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Improved Blade Tip Timing in Blade Vibration Monitoring with Torsional Vibration of the Rotor

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Abstract. Due to the complex conditions in rotating machinery, the blades usually encounter fluctuating loads, and failures may occur in the operation. Blade vibration is rarely monitored in the practical rotating machinery in power plants as the traditional blade vibration method using strain gauge method is hard to be applied in long-time and online monitoring. The blade tip timing method is a promising approach to monitor the blade vibration and several special sensors are developed to realize the online monitoring. Based on the traditional blade tip timing method, an improved approach is established in this work. The proposed method can modify the expected arriving time when the torsional vibration exists. The accuracy is therefore improved in the torsional vibration case. Then the blade vibration monitoring with the traditional blade tip timing method and the proposed method are carried out in the test rig in laboratory. The results validate that, the torsional vibration influences the expected arriving time, and the proposed method can modify the expected arriving time and improve the accuracy of the blade vibration monitoring.

1. Introduction

As the increasing capacity in turbine machinery, the dimensions of the blades assembled on the rotor are becoming larger and larger. In transmitting the power of the turbine, the torsional and centrifugal loads are exerted on the blades, which are complicated and probably unstable, especially in the off-designed conditions or the varying loads conditions. The failures of the blades are monitored in kinds of turbine machinery in recently years [1-4]. C. R. F. Azevedo reported the erosion fatigue of the steam turbine blades [5]. The damaged blades from the last stage of the steam turbine are analyzed using the approaches including visual inspection, non-destructive test, macrofractography, microfractography, metallography, microanalysis, microhardness, chemical analysis and sulphur combustion analyser. All of the above methods are processed after the blade failure and used for determining the failure causes. Moreover, blade vibration online monitoring can give indications of the failure and prevent the failure, which is important for the safety and reliability of turbine machinery in operation.

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In a long time, strain gauges are applied to monitor the blade vibration. Strain gauges are instrumented on the blades, and the deformation is measured based on the variations of the resistance. To output the signal, a slip ring is used and installed. As the noise and fluctuating resistance are unavoidable in the slip ring between the rotating component and the stationary component, the application of the strain gauge methods is greatly restrained in rotating machinery. Also, the service life of slip ring decreases rapidly with the increasing rotating speed [6-7].

Blade tip timing is a non-contact method, using the sensors to detect the time of arrival blade by blade. And the deformation of the blade is acquired based on the comparison of the expected time of arrival and the actual time of arrival. As there's no need to install the sensors on the blades, it avoids the usage of the slip ring and enhances the reliability. To identify each blade, the sensor installed in the rotor is applied to acquire the initial position of each revolution [8-10]. However, blade tip timing is based on the assumption that the rotor rotates in a steady state, without the speed variation or the torsional vibration. In the torsional vibration case, the angular speed changes rapidly. And the arriving time will be different even if there's no vibration in the blades. Therefore, blade tip timing will present errors.

The paper proposed a method to improve the performance of the blade tip timing when the torsional vibration exists. An additional sensor is introduced to detect the torsional vibration of the rotor, which can increase the accuracy of the time of arrival. Based on the proposed method, the experiments are carried out in the test rig. The comparisons between the traditional blade tip timing method and the proposed method are carried out.

2. Methods

2.1. Time of arrival in blade vibration monitoring

The basic principle in blade tip timing is to detect the arriving time of each blade. If the blade has defects, such as cracks, erosions, the vibration will be different from the normal state and the arriving time will be different, which can indicate the abnormal conditions of the blades.

In traditional blade tip timing, the sensor is installed in the centrifugal direction. Fiber-optic sensor and eddy current sensor are usually applied to detect the arrival of the blades. The recently developed eddy current sensor can be installed on the casing [11-12]. As the arriving time is determined by the blade vibration in amplitude, frequency and phase, detecting the arriving time can get the blade vibration through the data processing methods.

