Noncontact Vibrational Measurement Technology of Steam Turbine Blade*

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One of the important ways to increase reliability of a power plant is to measure the vibration of steam turbine blades during operation. The measurement of the rotating blades is usually executed by a strain gage; however, since the turbine has multiple stages, it is generally difficult to attach the strain gages to the rotating blades and obtain signals from the gages, especially in the intermediate stages. Furthermore, gages and wiring must endure high centrifugal force of rotating blades, steam pressure, and moisture in the turbine under operation. This paper presents noncontact measurement technology which measures the vibration of the steam turbine blades during operation using a laser beam installed in a stationary casing. Furthermore, this paper delineates technical problems in the measurement of the steam turbine blades, such as the severe environment in which light is irregularly reflected, the durability of sensors, and small amplitude due to the shroud blade.

Key Words: Vibration of Rotating Body, Rotor, Mode of Vibration, Vibration, Measurement

1. Introduction

One of the important ways to increase reliability of a power plant is to measure the vibration of rotating blades in steam turbines under operation. The usual measurement method for this purpose is to lead the strain gage signals to the stationary side through a slip ring or a telemeter. However, a hole is required at the center of the rotor shaft for installation of lead wires when the slip ring is used, and the problem of securing a source of electric power must be solved when the telemeter is used. Furthermore, it is important to secure installation and protection of long lead wiring under severe conditions such as high centrifu-

gal force during operation, drain due to moisture from steam, and high temperature. In addition, it is usually difficult to install lead wiring in the intermediate stages of the blading path. In order to cope with such problems, a noncontact measurement method which measures the vibration of rotating blades under operation using a laser beam sensor installed in the turbine casing has been developed. The location in the stages of rotating blades is not especially restricted in measuring since measurement is performed from the stationary side. However, since the rotating blades of a steam turbine operate in steam atmosphere, measurement is carried out in a severe environment in which the laser beam is subject to irregular reflection, and the durability of sensors is decreased. Furthermore, many blades have a shroud at the blade tip, therefore measurement is difficult due to small measurable amplitude. This paper discusses the problems of noncontact measurement of the vibration of steam turbine blades under operation and introduce examples of results of measurement with the same sensitivity as measurement by strain gage.

A comparison of the conventional method using strain gages and the noncontact measurement method

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Table 1 Comparison of vibration measurement methods for steam turbine rotating blade

Item	Noncontact	Strain Gage	Remark
Measured Blades	All blades	Gage-attached blades	---
Frequency Vibrational Mode	Fundamental frequencies & modes	Entire range	Increase of the number of sensors is necessary to measure higher frequencies in the case of noncontact method.
Vibrational Stress	Calculated from vibrational deflection	Direct Measurement	Vibration analysis is necessary to obtain vibrational stress from measured deflection.
Accuracy of Measurement	Measurable minimum deflection: 0.01~0.02mm	Measurable minimum strain: about 10 μ strain	A strain 10 μ is usually evaluated at blade tip deflection of 0.01~0.02mm but this value varies according to blade shape.
Maximum Temperature	350°C	600°C	Higher-temperature measurement will be possible by using the assemble bond with higher maximum temperature.
Measurement Duration	Nonrestriction	1~2 weeks	1) Telemetry measurement is restricted by battery lifetime. 2) Telemetry slip ring measurement are restricted by strain gage and wiring lifetime.
Location of Sensor	Stationary casing	Rotating blade	Wiring is extremely difficult in the case of intermediate-stage rotating blades.
Cost of measurement system	Expensive	Low cost	

is shown in Table 1.

2. Principle of Measurement

Several optical fiber sensors are circumferentially arranged on the turbine casing near the blade tips and pulse signals are generated when each blade passes over a sensor. Utilizing the time difference in generation of such pulse signals for vibrating blades and non-vibrating blades, the vibration of blades is measured. Figure 1 shows this principle. Many papers concerning this principle and examples of application have been reported⁽¹⁾⁻⁽³⁾. However, there are many problems to be solved in the measurement of vibration of the steam turbine under operation and measurement in the actual steam turbine entails various difficulties.

