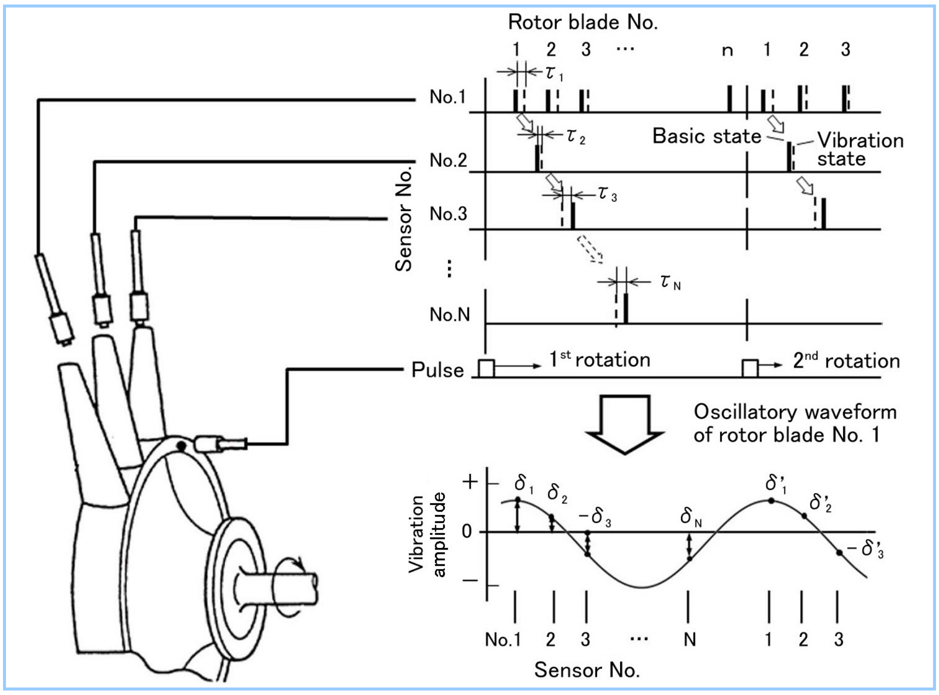

Figure 1 Principle of non-contact blade vibration measurement technology

2.2 Sensor probes used in the measurement of gas turbine rotor blade vibrations

Various types of sensors (e.g., optical, capacitance, and eddy current, etc.) are used in the non-contact measurement of blade vibrations. When the clearance between the tip of a turbine blade and the casing is large (for example, during the start-up of a gas turbine), capacitance or eddy current sensors have difficulty in obtaining signals with a good SN ratio, which affects their measurement of blade vibrations. As a result, we have decided to use optical sensors. However, there is a risk of having the tip of a sensor smeared because of combustion gas or sensor signals weakened because of deteriorated fibers. To prevent signal weakening, cooling air is supplied to the sensors. **Figure 2** shows sensor probes attached to the actual gas turbine.

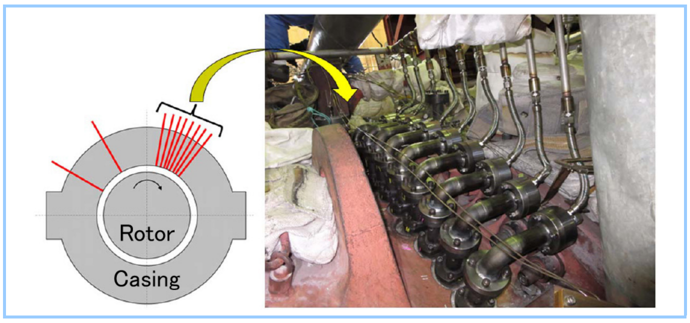

Figure 2 Sensor probes attached to the gas turbine casing

2.3 Data processing in non-contact measurement of blade vibrations

Depending on the type of data processing, non-contact blade vibration measurement technology can be divided into two types: (1) the method in which a small number of sensors are attached to the stationary side and the time difference of a blade passing between the sensors is measured to calculate vibration amplitude (hereafter referred to as the few-probe method) and (2) the multi-probe method in which many sensors are, as noted, also attached to the stationary side and the timing of a blade passing each sensor is measured to obtain the oscillatory waveforms of a blade.

In the few-probe method, at least a single sensor is required to analyze turbine blade amplitude. It is suitable to monitor (for abnormality detection) the vibrations of turbine blades for which sufficient design data was obtained and verification was completed. While the response of pass-through resonance can be measured and evaluated when the rotation speed varies (e.g., during acceleration), it is impossible to accurately measure the synchronous vibration response such as the resonant response when the rotation speed is constant. There are limitations in estimating the vibration frequency even in the case of non-synchronous vibrations. Therefore, since every possible vibratory phenomenon can occur in demonstration tests of newly-developed blades, it is difficult to say that the few-probe method is sufficient to manage vibration measurement and monitoring in such testing.

