Research Article

Effect of Detuning of Clamping Force of Tie Rods on Dynamic Performance of Rod-Fastened Jeffcott Rotor

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In view of the advantages of lightweight, high strength, easy cooling, and easy assembly, the rod-fastened rotor is widely used in the aeroengine and gas turbine. However, because of assembly, stress relaxation, material creep, and other reasons, the clamping force of the tie rods will be out of tune during the long-term operation of the rotor. The detuning of the clamping force of the tie rods not only affects the contact stiffness of the contact interface but also causes the rod-fastened rotor with a certain residual shaft bow, which will affect the dynamic characteristics of the rod-fastened rotor. Based on the statistical model of rough surface contact (GW contact model), this paper presents a method to calculate the equivalent flexural stiffness of rough surface considering the detuning of the clamping force of the tie rods and gives the calculation method of the residual shaft bow deformation of the rod-fastened Jeffcott rotor with detuning of the tie rods. The effect of the preload, the rate of detuning of the tie rods, the number of detuning tie rods on the natural frequency, and the response of residual shaft bow of the rod-fastened Jeffcott rotor at a certain speed are investigated. The results show that the detuning of the tie rods makes the flexural stiffness of the rotor inconsistent along with two main stiffness directions of the rotor, which makes the natural frequency of the rotor divided into two. The negative detuning of the tie rods decreases the natural frequency of the rotor, while the positive detuning of the tie rods increases the natural frequency of the rotor. The smaller preload or the larger rate of detuning of the tie rods makes the detuning of the tie rods have a greater influence on the natural frequency of the rotor. These results will provide a theoretical reference for the dynamic analysis and design of the rod-fastened rotor.

1. Introduction

The rod-fastened rotor is a kind of rotor structure widely used in aeroengine and gas turbines. It depends on one central tie rod or several circumferential tie rods to clamping the discs together. The rod-fastened rotor is a typical assembled structure, which has the advantages of lightweight, easy cooling, convenient assembly, and flexible selection of disc material. However, the complex structure also brings some difficulties in the dynamic analysis. The contact states of the interfaces between the discs are mainly ensured by the clamping force from the tie rods. Therefore, the clamping force is crucial, which will directly affect the contact stiffness of the contact interfaces of the discs. In the process of assembling, the tie rods are elongated to offer the preload to the discs. However, because of assembling, stress relaxation, and material creep, the clamping force of the tie rods will be uneven, which results in the detuning of the clamping force along the circumferential direction in the contact surfaces. It will affect the flexural stiffness of the rotor shaft segment and the dynamic performances. Besides, the detuning of the clamping force of the tie rods leads to the rotor with a residual shaft bow, which affects the amplitude of the rotor system. Some faults of the rotor system are from serious vibration. So the research on the effect of the detuning of clamping force on the dynamic characteristics of the rod-fastened rotor is quite necessary. However, few investigations have been focused on this aspect.
In recent years, some scholars put forward the dynamic model of the rod-fastened and analyze the dynamic behavior of it. Rao [1] built a mechanic model of the rod-fastening rotor based on a comprehensive analysis of the structural characteristics of the rod-fastened rotor. The correctness of the model is proved by comparing it with experimental results. Qi et al. [2] studied the dynamic characteristics of the gas turbine rotor considering contact effects and pretightening forces. An improved 2-D FEM method considering the contact effect was given and improved the computing accuracy of the critical speed of the rotor. Sanches et al. [20] discussed how to identify the bow of a rotor with a residual shaft bow by simulation and error were considered. Songet al.[19] studied the vibration characteristics of a geared rotor-bearing system in which the residual shaft bow. Kang et al. [18] studied the dynamic characteristics were proposed to identify the presence of a rotor with a residual bow during its operation time. Several observations were proposed to identify the presence of a rotor with the bow. Kang et al. [18] studied the dynamic characteristics of a geared rotor-bearing system in which the residual shaft bow, the gear eccentricity, and the gear’s transmission error were considered. Song et al. [19] studied the vibration of a rotor with a residual shaft bow by simulation and experiment. Sanches et al. [20] discussed how to identify the two most common faults of unbalance and residual shaft bow in rotating machines by theoretical and experimental techniques.