In this measurement method, the time when the rotating pulse signal is generated is defined as reference time and the time when each blade tip passes over each sensor is measured. Circumferential speed of the blade tips is over 500 m/s in the high-speed and large-diameter steam turbine, and measurement accuracy of 0.1 to 0.01 μ s is required to measure vibrational amplitude including minute amplitude (roughly 0.05 mm in measured deflection), that is, measured vibrational deflection is defined by the following equation.

$$\delta_{ij} = \tau_{ij} \times \text{Circumferential speed of blade tip} \quad (1)$$

where, $i=1, 2, 3, \dots, n$ (Number of blades or number of shrouds)

$j=1, 2, 3, \dots, N$ (sensor number)

Fig. 1 Principle of measurement

δ_{ij} : Deflection of blade or shroud

τ_{ij} : Measured time difference caused by deflection of blade or shroud

Accuracy of measurement for vibrational amplitude is governed by accuracy of measurement for time difference τ_{ij}

Furthermore, since the vibrating blades pass over the sensor row fixed on the turbine casing, vibrational direction is closely related to measurement accuracy. When the vibrational direction is the same as the direction in which blades pass (circumferential direction), the optimum measurement can be made. However, as shown in Fig. 2, the vibration of blades is not necessarily in such a direction. Consequently it is

necessary to convert measured amplitude to the actual amplitude by the following equation.

$$aa' = Y + X \tan \theta \quad (2)$$

Where,

aa' : Measured amplitude by sensor

θ : Camber angle of blade

ab : Actual amplitude

X, Y : Components of actual amplitude

Therefore it is required to obtain vibrational characteristics of the blade such as natural frequency, vibrational mode, and vibrational stress in advance, and the actual amplitude should be evaluated by analysis using the finite-element method(FEM).

3. Types of Steam Turbine Rotating Blades

The steam turbine rotating blades are classified into the following types by structural shape.

- (1) Free-standing blade... Free-standing blade
Integral shroud blade
- (2) Grouped blade... Lashing wire welding blade
Tenon shroud blade

Figure 3 shows these typical shapes. The vibrational characteristics are completely different depending on the structures. Grouped blades jointed at the middle part of the blade with lashing wires are generally long blades and usually have large amplitude in resonance or random vibration. Free-standing blades are also comparatively long blades in many cases and the amplitude inevitably becomes large. Large amplitude is extremely favorable in terms of measurement. A tenon shroud blade which is jointed with a shroud by tenon revetting is widely used in the intermediate-stage rotating blades of a steam turbine. Figure 4 shows the vibrational modes of the tenon shroud blade. In consideration of the principle of measurement which measures the deflection of the rotating blade passing below the sensor, the larger the amplitude in the rotational direction is, the easier the measurement. Most of the vibrational modes of the

tenon shroud blade have small amplitude in the rotational direction and large amplitude in the axial direction. Furthermore the absolute value of the amplitude decreases with smaller blade height. Therefore it is more difficult to measure the amplitude for the tenon shroud blade compared with other blade shapes.

It is also difficult to measure amplitude for the integral shroud blade for the same reason, since the vibrational mode usually has relatively large amplitude in the axial direction.

4. Measurement System

Requirements for the measurement system for the steam turbine rotating blade, in particular the blade with shroud, are summarized as follows.

(1) Requirements for sensor

<1> Highly sensitive responsiveness so as to be able to measure the deflection of blades at high-speed rotation.

<2> Distance between shrouds is 1 to 2 mm. A trigger should be applied between shrouds. Therefore the beam spot diameter from the sensor is required to be less than the above distance.

<3> The distance between the casing and rotating blades is usually as wide as 10 to 15 mm. Measurement must be possible over this distance.

Fig. 3 Shapes of steam turbine rotating blades

Fig. 2 Relation between blade vibration mode and measured amplitude

Fig. 4 Vibrational mode of shroud blade

<4> The sensor is required to be airtight and heat-means permanent hyphen resistant, since the high-pressure stage is at high pressure and high temperature and the low-pressure stage is at low temperature and near-vacuum.

<5> Since measurement is carried out in the steam atmosphere, the sensor is required to have sufficient resistance to corrosion.

<6> Sufficient light is required so that measurement can be carried out even amidst water droplets.

Table 2 shows the investigation results of sensor functions considered so far for these requirements, and it has been concluded that only laser light with lens can satisfy these requirements. Figure 5 shows the details of the sensor tip part which can satisfy all the requirements. The following are the specifications of this sensor.

<1> The sensor is 2 mm in diameter and equipped with a lens with focal distance of 5 to 12 mm.

<2> Focus spot diameter is 0.2 mm.

<3> Sapphire glass at the top of the sensor is used to maintain airtightness and erosion resistance. Maximum operating temperature of the sensor of up

to 350°C can be achieved by selection of adhesives.

<4> In order to be able to carry out measurement even amidst water droplets, a 40 mW laser light source is used and the transmitting quartz fiber is arranged so as to be surrounded by receiving quartz fibers.

