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Research Article

Blade Serial Number Identification Based on Blade Tip Clearance without OPR Sensor

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Blade serial number identification is one of the key issues in blade tip-timing vibration measurement without once-per-revolution (OPR) sensor. In order to overcome the shortcomings of the existing blade serial number identification methods without OPR sensor, a new identification method of blade serial number based on blade tip clearance is proposed in this paper. The relationship between blade tip-timing data and blade serial number can be identified by the matching relationship between blade tip clearance under static state and dynamic state. According to the finite element simulation and experimental data, the accuracy of the blade serial number identification method based on blade tip clearance is verified by using the OPR sensor method. The results show that in the nonresonant rotation speed region, the method can identify the blade serial number, and the identification result is consistent with the result of the OPR sensor method. In the resonance rotation speed region, when the blade tip clearance change caused by the blade circumferential bending vibration is less than the dispersion of initial blade tip clearance, the method in this paper can accurately identify the blade serial number. Otherwise, the inference method can be used. It provides theoretical support and technical basis for the engineering application of blade tip-timing vibration measurement technology without OPR sensor.

1. Introduction

The rotor blades are significant components of aeroengine, which are subjected to high speed, high temperature, high pressure, and other loads. Due to the superposition of various loads, the blades are the most easily vibrated component. One of the important causes of engine accidents is the high cycle fatigue of blades' vibration. In order to reduce the risk of high cycle fatigue failure, it is necessary to monitor the blade vibration in real time, which is an effective way to ensure the safety of aeroengine operation.

The main methods of blade vibration monitoring are contact measurement and noncontact measurement. The contact measurement method [1] is mainly the strain gauge method. Although this method can directly and accurately reflect the dynamic characteristics of the blades, there are numerous shortcomings in the measurement process, which make the contact measurement method difficult to meet the requirements of online monitoring of blade vibration for a long time. In view of the shortcomings of the contact measurement method, the noncontact measurement method was proposed [2]. Compared with the contact measurement method, the sensors of the noncontact measurement method are mounted on the casing and do not contact the blades directly. It can measure the vibration of all blades in the whole circle without additional mass and leading-out device. The main noncontact measurement methods are frequency modulation method [3], laser holography method [4], laser doppler method [5], acoustic response method [6], and blade tip-timing method [7]. Compared with other noncontact measurement methods, the blade tip-timing method not only has the advantages of simple measurement principle, convenient use, low installation cost, and high sensitivity, but also can measure the vibration of all blades at the same time. Therefore, the blade tip-timing method is one of the most hotspot problems with online vibration monitoring of noncontact rotating blades.

The basic principle of the blade tip-timing method is to use the sensors mounted on the casing to sense the arrival time of the blades. Due to the blade vibration, the arrival time of the blade may be ahead or behind. Different blade tip-timing algorithms are used to process the time series to obtain blades' vibration information [7]. Existing blade tip-timing vibration measurement systems need to install the OPR sensor. The three functions of the OPR sensor are to measure the rotation speed of the blade and provide the time reference and the reference signal of the blade vibration. In some cases, there is a certain distance between the installation position of the OPR sensor and the rotating blade. The internal complexity of the engine makes the measurement of the OPR sensor easy to be interfered, resulting in errors in the measurement results, which have a negative impact on the subsequent data acquisition and analysis. In addition, due to the limitation of engine structure, environment, and space, it is often unrealistic to install the OPR sensor to the best measurement position. Even if it can be installed in the best measuring position, due to the poor internal environment of the engine, it is easy to cause sensor failure or even fall off, resulting in the failure of the measuring system, leading to serious safety accidents [8]. As previously mentioned, the blade tip-timing measurement system without OPR sensor is more in line with the development needs of safety, reliability, and economy of aeroengine, but there is little related research work at present. If there is no OPR sensor, there is no rotation speed information and time reference. The existing blade tip-timing measurement system and data analysis methods may be failed. Therefore, it is urgent to study the blade tip-timing measurement technology without OPR sensor.

Zielinski and Ziller first proposed the measurement concept of blade tip-timing measurement without OPR sensor [9]. At present, there are few researches on blade tip-timing measurement technology without OPR sensor and parameter identification method. Guo et al. [10] presented a method to locate the blade tip-timing data to the corresponding blade based on the blade installation error. At the same time, based on the variable-speed sweep test, two sensors were used to identify the synchronous vibration amplitude of the blade, and three sensors were applied to identify the excitation order of the blade vibration. This method needs to know the installation error of the blade in advance, and it is only effective when the vibration of the blade is relatively small. Guo et al. [11] proposed a parameter identification method for synchronous vibration of sensors layout at any angle under the condition of constant rotation speed. Five sensors are used to realize the blade tip-timing measurement without the reference sensor, which also needs to know the installation error of blades. Zhang et al. [12] put forward a method of synchronous blade tip-timing signal preprocessing without OPR sensor, through the vibration displacement difference of the same blade arriving at different blade tip-timing sensors to identify the vibration parameters and measure the rotating speed. This method can reduce the measurement error of rotating speed and the influence of rotating speed error on vibration displacement measurement, but it also needs to know the installation error of blades.