However, the rotor operates in complicated conditions, and the disturbances are usually occurred. For example, the rotor of the steam turbine can be influenced by the flow fluctuation, the load fluctuation, and other off-designed conditions. These off-designed conditions will influence the speed of the rotor in different frequencies. The frequency of load fluctuation of the network in a power plant varies from the range several Hertz to a few hundred Hertz. Therefore these disturbances will cause the torsional vibration of the rotor. The blade vibration will be influenced by the torsional vibration. And if the traditional blade tip timing method is applied in this situation, the error will be induced by the torsional vibration. As the arriving time fluctuates with the disturbance, the traditional blade tip timing methods do not consider the variation of the angular speed in one revolution.

Considering the blade vibration in a frequency,

$$d = A_0 \sin(\omega t + \varphi_0), \quad (1)$$

where, A_0 is the amplitude of the vibration, ω is the angular speed of the vibration, φ_0 is the initial phase.

If the torsional vibration exists in the rotor, the blade vibration will be,

$$d = A_0 \sin(\omega t + \varphi_0) + B_0 \sin(\omega_t t + \varphi_t) \quad (2)$$

where, B_0 is the amplitude caused by the torsional vibration, ω_t is the angular speed of the torsional vibration, φ_t is the phase.

The vibration acquired by the blade tip timing method is influenced by the torsional vibration of the rotor. As the torsional vibration changes the transient rotating speed in one revolution, the arriving time is different from that in the steady rotating speed, even if there's no vibration in the blades. Errors are therefore presented.

2.2. Improved blade tip timing method

The blade tip timing is based on the time of arrival in the blades. If the time of arrival is changed, the vibration is detected. Then the deformation is calculated based on the measured time of arrival and the expected time of arrival. The error induced by the torsional vibration of the rotor is the error of the expected time of arrival.

When the torsional vibration exists, the rotating speed varies with the torsional vibration frequency,

$$\omega' = \omega_0 + B_1 \sin(\omega_t t + \varphi_t) \quad (3)$$

where, ω_0 is the rotating speed without torsional vibration, B_1 is the amplitude of rotating speed caused by the torsional vibration, ω_t is the frequency of the torsional vibration, φ_t is the initial phase.

If there's no torsional vibration, the expected time of the arrival can be acquired using the distance divided by the rotating speed. If the torsional vibration exerted on the rotor, the expected time of arrival will be determined by the rotating speed and the amplitude of the torsional vibration. Considering the distances from the phase sensor in φ_i , the expected time of arrival t_i is determined by the fluctuating rotating speed.

$$\varphi_i = \int_{t_0}^{t_i} (\omega_0 + B_1 \sin(\omega_t t + \varphi_t)) dt \quad (4)$$

As there's no information of the amplitude and frequency of the torsional vibration, the expected time of arrival is constant in traditional blade tip timing method.

The traditional blade tip timing methods using the distance divided by the mean rotating speed in one revolution as the expected time of arrival. It's the sources of the error.

Therefore, if the expected time of arrival can be modified, the error can be excluded. The paper proposed the method to acquire the expected time of arrival in the blades, with the additional sensor to detect the time of arrival in the root of the blade, shown in figure 2. The additional sensor can detect the arriving time in the blade root. Then the difference of the arriving time between the blade root and blade tip is acquired.

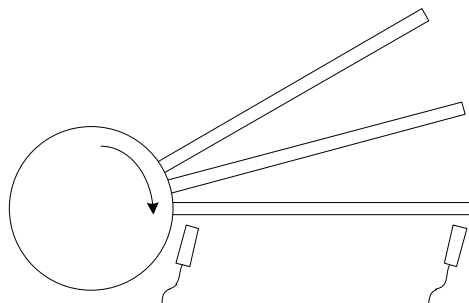


Figure 1. lade tip timing method.

