Rotor Connection Structure Interface Damage Control and Robust Design Method for Its Mechanical Properties

Chao Li, Binglong Lei, Jing Tian, Yanhong Ma, and Jie Hong

Abstract Aiming at the structural mechanics of aero-engine rotor structure with uneven distribution of mass and stiffness, interfacial connection and large bending loads, the relationship between the mechanical properties of the rotor connection structure and the interface contact state is analyzed, reveals the influence of the degree of interface damage on the mechanical properties of the connection structure. And the quantitative evaluation parameters of connection interface slip and friction-fatigue damage degree suitable for engineering design are proposed. A robust design method for mechanical properties of rotor systems based on connection interface deformation coordination and rotor strain energy distribution control is established. By optimizing the geometrical characteristic parameters of the rotor structure, the bending strain energy distribution of the rotor under the working load environment is adjusted, it can effectively control the deformation and coordination of the connection interface, reduce the friction-fatigue damage of the connection interface, so that the sensitivity of the mechanical properties of the connection structure to the applied load can be reduced, further ensure the robustness of the rotor's dynamic characteristics. Taking the connection structure in the high-speed rotor system as an example, the simulation results show the effectiveness of the robust design of the mechanical connection with the interface connection rotor connection structure.

Keywords Discontinuity · Connection structure · Damage control · Robust design

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1 Introduction

With the development of modern aviation engines to lightweight, high efficiency and high power, the safety, and reliability problems have become more and more prominent. Due to limitations of processing, assembly and other factors, there are many connection structures in the rotor of the engine. The change of the local contact state of the connection structure and the relative slip will cause a change in the relative positional relationship, so that the center of mass of the rotor system deviates from the center line of rotation, thereby generating additional the amount of imbalance causes the vibration of the whole machine. Due to the non-linearity and discontinuity of the mechanical properties of the interconnected rotor structure system, as well as the dispersion of dimensional parameters, initial assembly parameters and load characteristic parameters, the mechanical properties of the rotor system have certain non-determinism in the work. Therefore, the robustness of the rotor connection structure has important engineering application value for the rotor dynamics.

In the rotor dynamics design with low rotor structure load, the rotor can be analyzed as a continuous structure [1]. In recent years, domestic and foreign scholars have carried out a lot of research work on the influence of the connection structure on the dynamic characteristics of the rotor. Ma [2] studied the interval analysis of rotor dynamic response under non-determined load, Wang [3] studied the bending stiffness loss factor of bolted connection structure and used elastic modulus correction method to model the complex rotor structure of aero-engine. Jing [4] established a mechanical model that influences the deformation of the interface on the dynamic characteristics of the rotor. It is studied that the interface deformation will cause additional vibration force in the rigid rotor system. Truman [5] had an interference fit between the gear hub and the shaft caused by the connection interface. Invalidation, the failure mechanism of the micro-action and slip interface and their correlation are analyzed. Qin [6] analyzed the deformation of the fan-disk bolt structure under bending load, indicating Loss of stiffness causes a drop in the critical speed of the rotor. Because the rotor dynamic characteristics are particularly sensitive to the interface contact state under certain conditions, the connection interface will undergo macroscopic slip and collision with the load cycle [7, 8]. Hong [9] studied the mechanism of the stiffness loss of the high-speed rotor connection structure and the influence of the stiffness damage of the connection structure on the dynamic characteristics of the rotor.

The interface contact damage of the connection structure causes its mechanical properties to have a certain dispersion under different load environments, which leads to the non-determinism of the rotor mechanical properties. The robust design proposed by Dr. Genichi Taguchi is to reduce the working load and load environment to the structural mechanics. The sensitivity of the characteristics to improve the robustness of the mechanical properties of the structural system [10]. The robust design of modern mechanical systems is designed to reduce the sensitivity of working loads and environmental noise to structural mechanical properties, and to improve the robustness of structural system mechanical properties, having become the mainstream method of current engineering optimization [11]. Hong [12] analyzed the failure of the rotor connection interface and based on the design flow of the tolerance model method, the robust design of the contact stress of the rotor structural system connection interface.

In the discontinuous rotor structure system, the current research does not consider the manufacturing, assembly and load environment and other factors leading to the dispersion of the stiffness characteristics of the connection interface and its control method. This paper analyzes the mechanical relationship between the rotor connection structure and the contact interface. Based on the structural characteristics of the rotor, the mechanism and quantitative description method for the dispersion of the mechanical properties of the connection structure are carried out. By optimizing the geometrical parameters of the rotor connection structure and the strain energy distribution of the connection structure, the deformation and coordination of the connection interface can be effectively controlled, the friction-fatigue damage of the connection interface can be reduced, and the sensitivity of the mechanical properties of the connection structure to the change of the load environment can be reduced.