Zhou et al. [13, 14] carried out the research on the identification method of synchronous vibration parameters of blades without OPR sensor and improved the two-parameter method. By increasing the number of blade tip-timing sensors, based on the analysis and processing of blade vibration displacement difference, the identification of synchronous vibration amplitude and excitation order of blade was realized. This method approximates to processing recognition algorithm so that there is a certain theoretical error in the identification results. Russhard [15] proposed a method to generate virtual OPR signal, analyzed and estimated the relationship between the arrival time of the blade and the rotation angle of the blade, obtained the start and end time of each circle, as a virtual reference signal, analyzed the frequent cases of less or more counts in the measurement process, and proposed the corresponding solutions. On the basis of Russhard's research, Wang et al. [16, 17] carried out the research on vibration monitoring and fault early warning methods of large axial-flow compressor blades and proposed a new blade tip-timing method without OPR sensor based on composite reference. This method takes into account the installation angle error of the blades, the installation angle error of the sensors, the mistuned bladed disk and other factors, and can eliminate most of the noise caused by the speed fluctuation and other factors. These methods cannot locate the blade tip-timing data without OPR sensor; that is, the corresponding relationship between the blade tip-timing data and the blade serial number cannot be obtained.

One of the key problems of blade tip-timing measurement is how to match the measured data with the blade serial number. If the arrival time data of the blade are mapped to other blades, the parameter identification will produce wrong results. At present, the common methods for positioning the data of blade tip-timing measurement are as follows: OPR sensor positioning method; when the marks on the rotating shaft pass through the OPR sensor, a pulse signal would be generated, and the blades with the same circumference position as these marks would be used as a reference and numbered so as to obtain the numbers of the remaining blades [18]. Blade installation error positioning is another method; due to the inevitable errors in blade installation, for a single blade, its installation error is specific. However, the installation error of adjacent blades is continuous, and there is an obvious discontinuity between the last blade and the first blade. According to this property, the first blade can be determined in the blade installation error diagram [19]. Compared with the OPR sensor positioning method, this method requires that the blade installation error is known, resulting in low measurement efficiency. At present, blade tip-timing methods without OPR sensor are mainly divided into two categories: one is to improve the existing blade tip-timing measurement and data analysis methods, by increasing the number of blade tip-timing sensors to replace the role of OPR sensor. In this method, the displacement measured by the first blade tip-timing sensor is selected as a reference, and the displacement measured by other blade tip-timing sensors is compared with it respectively to get the vibration displacement difference of the blade. The vibration displacement difference of the blade is analyzed, and the vibration parameter identification of the blade is completed. This method cannot identify the constant deviation and the initial phase of the blade, and it has strict preconditions; that is, the blade amplitude is very small, and the blade installation error is known. The other is to use the data processing method, using the relationship between the measurement data of different blade tip-timing sensors and the blade rotation angle, to generate a virtual OPR signal to replace the role of the OPR sensor. This method cannot locate the blade tip-timing data.

In view of the above shortcomings, the blade serial number identification method is proposed based on blade tip clearance, and it accurately identifies the corresponding relationship between blade tip-timing data and blade serial number by using the matching relationship between blade tip clearance under static state and dynamic state. It provides theoretical support and technical basis for the engineering application of blade tip-timing measurement technology without OPR sensor. This paper is organized as follows. The blade serial number identification theoretical model based on tip clearance is constructed in Section 2. In Section 3, the finite element simulation is used to verify the accuracy of the blade serial number identification method. In Section 4, the experimental parameters are tested and the identification results are verified based on the OPR sensor method. Finally, Section 5 offers the main conclusions of this paper.

2. Identification Theory of Blade Serial Number Based on Blade Tip Clearance

2.1. Static Measurement of Blade Tip Clearance. It is assumed that N blades are installed on the rotor, and the serial number is $1, 2, \ldots, N$. The casing is equipped with S blade tip-timing sensors numbered $1, 2, \ldots, S$. Through the blade tip-timing technology, not only the arrival time of each blade can be obtained, but also the blade to which the blade tip-timing data belong can be identified. When the OPR sensor is installed, the time difference between the OPR sensor and the blade tip-timing sensor can be obtained. When the OPR sensor is not installed, the identification process of blade serial number is as follows.

Fiber optic, eddy current, and capacitive displacement sensors are used to collect the blade tip-timing data. When the blade tip passes through the sensor probe, not only the arrival time of each blade can be obtained, but also the tip clearance value of each blade can be measured.

When the rotor system is not working, the jth blade is rotated directly under the ith blade tip-timing sensor by external force or turning gear, and the blade tip clearance δ_{ij} of the jth blade relative to the ith blade tip-timing sensor is measured at rest. The blade tip clearance value of blades relative to all blade tip-timing sensors is

$$[\delta] = \begin{bmatrix} \delta_1 \\ \vdots \\ \delta_i \\ \vdots \\ \delta_s \end{bmatrix} = \begin{bmatrix} \delta_{1,1} & \cdots & \delta_{1,j} & \cdots & \delta_{1,N} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \delta_{i,1} & \cdots & \delta_{i,j} & \cdots & \delta_{i,N} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \delta_{s,1} & \cdots & \delta_{s,j} & \cdots & \delta_{s,N} \end{bmatrix}. \tag{1}$$

Due to factors such as blade processing, installation error, and deliberate mistuned and radial installation position of sensor, the tip clearance value of each blade is not equal, and each blade has a specific tip clearance value δ_{ij} relative to each blade tip-timing sensor. Therefore, the blade serial number can be identified by the matching relationship between the tip clearance value in the static state and in the rotating state. The row sequence in equation (1) would be used as a template series in the next blade sequence identification process.

2.2. Dynamic Measurement and Correction of Blade Tip Clearance. The rotating speed of the rotor system is adjusted to a lower nonresonance speed. The blade tip dynamic clearance and time interval sequences are measured by the blade tip-timing sensors. Since there is no OPR sensor, the corresponding relationship between blade tip-timing data and blade serial number cannot be located. It is necessary to use the blade tip dynamic clearance sequence for identification.