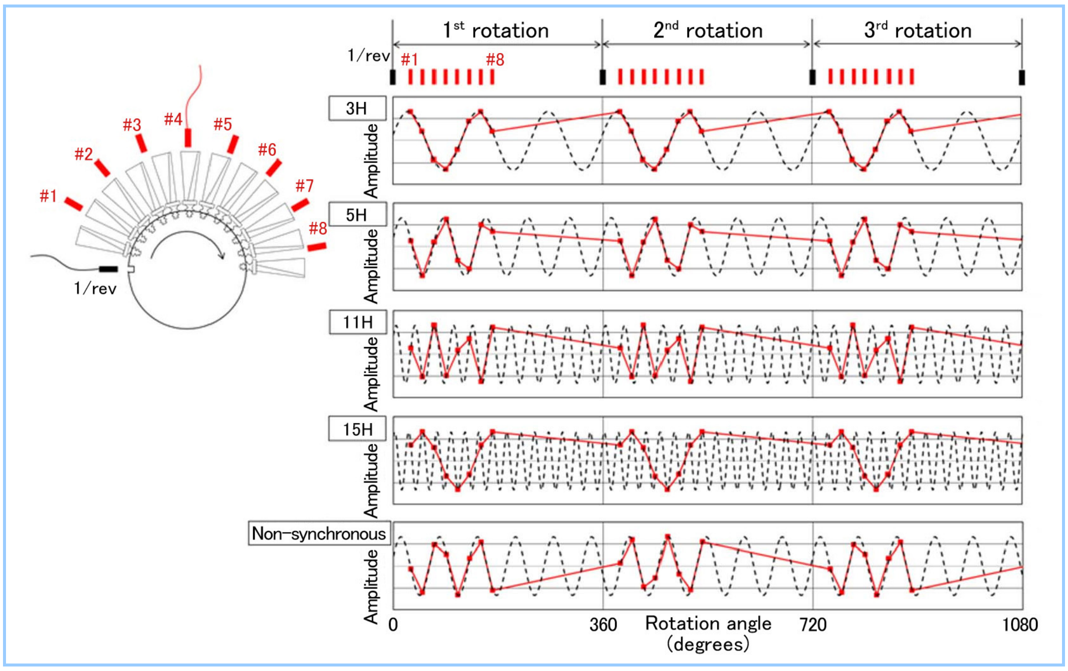

Figure 3 Typical results of non-contact blade vibration measurement (multi-probe method)

On the other hand, in the multi-probe method, the results can be obtained in the form of oscillatory waveforms and the amplitude of either synchronous or non-synchronous vibrations of turbine blades can be measured accurately. The evaluation of turbine blade frequency is also relatively easy. It is therefore desirable to adopt the multi-probe method in demonstration tests of gas turbines with newly-developed blades. **Figure 3** shows an example of a case of non-contact blade vibration measurements (multi-probe method).

The measurement results with the use of a single sensor probe have already been reported in the MHI Technical Review (Vol. 51, No. 1 (2014)). This report presents the results of measurement by multi-probe method, which was conducted with the aim of improving the measurement accuracy.

3. Results of non-contact measurement of blade vibrations using an actual gas turbine

Non-contact blade vibration measurement technology was applied during test operation of the M501J gas turbine at the power generation demonstration facility of our Takasago Machinery Works (T-point). This section presents the results of the turbine's first-stage rotor blade vibration measurement in which optical sensors were used. As mentioned earlier, when using optical sensors during gas-turbine load operation, the measurement of blade vibrations may become impossible because of signal weakening due to smeared sensor tips. The preventive measures we employed include the use of an improved laser source and the air cooling of sensors.

The blade vibrations were also measured consecutively over several days under the high-load operating conditions of gas turbines (turbine inlet temperature: 1,500°C to 1,600°C). The results are shown in **Figure 4**, which indicate that there is no substantial weakening of sensor signals despite the presence of some fluctuations due to the change in clearance between the turbine blade and the casing. Such retaining of signals at a certain level represents the capability of continuously measuring the first-stage rotor blades of gas turbines.

Figure 5 shows the resonant response data results of the turbine's first-stage rotor blades with the increasing rotation speed of the turbine, which were obtained by non-contact blade vibration measurement (multi-probe method). As indicated in the figure, the response of pass-through resonance is clearly measureable. The frequency analysis of blade vibrations during resonant response has also become possible.