The above reports are all focused on the normal rotors, which have no detuning of the clamping force of the tie rods. However, in engineering, the uneven clamping force is unavoidable because of the assembling, self-loosening of the bolt, and material creep. Therefore, this paper investigates the dynamic performances of the rod-fastened rotor with the uneven clamping force of the tie rods. First, based on the GW contact model (the statistical model of rough surface contact proposed by Greenwood and Williamson), a method of calculation of the flexural stiffness of the interfaces with the detuning of the clamping force of the tie rods is proposed. Meanwhile, residual shaft bow deformation of the rotor resulted from the detuning of the clamping force of the tie rods is given. Then, the effect of preload, the rate of the detuning of the tie rods, and the number of the detuning tie rods on the dynamic performance of the rotor system are investigated. Some useful conclusions will provide a reference to the dynamic design of the rod-fastened rotor.

2. Theoretical Analysis

2.1. The Flexural Stiffness of the Rod-Fastened Jeffcott Rotor.

The rod-fastened Jeffcott rotor depends on the eight circumferential tie rods to clamping the two shaft heads, and there is an annular contact interface between the two shaft heads (see Figure 1). The length of both end shaft segments is \( L_1 \), respectively. The length of the clamped shaft segment is \( L_2 \). The elastic modulus of the material is \( E \). The moment of inertia of the end shaft segments is \( I_1 \), and the moment of inertia of the clamped shaft segment is \( I_2 \). Due to the series relation between the shaft segments and the contact interface in the structure, the flexural stiffness of the rod-fastened Jeffcott rotor can be expressed as

\[
K_s = \frac{2L_1 + L_2}{(2L_1/EI_1) + (L_2/EI_2) + (1/G_s)},
\]

where \( G_s \) is the equivalent flexural stiffness of the contact interface and \( E \) is the elastic modulus of the material.

According to the statistical model of rough surface contact proposed by Greenwood and Williamson, the contact of the two rough surfaces is the contact behavior of the microconvex bodies distributed on them. The relationship of the pressure between the contact surfaces and the distance between the two reference surfaces of the rough contact surface [21] can be written as

\[
P = \frac{4}{3\sigma\sqrt{2\pi}} \eta A_{nom} E' \beta^{1/2} \int_0^{\infty} (z - d_0)^{3/2} e^{-z^2/(2\sigma^2)} dz,
\]

where \( P \) is the pressure between the contact surfaces and \( z \) is the root mean square of the height distribution of the microconvex body. \( \eta \) is the distribution density of the microconvex body of the rough contact surface. \( E' \) is the equivalent elastic modulus of the material. \( A_{nom} \) is the nominal contact area of the contact interface. \( d_0 \) is the distance between two reference contact planes without relative rotation after the preload is applied. \( z \) is the height parameter of the microconvex body.
The equivalent flexural stiffness of the contact interface [21] can be written as

\[ G_r = \frac{\partial M}{\partial \theta} = -\frac{2}{\sigma \sqrt{2\pi}} \eta E' \beta^{1/2} \int_{\lambda_{nom}} \int_{d_i} (z - d_0 - y\theta)^{3/2} e^{-\left(z^2/2\sigma^2\right)} y^2 dz \, d\lambda_{nom}, \]

where \( G_r \) is the equivalent flexural stiffness of the contact interface. \( M \) is the bending moment applied to the contact interface. \( y \) is the radial parameter of the contact surface. \( \theta \) is the rotation angle between two contact planes.

Due to the detuning of the clamping force of the tie rods, the equivalent flexural stiffness of the contact interface along the \( x \)-direction and \( y \)-direction will be not equal, which will lead to the rod-fastened Jeffcott rotor with asymmetric flexural stiffness along with the two main stiffness directions.

2.2. The Equation of Motion of the Rod-Fastened Jeffcott Rotor. According to Euler–Bernoulli theory, the lateral stiffness of the rod-fastened Jeffcott rotor can be given by

\[ K_{ji} = 48K_m(2L_1 + L_2)^{-3} = 48 \left( \frac{2L_1}{E_1} + \frac{L_2}{E_2} + \frac{1}{G_m} \right)^{-1} \left( 2L_1 + L_2 \right)^{-2}, \]

where \( i = x, y \). The \( x \)-direction and \( y \)-direction respect two main stiffness directions.