The first value of the 1st circle measured by the ith sensor is the tip dynamic clearance value of the jth blade. The first tip dynamic clearance measured by the ith sensor at the kth circle is $\delta^k_{i,(k-1)N+1}$, $k = 1, 2, \ldots, M$, where M is the total number of circles of the rotor during the measurement. Under the operating condition of high speed, the problem of undersampling error occurs in the eddy current tip-timing sensor. If only static radial calibration of blade tip clearance is carried out, and the peak positioning method is used for clearance measurement, the sensitivity corresponding to the measured output voltage shows obvious deviation, and the measured tip clearance results increase with the increase of speed. Therefore, the trigger pulse method is used to measure the blade tip clearance under the operating condition of high speed [20]. When the rotor system rotates dynamically, the sequence matrix of tip clearance values measured by all blade tip-timing sensors is

$$\left[\delta^d\right] = \begin{bmatrix} \delta^d_1 \\ \vdots \\ \delta^d_i \\ \vdots \\ \delta^d_s \end{bmatrix} = \begin{bmatrix} \delta^1_{1,1} & \cdots & \delta^1_{1,N} & \cdots & \delta^k_{1,(k-1)N+1} & \cdots & \delta^k_{1,kN} & \cdots & \delta^M_{1,(M-1)N+1} & \cdots & \delta^M_{1,MN} \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \delta^1_{i,1} & \cdots & \delta^1_{i,N} & \cdots & \delta^k_{i,(k-1)N+1} & \cdots & \delta^k_{i,kN} & \cdots & \delta^M_{i,(M-1)N+1} & \cdots & \delta^M_{i,MN} \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \delta^1_{s,1} & \cdots & \delta^1_{s,N} & \cdots & \delta^k_{s,(k-1)N+1} & \cdots & \delta^k_{s,kN} & \cdots & \delta^M_{s,(M-1)N+1} & \cdots & \delta^M_{s,MN} \end{bmatrix}. \tag{2}$$

As the blade rotates, the tip clearance of the same blade measured by the same sensor is not the same every rotation, and there is measurement error, so it is necessary to correct the tip clearance measurement of each blade.

When $j+p \le N$, the correction value of tip dynamic clearance of the $j+p$th blade measured by the ith sensor is

$$ {}^{j+p}\overline{\delta}_i = \frac{\sum_{k=1}^{M} \delta^{k}_{i,(k-1)N+p}}{M} \quad (0 \le p \le N-j). \tag{3}$$

When $j+p > N$, the correction value of tip dynamic clearance of the $j+p-N$th blade measured by the ith sensor is

$$ {}^{j+p-N}\overline{\delta}_i = \frac{\sum_{k=1}^{M} \delta^{k}_{i,(k-1)N+p}}{M} \quad (N-j < p \le N-1). \tag{4}$$

The correction value sequence of blade tip dynamic clearance measured by the ith sensor is

$$ \left[\overline{\delta}_i\right] = \left[\, {}^{j}\overline{\delta}_i \ \cdots \ {}^{j+p}\overline{\delta}_i \ \cdots \ {}^{N}\overline{\delta}_i \ {}^{1}\overline{\delta}_i \ \cdots \ {}^{j+p-N}\overline{\delta}_i \ \cdots \ {}^{j-1}\overline{\delta}_i \,\right]. \tag{5}$$

There are N elements in the modified value sequence. Extend the sequence for one cycle and remove the last element. The sequence is as follows:

$$ \left[\overline{\delta}^{y}_i\right] = \left[\, {}^{j}\overline{\delta}_i \ \cdots \ {}^{j+p}\overline{\delta}_i \ \cdots \ {}^{N}\overline{\delta}_i \ {}^{1}\overline{\delta}_i \ \cdots \ {}^{j+p-N}\overline{\delta}_i \ \cdots \ {}^{j-1}\overline{\delta}_i \ {}^{j}\overline{\delta}_i \ \cdots \ {}^{j+p}\overline{\delta}_i \ \cdots \ {}^{N}\overline{\delta}_i \ {}^{1}\overline{\delta}_i \ \cdots \ {}^{j+p-N}\overline{\delta}_i \ \cdots \ {}^{j-2}\overline{\delta}_i \,\right]. \tag{6}$$

The sequence consists of $2N-1$ elements, and the lth element can be expressed as $\overline{\delta}^{y}_{i,l}$.

2.3. Identification of Blade Serial Number. The correlation between the tip clearance value sequence measured by the first tip-timing sensor in the static state and the tip clearance value correction continuation sequence measured by the first tip-timing sensor in the dynamic rotation is calculated as follows:

$$ C_i(\tau) = \sum_{l=1}^{N} \overline{\delta}^{y}_{i,l+\tau}\delta_{i,l} = \sum_{l=1}^{N} \overline{\delta}^{y}_{i,\mathrm{mod}(l+\tau+j-1,N)}\delta_{i,l}. \tag{7}$$

The parameter τ is defined as a variable of cross-correlation function $C_i(\tau)$, and it is used to identify the blade serial number. In equation (7), the $\mathrm{mod}(i+\tau+j-1,N)$ is the remainder of $i+\tau+j-1$ divided by N. When blade j reaches a sensor probe, a sequence of time intervals between adjacent blades is measured. The following $2N-1$ tip clearance values are substituted into equation (7) to calculate the correlation function $C_i(\tau)$.