Perpendicularity of reflection angle and measured object surface is important for effectively receiving the reflected light from the measured object. Figure 6 shows the test results for perpendicularity. It is concluded from this figure that when the setting angle of the sensor is within $\pm 2^\circ$ in squareness the same reflected light as in the case of $\pm 0^\circ$ in squareness can be obtained. Furthermore, sharpness in the corner part of the shroud end face is also an important factor for measurement accuracy. Figure 7 shows the investigation results for sharpness. When the corner part is not sharp, but somewhat round, rise of pulse signals becomes slow, resulting in error of measurement. Therefore it is desirable to finish the shroud end face to be as sharp as possible.

(2) Requirements for data processing unit

The laser signal obtained from the sensor is

Table 2 Comparison of sensor characteristics

Sensor	Lift off mm	Response	Sensor Spot Diameter mm	Decision
Laser Light (With Lens)	15	0.01 μ s	0.2~0.4	OK
Laser Light (With out Lens)	2	0.01 μ s	2~4	NO
Electromagnetic	5	20 μ s (50Hz)	10~30	NO
Eddy Current	3	10 μ s (100Hz)	10~30	NO
Electrical Capacity	2	3 μ s (300Hz)	10~30	NO
Requirement of Steam Turbine Blade	10~15	0.1~0.01 μ s	0.5~1

Fig. 5 Details of optical sensor tip portion

Fig. 6 Relation between sensor mounting angle and reflection output

Fig. 7 Example of reflection output in shroud blade

Fig. 8 Outline of measurement system

converted to the voltage signal by an optical-electric convertor and is digitally processed. The requirements for the data processing unit are as follows.

< 1 > Vibration amplitudes as small as 0.01 - 0.02 mm must be measured. For this purpose measuring speed should be increased so that measuring time difference is 0.01 to 0.02 μ s (100 to 50 MHz) according to the relation shown in Eq. (1).

< 2 > In order to measure the vibrational modes, the number of channels should be as high as possible.

< 3 > On-line processing can be performed.

< 4 > The computer must have sufficient capacity and operation speed to process increasing data with higher speed.

Figure 8 shows the outline of the unit meeting these requirements. Increase in speed of signal processing for 1 - 2 channels can be achieved without any problem; however, in the case of multiple channels, it is essential for avoiding time lag among channels to use equal lengths of wiring in the processing circuits of the signals from each sensor.

5. Examples of Actual Measurement

5.1 Lashing wire welding blade

The measurement results of a 3 600 rpm 1 000-mm-length class low-pressure turbine end blade with 4 blades per group connected by three lashing wires are shown. Circumferential speed of the blade tip can exceed 700 m/s. The measurement has been made using the actual loading test facility for a steam turbine shown in Fig. 9.

Sensors are circumferentially installed at seven points as shown in Fig. 10 and also strain gages are attached to the blades and the signals are output through a slip ring.

In the actual loading test facility, the turbine is

Fig. 9 Actual loading test facility for steam turbine

Fig. 10 Mode X vibrational wave of 4 blades per group

operated by steam of normal pressure and temperature and the same steam flow as in the actual turbine is supplied. The turbine output is absorbed by a liquid water dynamometer. Conditions such as resonance of the rotating blade can be easily set since the turbine revolution can be varied.

By marking the blade resonate in the third mode (mode X), comparison of noncontact measurement with strain gage measurement has been attempted. Figure 10 shows the third vibration mode obtained by noncontact measurement. The sensors are installed at seven points on the upper half portion of the turbine casing and amplitude data at seven points can be obtained in one revolution. Clear resonance amplitude can be measured due to the large amplitude of the long blade. As the type of this blade is the grouped blade which consists of 4 blades per group, blade No. 7 is the leading blade and blade No. 4 is the trailing blade. The symbols enclosed by circles in the figure show the amplitude measured by each sensor. After blade No. 7 passes the sensor, blade Nos. 6, 5 and 4 pass the same sensor in that order. As a result time lag occurs when each blade reaches each sensor. Therefore the waveforms of each blade in Fig. 10 exhibit this phenomenon, being more advanced forwards the right-hand side. Since all blades per row can be measured by this noncontact measurement method, the measurement results for all blades in a row are shown in Fig. 11. These results are plotted together with the results obtained by strain gage. Since the signal of a strain gage represents stress, the results measured by strain gage are converted to amplitude, considering phase and the analysis by FEM. By this comparison it is found that the results of both measurement methods show good agreement.

