FEASIBILITY STUDY OF ROTATING BLADE HEALTH MONITORING USING BEARING PEDESTAL ACCELERATION SIGNAL

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ABSTRACT

This paper describes the feasibility study on the technique of detecting the abnormalities of a rotating blades with the acceleration at bearing pedestal as on-line health monitor of a turbine rotor blade. It checked that FEM analysis estimated the bearing pedestal acceleration response at the time of blade excitation, and an acceleration response detectable with a general-purpose accelerometer was obtained in it for the high-pressure-stage blade of a steam turbine at a bearing pedestal. Next, we carried out the rotational vibration examination test with a test rotor. In this test, for 1 blade of the ISB(Integral Shroud Blade) groups, the both ends of a shroud are deleted and made isolated-blade condition, the air vibration test was done, and the bearing pedestal acceleration at the time of isolated-blade resonance checked that it could detect more highly (about 20 times) enough than the detection limit of an accelerometer.

IoT technology is quickly developed in recent years, there is possibility of on-line monitor realization by application of this technique, and expansion of After Service enterprise will be expected from now on.

NOMENCLATURE

\( x \)  acceleration in axial direction at rotational coordinate system  
\( y \)  acceleration in tangential direction at rotation coordinate system  
\( z \)  acceleration in radial direction at rotational coordinate system  
\( X \)  acceleration in axial direction at stationary coordinate system  
\( Y \)  acceleration in horizontal direction at stationary coordinate system  
\( Z \)  acceleration in vertical direction at stationary coordinate system  
\( \omega \)  Blade vibration angular frequency  
\( \Omega \)  Rotor rotational angular frequency

INTRODUCTION

For the on-line health monitor of a steam turbine blade, added to the generally stress measurement by the strain gage stuck on blades, noncontact type measurement by optical sensor, or eddy current probe is being applied to a low pressure stage blades in recent years. [1],[2],[3] However, for high-pressure stage turbine or gas turbine, few monitoring method by an acoustic signal or wavelet are reported[4],[5], a breakdown maintenance is still in use. Even about above-mentioned low-pressure stage monitoring, its application is not easy for the durability of a sensor and needs for machining the turbine systems.

Then, if the abnormalities of blades are detectable with the acceleration of stillness structure such as bearing pedestal or casing, the cost/time necessary for completion of measurement can be shortened substantially, and it will count upon application expansion. The report of study of the contents, which monitor the vibrational state of rotating blades with the acceleration signal of bearing housing until
now is not checked. It seems to be because that detecting blade vibration at pedestal is recognized to be difficult because of that blade vibration signal at bearing pedestal is small which is transmitted from blade root to rotor, bearing, bearing pedestal, and other background vibration is mixed.

So in this paper, firstly the frequency feature in the case of monitoring at the stillness side the blade vibration under rotation was examined. FEM full model analysis estimated the bearing pedestal acceleration response at the time of blade excitation for the high-pressure-stage blades of a steam turbine. Moreover, it was checked whether it would be detectable with a general-purpose accelerometer. Since there were many examples from which the vibration mode before breakage had turned into isolated-aerofoil mode as a result of the inverse analysis of the past blade breakage example as a group of blades and each blade height is 210.0 mm, 105.5 mm, and 20.0 mm. All blades are ISB which have a shroud and a spring of a journal bearing. The excitation point and response with the spring element that has the rigidity of the oil-film spring is examined.

FEATURE OF BLADE TRANSFER SIGNAL TO BEARING PEDESTAL

The vibration transmission ingredient by the side of stillness as shown in Fig.1, in case the blade under rotation vibrates by $\omega$ by angular velocity $\Omega$ is examined. Vibration of rotational motion blades is denoted as follows.

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} x_0 \sin \omega t \\ y_0 \sin \omega t \\ z_0 \sin \omega t \end{bmatrix}$$

(1)

A rotation-station frame transformation matrix is denoted by a lower type,

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi t & -\sin \phi t \\ 0 & \sin \phi t & \cos \phi t \end{bmatrix}$$

(2)

By hanging (2) on the formula (1) of rotational motion blades, the vibration formula of the stationary system is obtained as follows.