When $\tau+j-1$ is an integer multiple of N, equation (7) would reach the maximum. Assuming the maximum value of $C_i(\tau)$ is $C_i(\tau_m)$, the blade serial number j is calculated as follows:

$$ \begin{gathered} \max C_i(\tau) = C_i(\tau_m), \\ j = N - \tau_m + 1. \end{gathered} \tag{8}$$

Since the main vibration mode of the blade is circumferential bending vibration. When the blade tip clearance change caused by the blade circumferential bending vibration is less than the dispersion of initial blade tip clearance, the method in this paper can accurately identify the blade serial number. If the blade tip clearance change caused by the blade circumferential bending vibration is greater than the dispersion of initial blade tip clearance, the inference method is applied to identify the blade serial number corresponding to the constant rotating speed synchronous vibration tip-timing signal without the OPR sensor. In the nonresonant rotation speed region, when the blade vibration is not large, the blade tip-timing data which belong to blade serial number j is identified, then the mth data after this data would belong to the blade serial numbered $\mathrm{mod}[j+\mathrm{mod}(m,N),N]$.

3. Numerical Simulation Verification

The finite element method is used to verify the accuracy of the blade serial number identification method based on the blade tip clearance, and the finite element model of the bladed disk structure is established as shown in Figure 1. The number of blades is 8; the blade type is straight blade. The material parameters of the blades and the disk are as follows: the density is 7800 kg/m^3, the elastic modulus is 210 GPa, and the Poisson ratio is 0.3. The static state tip clearance value of each blade is shown in Table 1. The fixed displacement constraint is imposed on the cylindrical surface of the shaft hole, and the rotation speeds' load of 0–6000 r/min is applied to the bladed disk structure with a step length of 1000. Based on the finite element analysis, the tip clearance value of each blade of the bladed disk structure under different speed loads is shown in Figure 2. It can be seen from Figure 2 that the tip clearance of each blade decreases according to the law of the quadratic curve with the increase of the rotation speed, but the decrease is not large. The main reason is that the blades are slightly elongated in the radial direction due to the rotating centrifugal force.

Based on the data in Figure 2, the dynamic state blade tip clearance sequences measured by the blade tip-timing sensor under 6 different working conditions are randomly constructed, as shown in Figures 3(a)–3(f). In Figures 3(a)–3(f), the operating speeds are 1000, 2000, 3000, 4000, 5000, and 6000 r/min. Assume that the initial (first) dynamic state tip clearance pulses of each sequence correspond to No. 4, No. 6, No. 3, No. 2, No. 7, and No. 5 blades, respectively, and the blade serial numbers are cyclically increased as the number of pulses increases. For example, the dynamic state blade tip clearance sequence intercepted in Figure 3(a) corresponds to

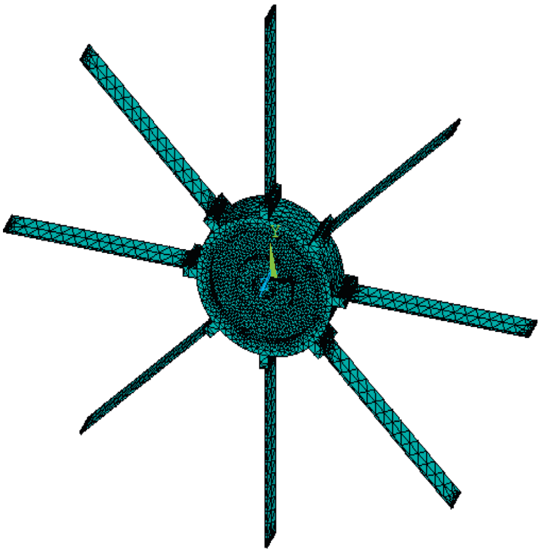


Figure 1: Finite element model of bladed disk structure.

Table 1: Static state tip clearance of each blade.

Blade serial number	1	2	3	4	5	6	7	8
Tip clearance (mm)	0.5	0.45	0.4	0.35	0.3	0.25	0.2	0.15

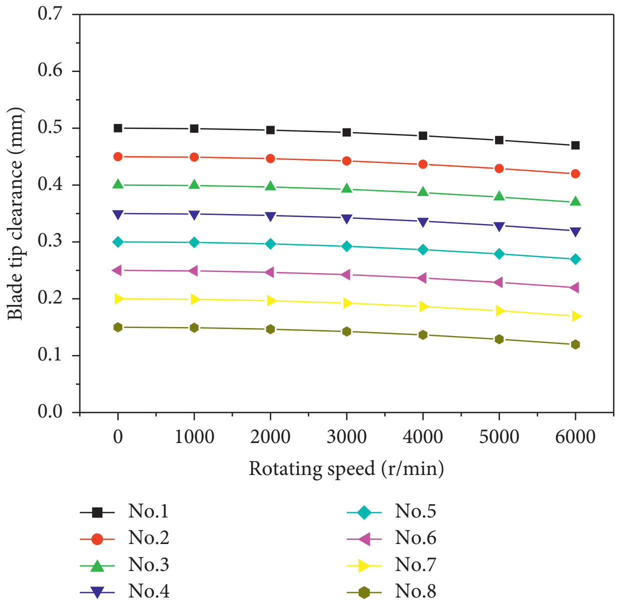


Figure 2: Tip clearance value of each blade at different rotating speeds.