2.3. Test rig

To validate the proposed method, the test rig is established and the experiments with the above two methods are carried out in laboratory. The blade assembly are shown in figure 2. Six blades are assembled in the rotor, and the rotor is supported by two sliding bearings. The DC electromotor is applied to drive the rotor in a range 0-5000rpm. The selection of the DC electromotor has another advantage that the torsional vibration can be simulated using the fluctuating DC power. A signal

generator and a power amplifier are applied to generating the fluctuating power together with the DC power supply.

The data acquisition system includes the eddy current sensors, the data acquisition card, the computer and the LabVIEW software. To acquire the accurate time of arrival of the blades, the synchronous acquisition is applied with high sample rates.

The data are acquired in the normal state and the torsional vibration state. There's no torsional vibration in the normal state and the rotor rotates steadily. In torsional vibration state, the excited power in a frequency of 10 Hz is exerted on the DC electromotor and the rotor vibrates with the excitation.

In this study, the rotating speed of 3500 rpm. The arriving time is measured using the eddy current sensors in the blade root and blade tip. The phase is measured using another eddy current.

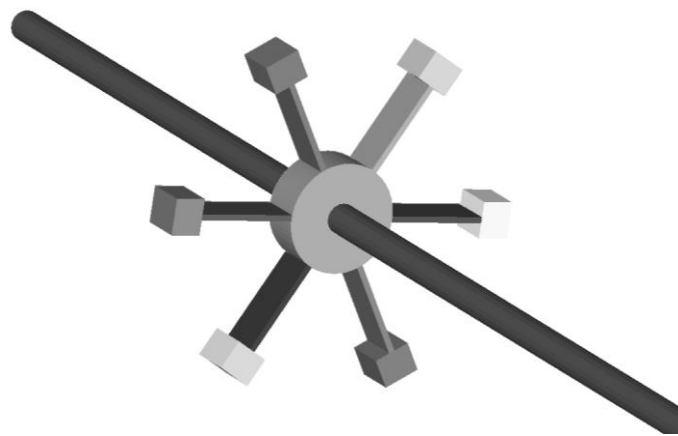


Figure 2. Blade assembly of the test rig.

3. Results and Discussions

3.1. Blade vibration using the traditional blade tip timing method

Traditional blade tip timing method calculates the blade vibration with the difference between the detected time of arrival and the expected time of arrival. The angular positions of the blades are stored previously to calculate the expected arriving time.

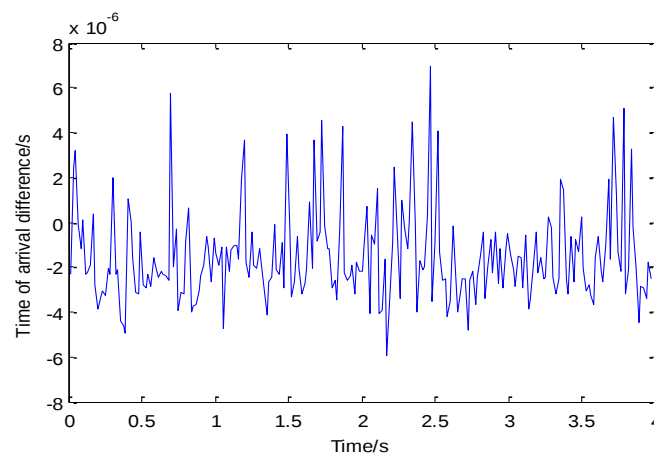


Figure 3. The blade vibration data in the normal case using traditional blade tip timing method.

The vibration of blade 1 is shown in figure 3, with the rotating speed in 3500rpm.

When the torsional vibration is exerted on the rotor, the vibration of blade 1 is shown in figure 4, with the same rotating speed of the normal case. The blade vibration is greatly affected by the torsional vibration of the rotor. However, the actual blade vibration may be smaller than this. The blade vibration data using the improved blade tip timing method will be analyzed and compared in the following sections.