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} x_0 \sin \omega t \\ y_0 \sin \omega t \\ z_0 \sin \omega t \end{bmatrix} + \begin{bmatrix} \frac{x_0}{2} (\sin(\omega + \Omega)t + \sin(\omega - \Omega)t) \\ -\frac{z_0}{2} (\cos(\omega - \Omega)t - \cos(\omega + \Omega)t) \\ \frac{y_0}{2} (\cos(\omega - \Omega)t - \cos(\omega + \Omega)t) \\ -\frac{z_0}{2} (\sin(\omega + \Omega)t + \sin(\omega - \Omega)t) \end{bmatrix}$$

(3)

From a formula (3), when transmitting the blade vibration which vibrates by $\omega$ to a pedestal, it is divided into three sorts of oscillating components of ($\omega - \Omega$), $\omega$, and ($\omega + \Omega$). It is a conclusive factor in case this phenomenon grasps the number of the vibration of rotor blades of a rotating body through vibration of a stationary coordinate system.

VERIFICATION TEST ROTOR

The test rotor used for the verification test is shown in Fig.2. Rotor length is 1670 mm, and the rotor has three groups of blades and each blade height is 210.0 mm, 105.5 mm, and 20.0 mm. All blades are ISB which have a shroud in a blade tip. In a verification test, the test rotor is installed in vacuum pit, from the nozzle which is installed close to blades at the stillness side, a high pressure air is injected on the blades under rotation, and blades are excited. And the blade vibration at the time of excitation is measured with the acceleration sensor installed in a bearing housing pedestal. In this examination, its attention is paid to the blades of 20.0 mm length for high-pressure-stage. There were many examples that the vibration mode before breakage had turned into isolated-aerofoil mode as a result of the inverse analysis of the past blade breakage examples. So in the verification test, in order to imitate blades abnormal vibration, the both ends of the shroud in contact with the contiguity blades of the measurement blades of one sheet were deleted and isolated-aerofoil-ized.

FEM ANALYSIS

In order to presume the acceleration response at pedestal in the time of blades excitation, by the model made to bearing housing, rotor, blades, the transfer function is calculated by the frequency response analysis at pedestal acceleration / blade force using general-purpose FEM code NASTRAN. A rotor and bearing housing were combined with the spring element that has the rigidity of the oil-film spring of a journal bearing. The excitation point and response
point of analysis are shown in Fig. 3. The transfer function, accelerance, is shown in Fig. 4, which calculated from the acceleration response of the pedestal part at the time of exciting the measurement blade that deleted the both ends of the shroud. (A rotor is a state of rest) In the transfer function of Fig. 4, a 3838Hz peak is for the primary blade mode in which the blade that deleted shroud both ends vibrate independently. (refer to Fig. 5) The transfer function level at this Frequency is 0.152m/s²/N. Since the exhaust air exciting force in the vibration test was presumed to be 0.54N, pedestal acceleration was presumed to be 0.152m/s²/N × 0.54N = 0.082m/s², and it was judged that it was larger than detection limit 0.005m/s² of acceleration P.U., and measurement was possible.

VERIFICATION TEST PROCEDURE

The verification test was carried out with the test rotor of Fig. 6. (This rotor is same as Fig. 2) The test rotor was set in the vacuum pit, and the nozzle which carries out the exhaust air excitation of each blades stage was installed so that the blow-off direction might turn into a rotor axial direction. Exhaust air excitation was carried out in the examination, carrying out rotation descent by decreasing speed rate 5 rpm/s, after carrying out a rotation rise to a maximum rotational speed (about 14,000 rpm). In this test, in order to distinguish whether the vibration signal of bearing housing is blade vibration, as shown in Fig. 7, the strain gage was stuck on the one blade near the blade root. Fig. 7 shows stress contour in primary blade mode, and has stuck the strain gage shown in red on the blade edge part with high stress.