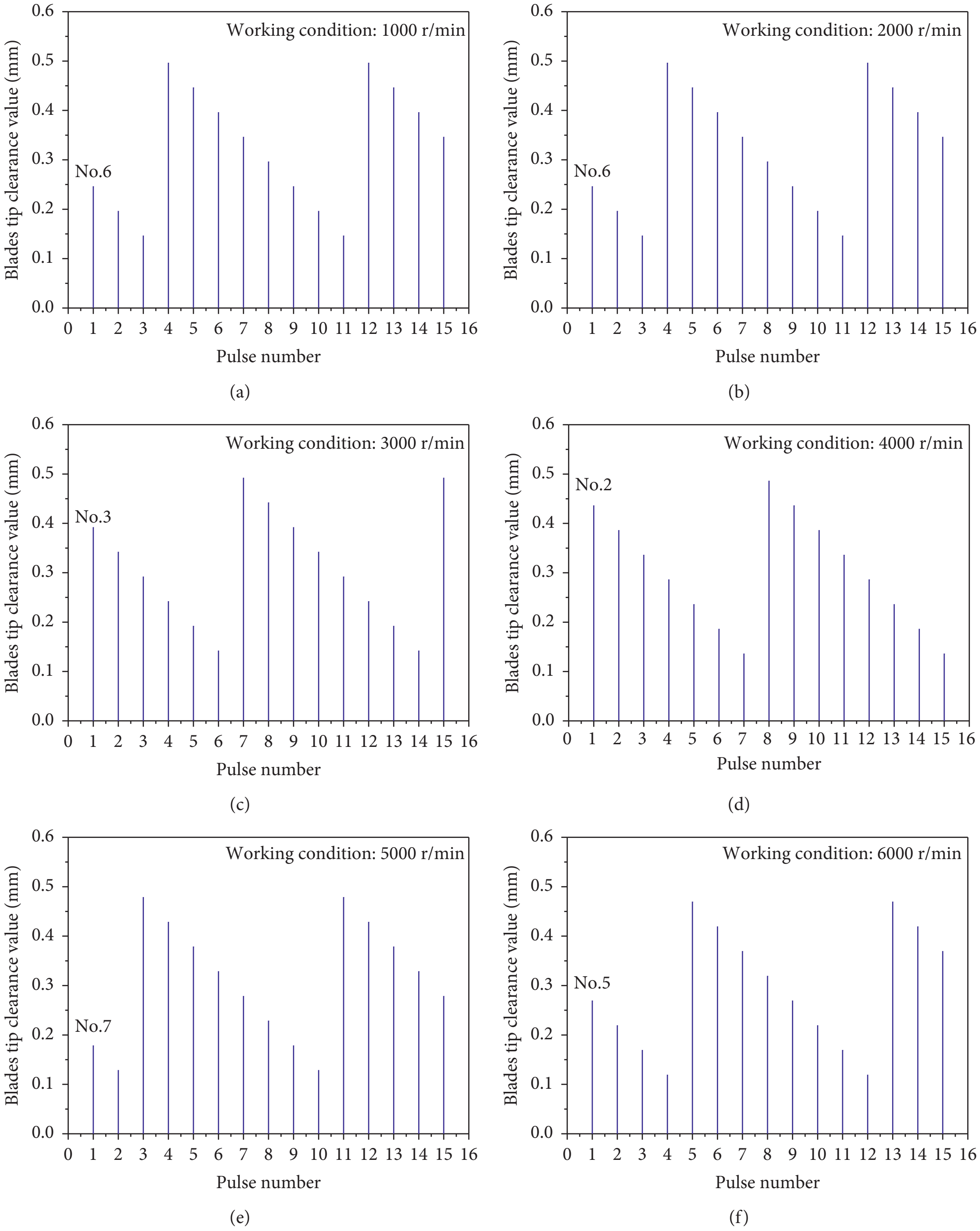
the blade serial number [4, 5, 6, 7, 8, 1, 2, 3, 4, 5, 6, 7, 8, 1, 2]. Each pulse value is the dynamic tip clearance value of blades with different serial numbers.

Substituting the static state tip clearance template sequence of the blades in Table 1 and the dynamic state tip clearance pulse sequence under different working conditions in Figure 3 into equation (7) for correlation calculation, the correlation function values of the sequence under 6 different working conditions are obtained as shown in Figures 4(a)–4(f), respectively. From Figures 4(a)–4(f), it can be seen that under the working conditions of 1000 r/min to 6000 r/min, when $\tau_m = 5$, 3, 6, 7, 2, and 4, respectively, $C_i(\tau)$ takes the maximum value. Substituting the values of τ_m into equation (8) to obtain the identification value of the blade serial number corresponding to each initial dynamic tip clearance pulse, the hypothetical value and identification value of the blade serial number corresponding to the initial dynamic tip clearance pulse are shown in Table 2. It can be seen from Table 2 that the identification value of the blade serial number corresponding to the initial dynamic blade tip clearance pulse of each working condition sequence is consistent with the hypothetical value. The accuracy of the blade serial number identification method proposed in this paper is verified by finite element simulation.

4. Experimental Verification

The experiment is conducted to verify the blade serial number identification method. A rotor with 8 blades is utilized, and the radius of the blade tip is 217 mm. Eddy current sensors are utilized for tip-timing, and as in Figure 5, signals of TIP0, TIP1, and TIP2 are analyzed. The angle between the TIP0 and TIP1 is 20° and the angle between TIP0 and TIP2 is 40°. An OPR sensor is applied to verify the accuracy of the identification method of blade serial number without OPR sensor.