2 Rotor and Connection Structure Features

2.1 Rotor Structure Discontinuity

As shown in Fig. 1, it is a schematic diagram of the high-pressure rotor structure of a typical high thrust-to-weight ratio turbofan engine. The rotor is composed of a front journal, a drum and a rear-cone shaped drum, and its geometric configuration is a "π"-shaped structure. Due to the abrupt change in the geometry of the rotor structure, the mass/stiffness is unevenly distributed along the axial direction, as shown in Fig. 2. Therefore, the geometry and mechanical properties of the rotor structure will exhibit a certain discontinuity.

In order to make full use of material properties and reduce structural quality, the rotor is a non-continuous structure, using components of different materials and

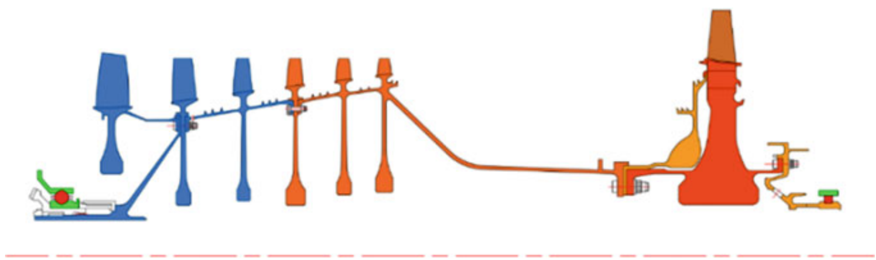


Fig. 1 High-pressure rotor structure

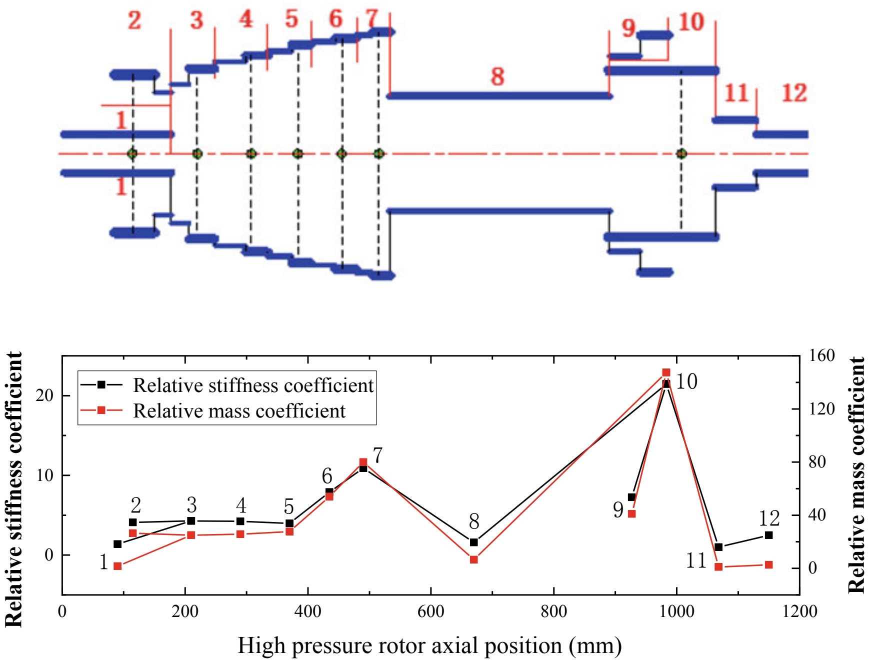


Fig. 2 High-pressure rotor stiffness/mass along axial distribution

different structures, such as components including wheels and drum shafts. Due to the limitations of processing and assembly, it is often necessary to use a connecting structure to form the rotor structure.

The discontinuity of the rotor structure is manifested in two levels: first, due to the rotor structure configuration, material and other factors, the rotor is axially rigid-mass discontinuous; second, due to the existence of the connection interface, the rotor is a non-continuous structure. Due to the structural geometry mutation and the existence of the connection interface, the rotor system must consider the structural discontinuity and its influence on the mechanical properties during the work. The stiffness characteristics of the connection structure directly affect the dynamic characteristics of the rotor system. In addition to its other parameters such as its own structure, the mechanical properties are decisive for the load environment that is subjected to the work, that is, only when a bending load acts on the rotor and a certain bending deformation occurs at the connection structure, the characteristics will show non-determinism and non-linearity. Therefore, the robust design of the rotor connection structure is mainly for high-speed rotor dynamics design.

2.2 Connection Structure and Contact Interface Characteristics

The connection structure is mainly carried and transmitted through the connection interface, and the connection interface mentioned here represents the contact interface between the interconnection components. The function of the contact interface can be divided into two aspects: load bearing and binding. (1) The contact interface transmits the load, and the load between the components is transmitted through the contact interface. The contact interface needs to maintain stable mechanical characteristics in the process. (2) The contact structure constrains the relative positional relationship between the components under the action of the load. In the process, the contact interface needs to restrain the relative motion of the components on both sides of the interface from the normal direction and the tangential direction. The connection interface generally has both the transfer load and binding functions.