VERIFICATION TEST RESULTS

SHORT BLADE RESULT

The Campbell diagram at the time of exciting the shortest blades is shown in Fig. 8, and an order tracking analysis result is shown in Fig. 9. The Fig. 8 upper part is a stress value by the strain gage stuck on blades, and Fig. 8 lower part is the acceleration of bearing pedestal. By the upper blade stress Campbell diagram, resonance in the primary mode is observed on 17 Harmonics line near 14,000 rpm, and, the primary mode response is appeared along the line which falls from right side to left side with rotation descent. If a vertical line is drawn from the intersection of the line in this primary mode, and harmonics line in each number of rotations, an intersection with up-and-down harmonics line
is taken and this intersection is connected horizontally, the line of $\pm 1H$ will be obtained to the resonance line in the primary mode of blades. Since a rotating blade vibration is observed at stationary side with being shifted $\pm 1$ harmonic, if the response which is a stationary side and met these lines was obtained, it means that rotating blade vibration is able to detect at stationary side. By Fig.8 lower part, it checked that the response in alignment with the $\pm 1$ harmonic line of the above-mentioned blades stress was accepted.

Furthermore, the order tracking analysis results are shown in Fig.9, in which upper graph is blade stress of 17H near 14000rpm, and middle and lower graph are acceleration at bearing pedestal of 18H and 16H near 14,000 rpm. In the examination case of these figures, although the level of bearing pedestal acceleration was low since excitation air pressure was a little small, it is confirmed that bearing pedestal acceleration served as the maximum near 13,600 rpm at which blade stress serves as the maximum. From these things, resonance in the blade primary mode of 17H was judged to be detected with the acceleration of bearing pedestal.

The relation of the blades stress and bearing pedestal acceleration to air pressure when changing the excitation air pressure in a rotational vibration examination is displayed in Fig.10 and Fig.11 respectively. Blades stress of 17H is shown in Fig.10 and bearing pedestal acceleration of 18H is shown in Fig. 11. From these, blades stress and bearing pedestal acceleration also has clear correlation with exhaust air excitation pressure, and it can judge to be a resonant response. As mentioned above, it was verified that isolated-aerofoil resonance is detectable with the acceleration of bearing pedestal. Moreover, about the bearing pedestal acceleration of Fig.11, since a vibration acceleration level hardly changed in the excitation force domain of 10 - 30MPa and has a relation of direct proportion with excitation force in the domain of 30 or more MPa, it is presumed that acceleration which is about 0.035m/s² up to 30MPa excitation pressure is almost background noise component.

**LONG BLADE RESULT**

Up to the preceding paragraph, the excitation response was evaluated about the short length blades in the test rotor of figure 2. Next, the bearing pedestal response at the time of exciting the long blades is shown in Fig. 12.

From Fig.12 upper, the resonant response of blade stress from 1st to 4th mode has appeared. About the bearing pedestal acceleration the response of $+1H$ component in the 1st mode and $\pm 1H$ component in the 3rd mode of blade stress have appeared notably. Comparing Fig.12 with Fig.7, it checked that the bearing pedestal acceleration response is clearer at long length blades than short length blades.

Since the excitation pressure of long blades was almost the same as short blade, it is presumed that the reason of clearer response of bearing pedestal acceleration in the case of forcing long blade is that the transmission force from the blades to the rotor was larger at long blades’ excitation than short blades.
CONCLUSION

In this paper, the technique of detecting the abnormalities of a rotor with the acceleration of bearing pedestal was taken up as on-line health monitor of a turbine rotor blade. It is estimated that the acceleration response level in bearing pedestal in FEM analysis first. The result checked that the acceleration response level of the bearing pedestal at the time of blades resonance is beyond a detection limit of a general-purpose acceleration sensor.

Next, Carrying out a rotational vibration examination with the test rotor which has three different height blades, it is verified that the blade resonance can be detect by the response acceleration at the bearing pedestal even in the case of the short blade at which the response is smallest when excited.

Although it checked that the blade resonance on a rotating rotor was detectable with the general-purpose acceleration sensor installed in bearing pedestal by this verification test, if it will turn to utilization from now on, the following subjects occur.

1. The measurement check of the bearing pedestal background vibration level at the time of system operation and the separation of the blade-signal component from the background vibration by signal processing.

2. Development of the detection technique of the unusual omen before a rotor results in breakage.

Examination of these will be performed from now on and development of the abnormality prediction system of the rotor by bearing pedestal vibration will be furthered.

REFERENCES