The blade serial number is marked and the blade tip clearance is measured under static state. Without turning on



(a)

(b)

(c)

(d)

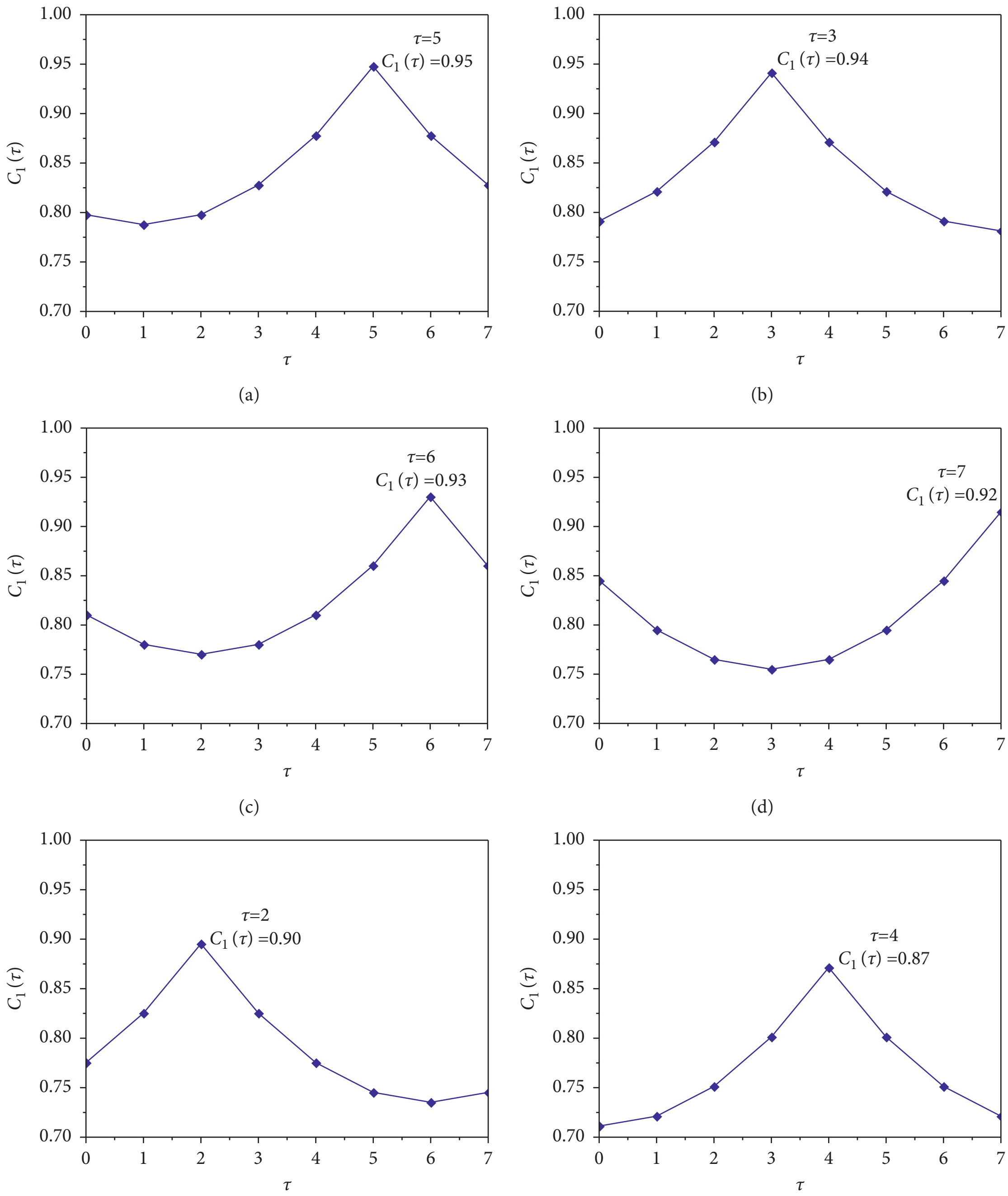
(e)

(f)

FIGURE 3: Dynamic blade tip clearance pulse sequence under different working conditions. (a) 1000 r/min. (b) 2000 r/min. (c) 3000 r/min. (d) 4000 r/min. (e) 5000 r/min. (f) 6000 r/min.

the servo motor driver, turn on the blade tip-timing sensors, data acquisition, and processing system. Manually rotate the blades in the order of number to directly below the first blade tip-timing sensor; measure the voltage value corresponding to the tip clearance of each blade under static state, and the sequence $[\delta_1]$ in equation (1) is obtained as shown in Table 3.

Turn on the servo motor drive, and according to the Campbell diagram, the rotating speed is increased to 2000 r/min of nonresonant rotating speed, and the rotating speed data is measured by the OPR sensor, which provides a time reference for the verification of the blade serial number identification method. When the rotating speed is stable at 2000 r/min, two sets of blade tip dynamic clearance sequences are measured by the blade tip-timing sensors TIP1 and TIP2. Use equations (3) and (4) to modify the sequences, and extend the modified sequences by one cycle. The modified and extended two groups of blade tip dynamic clearance sequences are shown in Figure 6.



(a) (b) (c) (d) (e) (f)

Figure 4: Correlation function calculation of various working conditions. (a) 1000 r/min. (b) 2000 r/min. (c) 3000 r/min. (d) 4000 r/min. (e) 5000 r/min. (f) 6000 r/min.

Table 2: Hypothetical value and identification value of blade serial number corresponding to the initial dynamic blade tip clearance pulse.

Working condition	1000 r/min	2000 r/min	3000 r/min	4000 r/min	5000 r/min	6000 r/min
Hypothetical value	4	6	3	2	7	5
Identification value	8 − 5 + 1 = 4	8 − 3 + 1 = 6	8 − 6 + 1 = 3	8 − 7 + 1 = 2	8 − 2 + 1 = 7	8 − 4 + 1 = 5


(a) (b)

Figure 5: Blade tip-timing vibration testing device of rotating bladed disk system. (a) Vibration test bench. (b) Signal acquisition and processing system.

Table 3: Measured voltage value corresponding to the blade tip clearance under static state.