Figure 4 is the sketch map of the motion of the Jeffcott rotor. In Figure 4, \( O_g \) is denoted as the geometry center of the disc, and \( O_g \) is denoted as the center of mass. \( \delta \) is the residual shaft bow, \( e \) is the eccentricity, \( \omega \) is the angular velocity of the rotor, and \( \Psi_0 \) is the initial phase angle of the eccentric. \( Z \) is the dynamic displacement of the geometry center of the disc, and \( Z_g \) is the dynamic displacement of the center of mass of the rotor. \( xoy \) is the static coordinate system, and \( \xi \eta_0 \) is the dynamic coordinate system. Because the flexural stiffness of the rotor along the \( x \)-direction and \( y \)-direction is not equal, it is necessary to express the equation of motion of the rod-fastened Jeffcott rotor in the dynamic coordinate system. In the \( xoy \) coordinate system, the equation of motion of the rod-fastened Jeffcott rotor can be written as
2.3. The Calculation of the Residual Shaft Bow Deformation.

The detuning of the clamping force of the tie rods will lead to the rotor with the residual shaft bow. The residual shaft bow deformation will directly affect the vibration response. Therefore, the accurate calculation of the residual shaft bow deformation is essential.

It is easy to write the equation of motion of the rod-fastened Jeffcott rotor in the ξη coordinate system. It can be given by

\[
\begin{bmatrix}
\cos(\omega t) & -\sin(\omega t) \\
\sin(\omega t) & \cos(\omega t)
\end{bmatrix}
\begin{bmatrix}
\ddot{\xi} \\
\ddot{\eta}
\end{bmatrix}
+ 2\omega
\begin{bmatrix}
-\sin(\omega t) & -\cos(\omega t) \\
\cos(\omega t) & -\sin(\omega t)
\end{bmatrix}
\begin{bmatrix}
\dot{\xi} \\
\dot{\eta}
\end{bmatrix}
+ \begin{bmatrix}
\omega_1^2 - \omega^2 & 0 \\
0 & \omega_2^2 - \omega^2
\end{bmatrix}
\begin{bmatrix}
\cos(\omega t) & -\sin(\omega t) \\
\sin(\omega t) & \cos(\omega t)
\end{bmatrix}
\begin{bmatrix}
\dot{\xi} \\
\dot{\eta}
\end{bmatrix}
= \omega^2
\begin{bmatrix}
\cos(\omega t) & -\sin(\omega t) \\
\sin(\omega t) & \cos(\omega t)
\end{bmatrix}
\begin{bmatrix}
\xi_0 \\
\eta_0
\end{bmatrix}
+ \omega^2 \cos(\psi_0) \sin(\psi_0),
\]

where \(\xi_0\) and \(\eta_0\) are the residual shaft bow deformation in the \(\xi\eta\) coordinate system. \(\omega_1 = \sqrt{K_s/m}\) and \(\omega_2 = \sqrt{K_t/m}\) are the two first-order natural frequencies. In the rotating coordinate system, \(\xi\), \(\dot{\xi}\), \(\eta\), and \(\dot{\eta}\) take two main stiffness directions. Thus, \(k_x = k_x\) and \(k_\eta = k_\eta\).

When there is no eccentric of the mass of the rotor, the amplitude of steady response of the rod-fastened Jeffcott rotor with residual shaft bow can be derived from Equation 8. It can be given by

\[
\begin{bmatrix}
\omega^2 \xi_0 \\
\omega^2 \eta_0
\end{bmatrix}
= \begin{bmatrix}
\omega_1^2 & 0 \\
0 & \omega_2^2
\end{bmatrix}
\begin{bmatrix}
\omega_1^2 \xi_0 \\
\omega_2^2 \eta_0
\end{bmatrix}
\]

where \(\omega\) is the angular speed of the rotor; \(\omega_1\) and \(\omega_2\) are the two first-order natural frequencies. \(A_r\) takes the maximum value of vibration response in two directions \(\xi\), \(\eta\).