5.2 Integral shroud blade

An example of measurement results for the integral shroud blade which have been measured in the above-mentioned actual loading test facility is given. Figure 12 shows the blade relevant to measurement. This is a rotating blade of 3 600 rpm 600-mm-length class low-pressure turbine end. Twist-back motion of the blade is caused by centrifugal force generated by

Fig. 11 Circumferential mode at resonance

rotation and this motion causes all blades to joint by contacting each other at the interlocked surface of the shroud. In the integral shroud blade, the upper surface of the shroud viewed from the sensor is flat. Therefore the gap between shrouds shown in Fig. 12 can be used to measure vibration of each blade.

This gap between shrouds is as narrow as 1 mm during rotation; however, measurement is possible due to the laser light focus of 0.2 to 0.4 mm. In this measurement strain gages are also attached to the blades for comparison with noncontact measurement. Figure 13 shows the results of the blade frequency measured by strain gages. It is confirmed that the first mode has the resonant point in the vicinity of 3 300 rpm.

Figure 13 also shows the results of the amplitude measured by noncontact measurement when rotation speed is varied. Since the peak is obtained in the vicinity of 3 300 rpm, which is the same as the results of the Camble diagram obtained by strain gage, this peak is determined to be resonance. This figure shows that the amplitude tends to increase with increase in

Fig. 12 Integral shroud blade

Fig. 13 Vibrational measurement results of integral shroud blade

rotation. The reason for this phenomenon is that the blade is deformed as shown in Fig. 14 with change in rotation speed and the measuring positions are changed, therefore apparent deformation is measured. Since this amplitude is not a vibration component but is a static deformation component, it is important that the total deformation be separated into dynamic and static components in data processing.

Fig. 14 Deformation of shroud due to rotation

Fig. 15 Vibrational analysis results by FEM of 6 shrouded blades per group

<Sensor Arrangement>

5.3 Tenon shroud blade

Vibrational measurement of a tenon shroud blade in the intermediate stage was carried out in the actual turbine under operation at the power plant. The measured blades are 3 600 rpm, with blade length of 380 mm and comprise 6 blades per group. The peripheral speed at the blade tip is 500 m/s. Figure 15 shows an example of FEM analysis of the measured blades, and the vibrational mode is the third mode(mode X). Before measurement, the guide tubes are installed in the turbine casing when the turbine is overhauled and for measurement the sensors are inserted into the guide tubes. As shown in Fig. 16 the sensors are arranged so as to measure the resonance of the higher-order vibration as well. Figure 17 shows the sensor arrangement. Shroud end faces are used as triggers. Since the measurements are carried out under turbine operation, large changes in the operating conditions such as change in rotational speed cannot be controlled, but vibration of the blades corresponding to the change of turbine loading, exhaust vacuum, and steam temperature, has been examined. The measurement results are shown in Fig. 18(a). The blades

Fig. 17 Sensor setting condition

<Expected Vibrational Wave>

Fig. 16 Sensor arrangement and expected vibrational wave

Fig. 18 Vibrational measurement results of steam turbine rotating blades during operation

scarcely vibrate due to constant-loading operation of the turbine. Figure 18(b) shows an example of measured deflection with the change of turbine exhaust vacuum. Since the sensor positions supported by the guide tube are moved by the deformation of the turbine casing due to the change of vacuum, the apparent deformation can be observed. Therefore observation is made as if vibrational value increases, but it is found that when this static deformation component is separated, hardly any vibration component remains.

It was confirmed by these measurement results that measurement of the minimum amplitude of 0.01 mm to 0.02 mm was attained in the actual turbine under operation and that vibration of the shroud blades could be accurately measured.

It was also confirmed that although measurement was made over a long period, the seal glass of the sensor remained intact and had sufficient durability.

6. Conclusions

By applying noncontact measurement from the stationary side to measure vibrational characteristics of steam turbine rotating blades and by considering factors involved in measurement and data processing, the following measurements have been realized.

(1) In the case of vibrational measurement of long lashing wire welding blades, the results of the noncontact measurement agree well with the results measured by strain gage.

(2) Since measurement of the minimum ampli-

tude of 0.01 mm to 0.02 mm has been attained, vibration measurement of the shroud blades has been realized.

(3) Establishment of a trigger has been realized for shroud clearance of around 1 to 2 mm by appropriate setting of developed focused sensors.

(4) Even when the distance from sensor to blade tip is as wide as 10 to 15 mm and sensors are in a steam atmosphere, which entails drain, etc., measurement has been realized and the sensors exhibited durability.

Furthermore, measurement of the vibrational condition for the rotating shroud blades in the intermediate stages of a steam turbine, which is difficult using the contact measurement method with strain gages, has been realized.

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