Marked blade serial number	1	2	3	4	5	6	7	8
Voltage value (v)	−3.6486	−4.0741	−3.8923	−4.2737	−3.7287	−4.3751	−4.1725	−3.8090

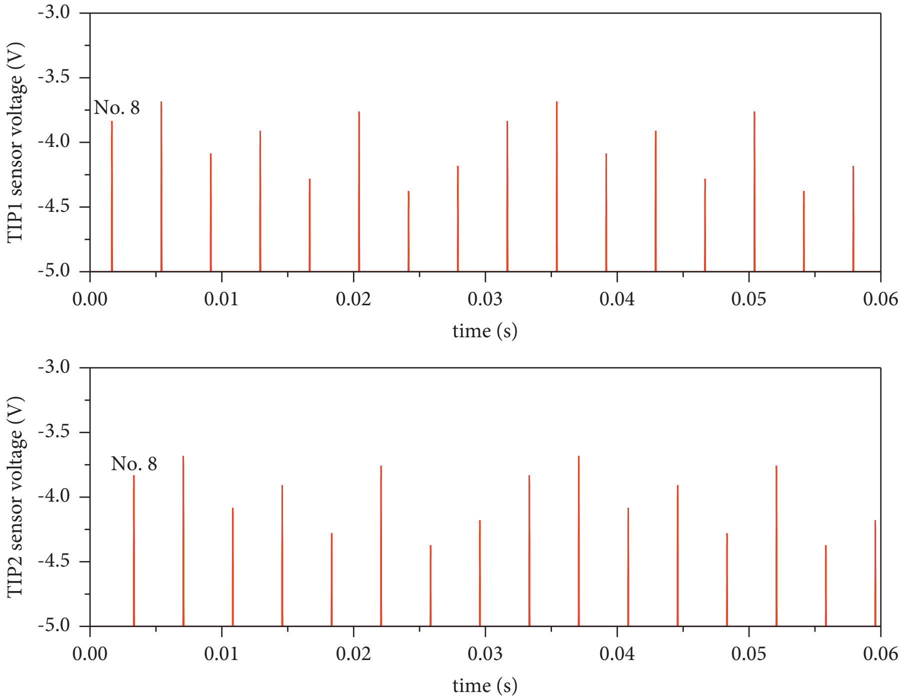


Figure 6: Measurement result of blade tip-timing sensors.

According to the OPR sensor, the first voltage pulse in Figure 6 is the correction voltage value of the No. 8 blade tip dynamic clearance. Based on equation (7), the correlation between the sequence $[\overline{\delta}_1^y]$ and the template sequence $[\delta_1]$ is calculated, and the calculation results are shown in Figures 7(a) and 7(b). When $\tau_m = 1$, the maximum value of $C_1(\tau)$ appears. According to equation (8), the number of the blade is identified as $j = N - \tau_m + 1 = 8$, which is consistent with the results of the OPR sensor method. Based on the OPR sensor method, the identification accuracy of the method proposed in this paper is verified by experimental data.

The above identification is in the nonresonant region, and the influence of blade vibration is ignored. The dynamic blade tip clearance sequences with relatively large blade amplitude close to the resonance speed of 2700 r/min are collected by the blade tip-timing sensors TIP1 and TIP2. The modified and extended dynamic blade tip clearance sequences are shown in Figure 8. According to the OPR sensor, the initial pulse of the sequence corresponds to the

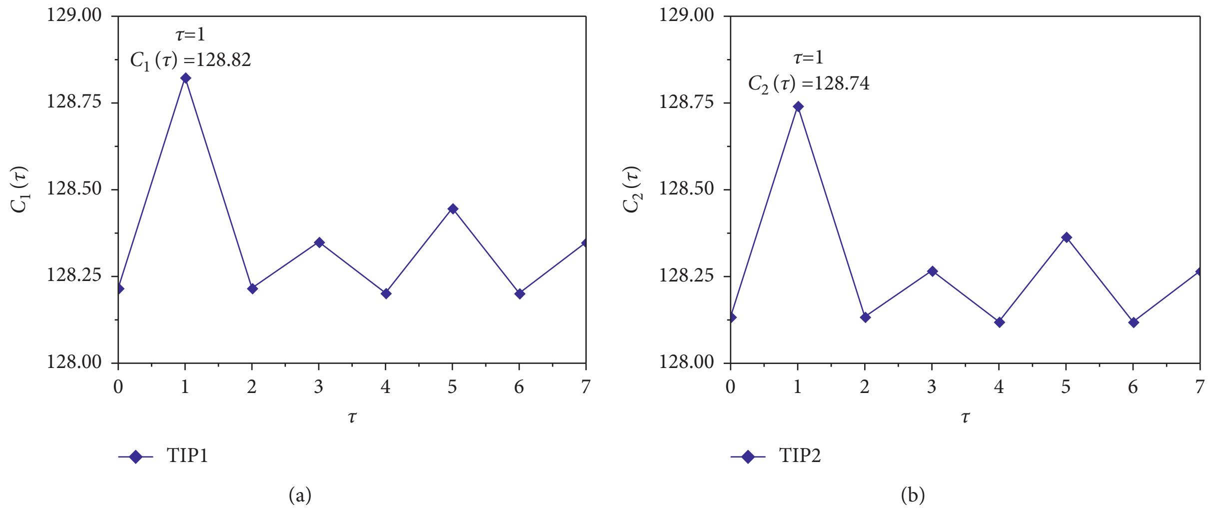


FIGURE 7: Correlation function calculation under nonresonant experimental condition of 2000 r/min. (a) TIP1 sensor. (b) TIP2 sensor.