3. Results and Discussion

3.1. The Rotor Model. The rod-fastened Jeffcott rotor is shown in Figure 1. The main physical parameters are listed as follows: \(L_1 = 0.2\) m and \(L_2 = 0.1\) m. The outer radius of the
contact annulus \( r_1 = 0.125 \) m, and the inner radius of the contact annulus \( r_2 = 0.1 \) m. The installation radius of the tie rods \( r_t = 0.075 \) m. The elastic modulus of the material is \( E = 1.99 \times 10^9 \) N/m². The density of the material is \( \rho = 7.85 \times 10^3 \) kg/m³. The mass of the rotor is \( m = 50.84 \) kg. The number of the tie rods is \( n = 8 \).

The detuning of the clamping force of the tie rod will affect the frequency and the residual shaft bow response of the rod-fastened Jeffcott rotor. The following paper is mainly to investigate the effect law of the preload, the rate of detuning of tie rods, and the number of the detuning tie rods on the dynamic performance of the rod-fastened Jeffcott rotor.

3.2. The Effect of the Preload. According to the reference papers mentioned above, the preload is crucial to the rod-fastened rotor. It directly affects the contact state of the contact interface between the discs, which in turn affect the dynamic performance of the rotor system. As shown in Figure 6, the frequency of the rod-fastened Jeffcott rotor is monotonously increasing with the increase of preload. When the preload is larger than \( 5 \times 10^4 \) N, the rate of increase of the frequency of the rod-fastened Jeffcott rotor is very slow. That is, because in this situation, the frequency of the rod-fastened Jeffcott rotor is almost very close to the frequency of the corresponding integral rotor. That is to say, when the preload is relatively small, the contact state of the contact interface has a greater influence on the dynamic performance of the rod-fastened rotor.

Figures 7 and 8 plot the effect of the preload on the frequency of the rotor system when one tie rod is out of tune. In the figures, \( rf_1, rf_2 \) respects the rate of change of two natural frequencies. \( rf_1, rf_2 \) can be given by

\[
rf_i = \frac{F_{di} - F_{f}}{F_{f}} \quad i = 1, 2
\]

where \( F_{f} \) is the natural frequency of the rotor system when the clamping force of the tie rods is uniform, while \( F_{di} \) is the natural frequency of the rotor system when the clamping force of the tie rods is detuning.

It shows that the detuning of the tie rods leads to the flexural stiffness of the rod-fastened is not equal along the two main stiffness directions, which makes the rotor have two first-order frequencies. The negative detuning of the tie rod makes the frequency of the rotor decrease, while the positive detuning of the tie rod makes the frequency of the rotor increase. The absolute value of the rate of change of the frequency of the rotor is decreasing with the increase of preload. It means that the detuning of the tie rod has a
greater effect on the frequency of the rotor when the preload is relatively smaller. When the preload is larger than 5e4N, the effect of detuning of one tie rod on the frequency of the rotor is very small and almost negligible. When the preload is the same, the larger absolute value of the rate of detuning of the tie rod has a greater influence on the frequency of the rotor. Comparing Figure 7 with Figure 8, under the same preload and the absolute value of the rate of detuning of the tie rod, the negative detuning of the tie rod has a large effect than the positive detuning of the tie rod.

Figure 9 plots the effect of the preload on the residual shaft bow deformation of the rotor system and the effect of the preload on the response amplitude of the rotor with a certain speed (2407 rad/s) when one tie rod has a negative detuning. It shows that the residual shaft bow deformation is monotonously increasing with the increase of the preload. However, the amplitude of response of the rotor with a certain speed decreases firstly and then increases with the increase of the preload. The preload of the trend turning point is about 2.5e3N. This is because, when the preload is smaller than 2.5e3N, the flexural stiffness of the rod-fastened rotor is relatively smaller. Although the residual shaft bow deformation of the rotor is small, the response amplitude of the rotor is not very small. In this situation, the flexural stiffness of the rod-fastened rotor is the deciding factor. The flexural stiffness of the rod-fastened rotor is increasing with the increase of the preload and the amplitude of response of the rotor decreases. When the preload is larger than 2.5e3N, the flexural stiffness of the rod-fastened rotor is relatively larger, and the rate of change of the flexural stiffness of the rod-fastened rotor is relatively smaller. In this situation, the residual shaft bow deformation of the rod-fastened rotor is the deciding factor. The residual shaft bow deformation of the rotor is increasing rapidly with the increase of the preload, and the response amplitude of the rotor also increases rapidly. The larger absolute value of the rate of detuning of the tie rod has a greater influence on the residual shaft bow deformation and the response amplitude of the rotor.