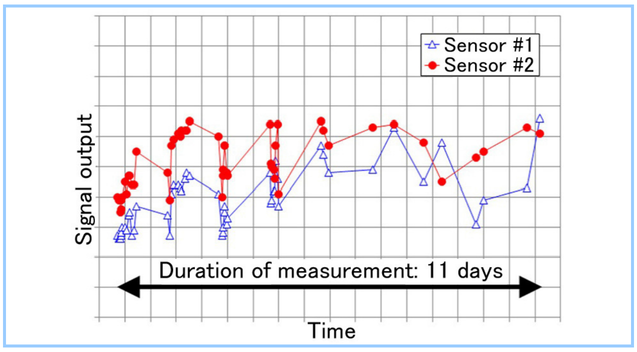

Figure 4 Change in sensor signal output over time

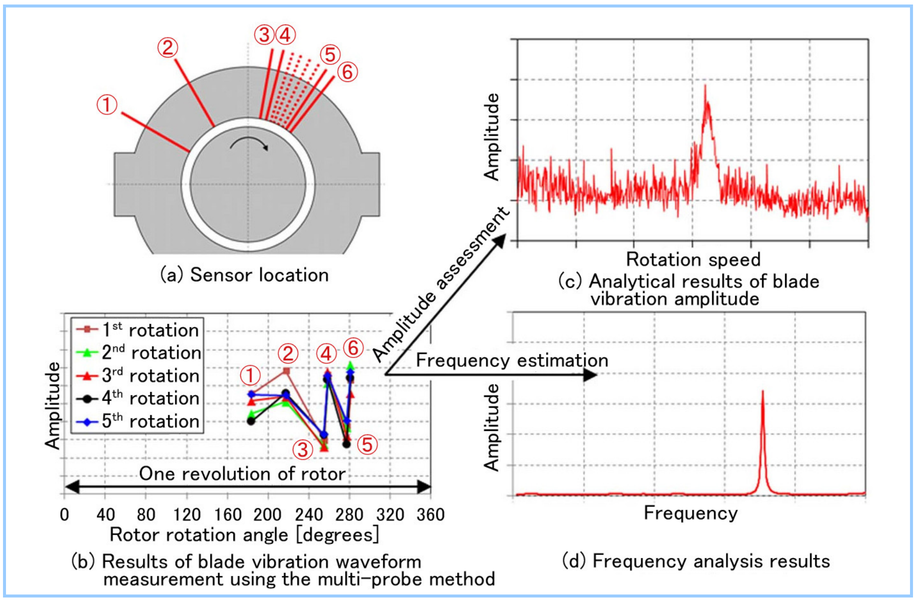

Figure 5 Results of non-contact blade vibration measurement of the turbine's first-stage rotor blades (multi-probe method)

Figure 6 presents the vibration response results of non-contact blade vibration measurement (multi-probe method) on the turbine's first-stage rotor blades under varying load operation conditions. As a reference, the same measurement was conducted using strain gauges (telemeter system) on a different day. The results show that the values of strain gauge estimation are more or less within the variation range of the non-contact blade vibration measurement results, despite the considerable fluctuation resulting from the measurement of the vibration response of all blades. For non-contact blade vibration measurement technology, therefore, the vibration measurement accuracy during load operation has been confirmed.

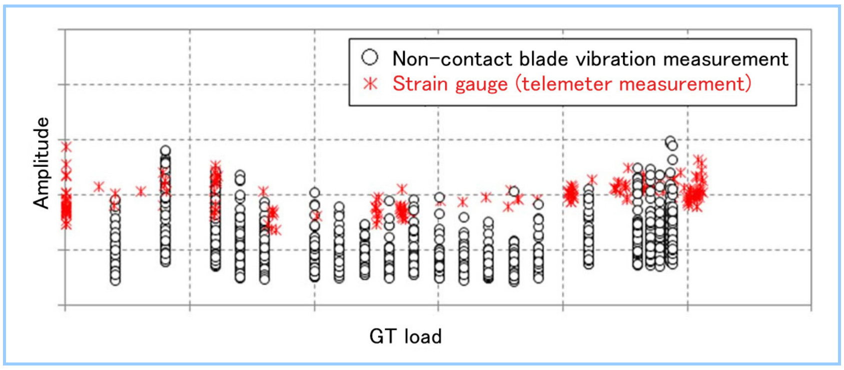

Figure 6 Accuracy verification results of blade vibration measurement during load operation

4. Conclusion

As the performance and output of gas turbines are improved, the vibration intensity of turbine rotor blades increases, making the design more demanding. To attain better reliability of turbine rotor blades, it is very important to properly interpret the data on turbine rotor blade vibrations in the high-temperature environment of actual units and utilize it in design. MHPS has developed a high-temperature non-contact blade vibration measurement technology that can be applied at a turbine inlet temperature of 1,600°C. It has been employed in the measurement of the turbine blade vibrations of our latest M701J gas turbine, thus contributing to the the verification of the reliability of our new products.

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