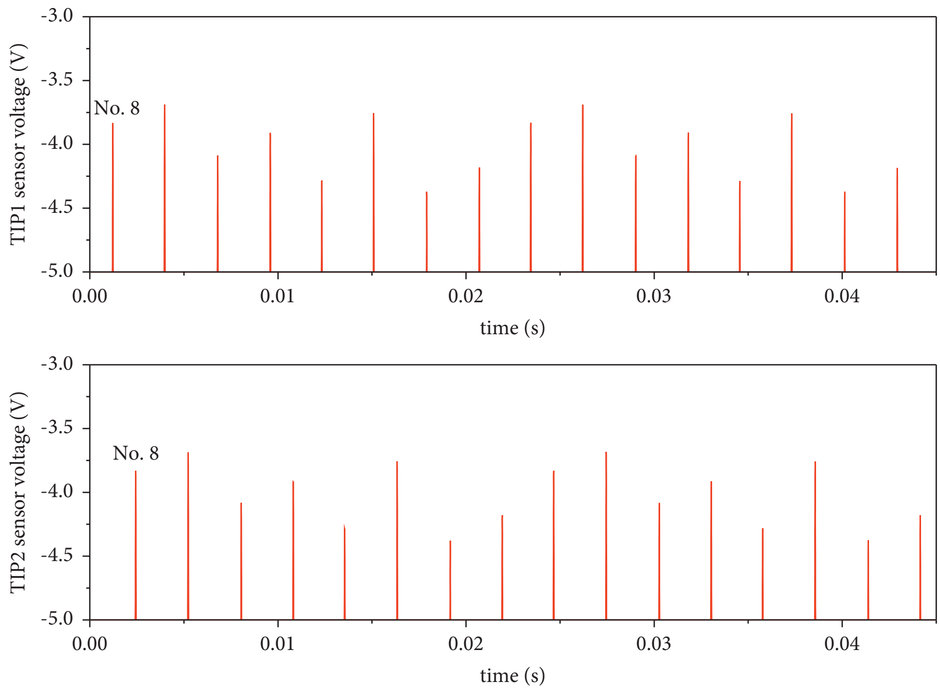


FIGURE 8: Measurement result of the blade tip-timing sensors under resonance condition.

dynamic tip clearance correction value of the No. 8 blade. The correlation calculation between these two sequences and the template sequence are shown in Figures 9(a) and 9(b). It can be seen from Figure 9 that the rotation speed is near the resonance region, when $\tau_m = 1$, $C_1(\tau)$ has the maximum value. The blade serial number identified according to equation (8) is 8, which is consistent with the identification result of the OPR sensor method.

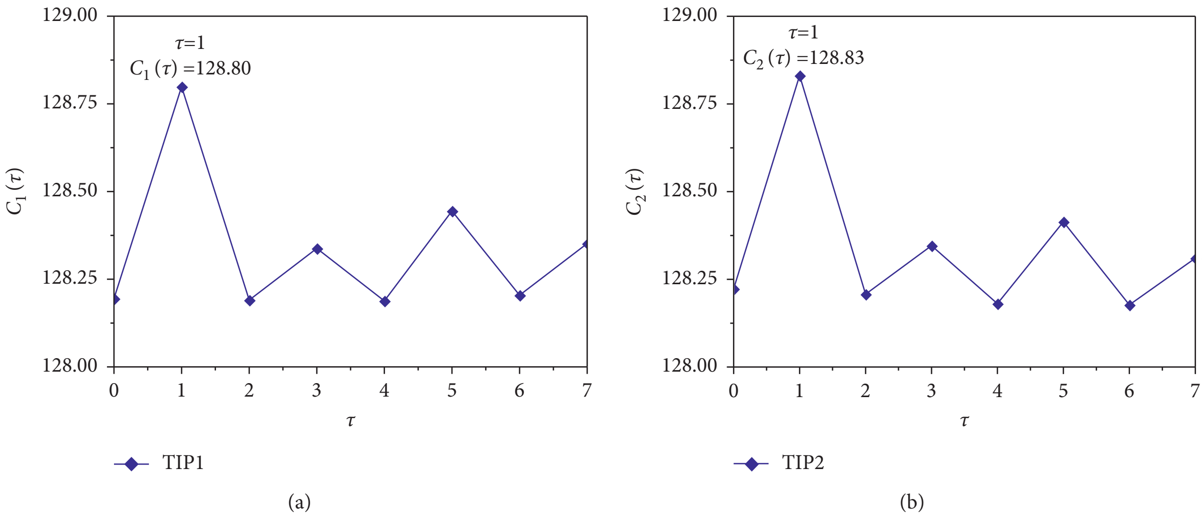


Figure 9: Correlation function calculation under resonant experimental condition of 2700 r/min. (a) TIP1 sensor. (b) TIP2 sensor.

5. Conclusions

In order to overcome the shortcomings of the existing identification methods of blade serial number without OPR sensor, a new identification method based on blade tip clearance is proposed in this paper. Firstly, a theoretical model of blade serial number identification based on blade tip clearance is established in the case of no OPR sensor, and the corresponding relationship between blade tip-timing data and blade serial number is identified by using the matching relationship between blade tip clearances under static state and dynamic state. According to the static and dynamic measurement experiment, the accuracy of the blade serial number identification method based on blade tip clearance is verified by the OPR sensor method. The specific conclusions are as follows: when the rotation speed is far away from the resonance region, the blade serial number identification method based on blade tip clearance can identify the blade serial number, and the identification results are consistent with the results of the OPR method. In the resonance rotation speed region, when the blade tip clearance change caused by the blade circumferential bending vibration is less than the dispersion of initial blade tip clearance, the method in this paper can accurately identify the blade serial number. Otherwise, the inference method can be used. The method proposed in this paper provides theoretical support and technical basis for the engineering application of blade tip-timing vibration measurement technology without OPR sensor.

Data Availability

The data used to support the findings of this paper are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this study.

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