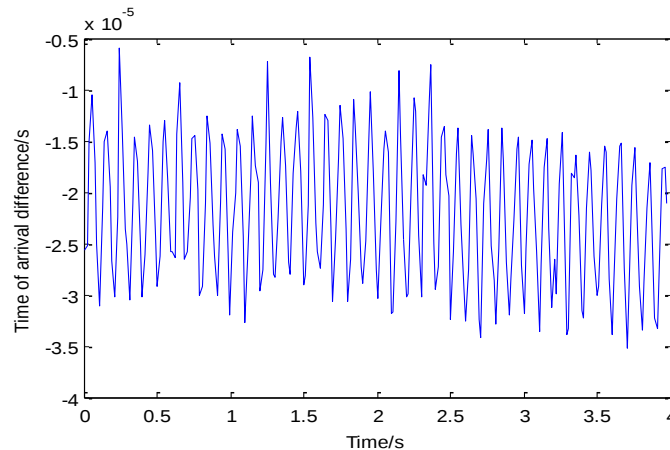


Figure 4. The blade vibration data in the torsional vibration case using traditional blade tip timing method.

3.2. Blade vibration using the improved blade tip timing method

Using the improved blade tip timing method, the difference of the arriving time between the blade root and blade tip is determined as the blade vibration. The phase sensor is used to distinguish the blades.

To validate the changes of the expected arriving time, the arriving time of the blade 1 is calculated using the proposed method in the normal case and the torsional vibration case. The results are shown in figure 5 and figure 6. The expected time of arrival varies in a larger range when the torsional vibration exists, with five times larger than that in the normal case. It is validated that, the torsional vibration greatly influences the expected arriving time and will decrease the accuracy of the blade vibration monitoring.

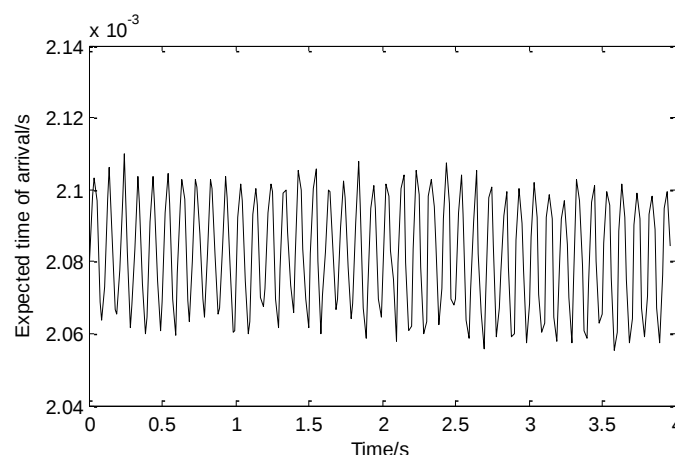


Figure 5. The expected arriving time in torsional vibration case using improved blade tip timing method.

The vibration of blade 1 in the normal case and the torsional vibration case are shown in figure 7 and figure 8. The fluctuations of the expected arriving time increase the amplitudes of the blade

vibration in traditional blade tip timing method, and it is the error source. The proposed method can eliminate the error.

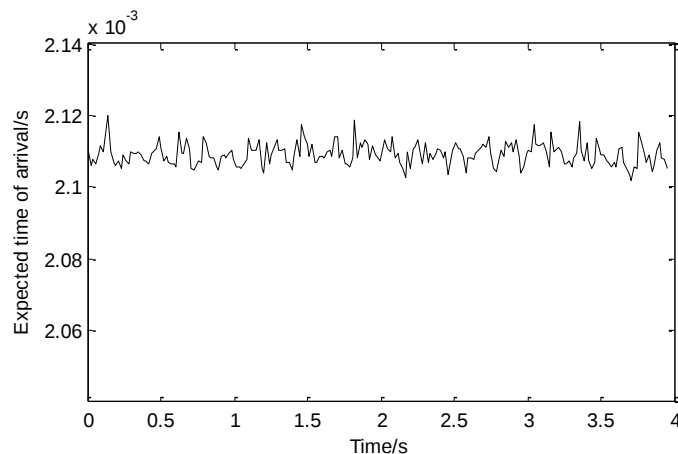


Figure 6. The expected arriving time in normal case using improved blade tip timing method.