Figure 10 plots a comparison of the residual shaft bow deformation and the response amplitude of the rotor under the conditions of the positive detuning and the negative detuning of one tie rod. It is shown that the effect law of the positive detuning of the tie rods and the negative detuning of the tie rods on the residual shaft bow deformation and the response amplitude of the rotor are the same. However, the negative detuning of the tie rods has a larger residual shaft bow deformation and the response amplitude of the rotor compared with the positive detuning of the tie rods at the same preload and absolute value of the rate of detuning of the tie rod, especially when the preload is relatively smaller.

3.3. The Effect of the Rate of Detuning of Tie Rods. Figures 11 and 12 plot the effect of the rate of detuning of one tie rod on the frequency of the rotor. It can be seen that the negative detuning of the tie rod and the negative detuning of the tie rod all make the absolute value of the rate of change of the frequency of the rotor increase with the increase of the rate of detuning of one tie rod. It means that the larger the rate of detuning of tie rods have a greater influence on the frequency of the rotor. Under different preload situations, the effect law of the rate of detuning of tie rods on the frequency of the rotor is the same. When the rate of detuning of the tie rod is the same, the smaller preload has a greater influence on the frequency of the rotor.

Figure 13 plots the effect of the rate of negative detuning of one tie rod on the residual shaft bow deformation of the rotor system and the effect of the rate of negative detuning of one tie
rod on the amplitude of response of the rotor with a certain speed. It shows that the residual shaft bow deformation is linear monotonously increasing with the increase of the absolute value of the rate of negative detuning of one tie rod. The response amplitude of the rotor with a certain speed also increases with the increase of the preload. When the preload is smaller, the amplitude of response of the rotor increases exponentially with the increase of the preload, and the speed of increase is faster. When the preload is larger than 2.5e3N, the increase of the response amplitude of the rotor is linear.

Figure 10: A comparison of the residual shaft bow deformation and the response amplitude of the rotor under the conditions of the positive detuning and the negative detuning of one tie rod.

Figure 11: The rate of change of the frequency of the rotor with the rate of negative detuning of one tie rod.

Figure 12: The rate of change of the frequency of the rotor with the rate of positive detuning of one tie rod.

Figure 13: The change of the residual shaft bow deformation and the response amplitude of the rotor with the rate of negative detuning of one tie rod.

Figure 14 plots a comparison of the change of the residual shaft bow deformation and the response amplitude of the rotor with the absolute value of the rate of detuning of one tie rod under the conditions of the positive detuning and the negative detuning of one tie rod. It is shown that the change of the residual shaft bow deformation and the response amplitude of the rotor with the absolute value of the rate of detuning of one tie rod is the same under the positive...
detuning of the tie rods and the negative detuning of the tie rods. The negative detuning of the tie rods have a larger residual shaft bow deformation and the response amplitude of the rotor compared with the positive detuning of the tie rods when the preload is relatively larger.

3.4. The Effect of the Number of the Detuning Tie Rods. Figure 15 plots the rate of change of the frequency of the rotor with the preload under the different numbers of detuning tie rods. The rate of detuning of the tie rods is $-0.5$. It shows that, under different numbers of detuning tie rods, the change law of the rate of change of the frequency of the rotor with the increase of preload is similar. However, the larger number of detuning tie rods have a greater influence on the frequency of the rotor. Especially, when the preload is small, the number of detuning tie rods is four, the rate of change of the frequency of the rotor almost reaches 4.5%. Besides, the larger number of detuning tie rods makes the two frequencies of the rotor closer to each other. It means that the larger number of detuning tie rods makes the flexural stiffness along the two main stiffness direction tend to be consistent. The positive detuning of the tie rods makes the frequency of the tie rods increase, and this is just contrary to the result of the negative detuning of the tie rods. But the effect law of the number of detuning tie rods on the frequency of the rotor is absolutely consistent.