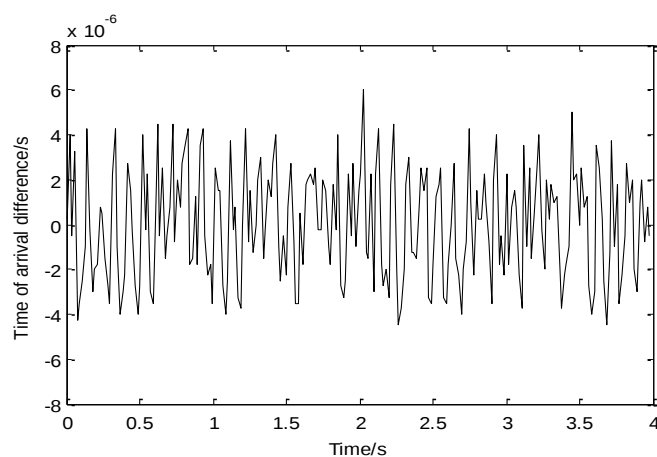


Figure 7. The blade vibration data in the torsional vibration case using improved blade tip timing method.

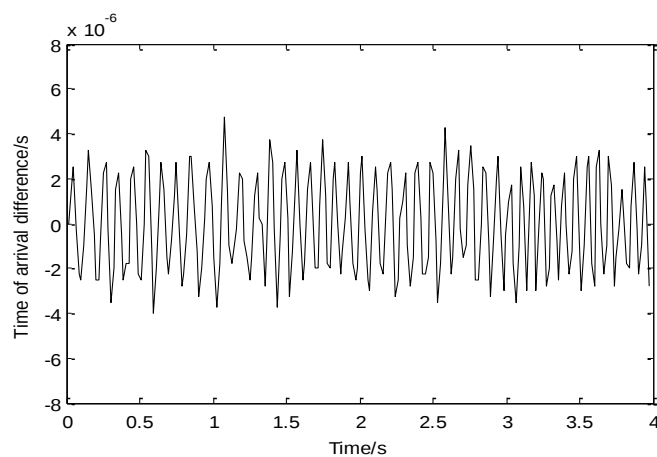


Figure 8. The blade vibration data in the normal case using improved blade tip timing method.

3.3. Comparisons

The blade vibrations using the traditional blade tip timing and improved blade tip timing are carried out in the above sections.

In the normal case, the expected time of arrival is not varying as the constant angular speed of the rotor. And the amplitudes are close between the two methods.

In the torsional vibration case, the measured amplitude with the traditional blade tip timing method is much larger than that in improved blade tip timing method, which is mainly caused by the variations of the angular speed. The torsional vibration of the rotor is not excluded by the traditional blade tip timing results, and it induces errors.

It is concluded that, compared with the traditional blade tip timing method, the improved blade tip timing performs better in the torsional vibration case, which can exclude the infuleces of the varying angular speed and get more accurate blade vibration results.

4. Conclusions

Blade tip timing method is developed in rotating machinery to measure the blade vibration and monitoring the blade conditions. As the disturbances usually exist in the turbine and generator, which influence the angular speed of the rotor. The varying angular speed will induce the error in the blade vibration monitoring using the traditional blade tip timing method.

Based on the traditional blade tip timing method, the improved blade tip timing is proposed to avoid the error prediction of the blade vibration in the rotor torsional vibration situation. The experiments are carried out using the traditional blade tip timing method and the improved blade tip timing method in laboratory. The results shows that, the improved blade tip timing method can improve the accuracy of the blade vibration monitoring in rotor torsional vibration case.

Acknowledgments

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