Figure 16 plots the rate of change of the frequency of the rotor with the rate of detuning of the tie rods under different number of detuning tie rods. The rate of detuning of the tie rods is $-0.5$. It shows that the effect law of the number of detuning tie rods on the frequency of the rotor is absolutely consistent.

Figure 17 plots the change of the residual shaft bow deformation and the response amplitude of the rotor with the preload under different numbers of detuning tie rods. The rate of detuning of the tie rods is $-0.5$. It shows that the effect law of the preload on the residual shaft bow deformation and the response amplitude of the rotor is absolutely consistent.

Figure 14: A comparison of the residual shaft bow deformation and the response amplitude of the rotor under the conditions of the positive detuning and the negative detuning of one tie rod.

Figure 15: The rate of change of the frequency of the rotor with the preload under the different number of detuning tie rods.

Figure 16: The rate of change of the frequency of the rotor with the rate of detuning of the tie rods under different number of detuning tie rods.
deformation and the amplitude of response of the rotor under the different number of detuning tie rods is consistent. The larger number of detuning tie rods makes the rotor have a greater residual shaft bow deformation, which leads to a greater amplitude of response of the rotor.

Figure 18 plots the change of the residual shaft bow deformation and the amplitude of response of the rotor with the rate of negative detuning of the tie rods under different number of detuning tie rods.

Figure 17: The change of the residual shaft bow deformation and the response amplitude of the rotor with the preload under different number of detuning tie rods.

the rate of negative detuning of the tie rods under the different number of detuning tie rods. The preload of the rotor is 2.5e3N. It shows that, when the rate of detuning of the tie rods is larger, the larger number of detuning tie rods has a greater influence on the frequency of the rotor.

4. Summary and Conclusions

Based on the GW contact model, this study presents a new method to calculate the equivalent flexural stiffness of rough surface considering the detuning of clamping force of the tie rods and gives the calculation method of the residual shaft bow deformation of the rod-fastened Jeffcott rotor with detuning of the tie rods. The effect of the preload, the rate of detuning of the tie rods, and the number of detuning tie rods on the dynamic performance of the rod-fastened Jeffcott rotor are investigated. Some conclusions can be drawn as follows:

(1) The detuning of the tie rods makes the flexural stiffness of the rotor inconsistent along the two main stiffness directions of the rotor, which makes the natural frequency of the rotor divided into two.

(2) The negative detuning of the tie rods decreases the natural frequency of the rotor, while the positive detuning of the tie rods increases the natural frequency of the rotor. The smaller preload or the larger rate of detuning of the tie rods make the detuning of the tie rods have a greater influence on the natural frequency of the rotor.

(3) With the increase of the preload, the residual shaft bow deformation of the rotor increases monotonically due to the detuning of the tie rods, and the response amplitude of the residual shaft bow of the
rotor decreases firstly and then increases. This is because, when the preload is relatively smaller, the flexural stiffness of the rod-fastened rotor is also relatively smaller. At this time, although the residual shaft bow deformation of the rotor is small, the amplitude of response of the rotor is not very small, because the flexural stiffness of the rod-fastened rotor is the deciding factor at present. The flexural stiffness of the rod-fastened rotor is increasing with the increase of the preload, and the amplitude of response of the rotor decreases. When the preload is relatively larger, the flexural stiffness of the rod-fastened rotor is also relatively larger, and the rate of change of the flexural stiffness of the rod-fastened rotor is relatively smaller. In this situation, the residual shaft bow deformation of the rod-fastened rotor is the deciding factor. The residual shaft bow deformation of the rotor is increasing rapidly with the increase of the preload, and the response amplitude of the rotor also increases rapidly.

(4) With the increase of the rate of detuning of the tie rods, the residual shaft bow deformation and response amplitude of the rotor all increase monotonically. Compared with the positive detuning of the tie rods, the negative detuning of the tie rods has a greater impact on the natural frequency of the rotor and makes the response amplitude of the rotor larger. The more number of detuning tie rods has the greater influence on the natural frequency and response amplitude of the rotor.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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