According to the analysis of the function of the contact interface, since the contact interface can only withstand the pressure, the mechanical behavior of the contact interface in the working state can be described by the formula (1). Where $\vec{F}_1$ and $\vec{F}_2$ are the stress tensors at the interface of the connection structure, $\vec{D}_1$ and $\vec{D}_2$ are the corresponding displacement tensors, $\delta\vec{D}$ is the relative position amount, and Ω is the contact surface area.

$$\begin{cases} \vec{F}_1(x) + \vec{F}_2(x) = 0 \\ \vec{D}_1(x) - \vec{D}_2(x) = \delta\vec{D}(x) \end{cases}, \forall x \in \Omega \tag{1}$$

$\vec{F}_1(x) + \vec{F}_2(x) = 0$ indicates the function of transmitting the load at the contact interface, that is, the forces received by the members on both sides of the interface under the loaded condition are mutually reactive, and the equation is established due to the balance condition of the force. $\vec{D}_1(x) - \vec{D}_2(x) = \delta\vec{D}(x)$ denotes the binding function of the interface, that is, the constraint effect of the contact interface on the relative displacement of the two members under the loaded condition, wherein $\delta\vec{D}$ represents the strength of the local constraint of the contact interface by the relative displacement, the most ideal state there should be $\delta\vec{D} = 0$ underneath, that is, the contact interface does not show relative displacement at all.

As shown in Fig. 3, it is a schematic diagram of a short bolt connection structure contact interface. The members 1 and 2 on both sides of the contact interface are brought into contact under the action of the bolt preload force F, and according to the above analysis, the mechanical behavior of the contact interface can be described by the following formula:

$$\begin{cases} \sigma_1(x) + \sigma_2(x) = 0 \\ \tau_1(x) + \tau_2(x) = 0 \\ d_{n,1}(x) - d_{n,2}(x) = \delta d_n(x) \\ d_{t,1}(x) - d_{t,2}(x) = \delta d_t(x) \end{cases}, x \in [0, L] \tag{2}$$

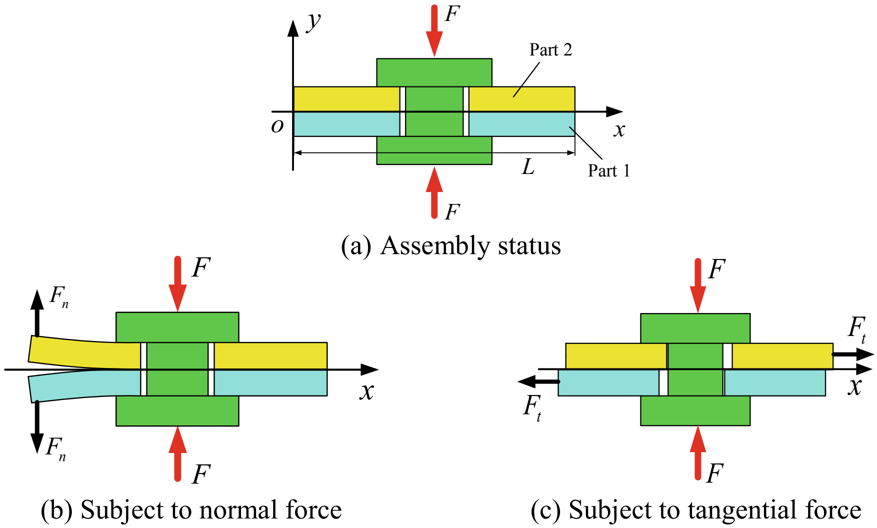


Fig. 3 Mechanical behavior of contact interface of short bolt connection structure

where σ, τ, d_n, d_t represent the normal stress, tangential stress, normal displacement and tangential displacement of the contact interface, respectively, and subscripts 1 and 2 represent the contact interface of the part 1 and the part 2.

Since the contact interface length is L, the domain of x is [0, L]. As shown in Fig. 3b, when the member is subjected to the normal force F_n, the contact interface is separated, and the mechanical behavior is as shown in the formula (3).

$$\delta d_n(x) \neq 0, \exists x \in [0, L] \tag{3}$$

$$\delta d_t(x) \neq 0, \exists x \in [0, L] \tag{4}$$

As shown in Fig. 3c, under the action of the tangential force F_t, if the contact interface is relatively slipped, the mechanical behavior is as shown in Eq. (4), and the connection structure has constrained failure, which may cause constraints. The boundary stress distribution deteriorates. In addition, under the action of different external loads, the distribution of stress σ and τ at the contact interface still satisfies Eq. (2), but the stress value changes, resulting in a change in the stress distribution at the contact interface and further a change in the interface mechanical properties.

In summary, the connection structure needs to function as a "transfer load" and a "constraint" in the rotor, making the design of the connection structure critical in the rotor structure. Due to the structural geometry and material properties, the high speed of the aero-engine rotor and the large variation range of the inertia load of the wheel, the working load that the connecting structure needs to bear during the work have interval distribution features. The robust design of the mechanical properties of the rotor system requires that the mechanical properties of the connection structure are least sensitive to changes in load under non-deterministic loads.

3 Connection Structure and Its Mechanical Characteristic Parameter Dispersion

3.1 Mechanical Properties of the Connection Structure

Because the contact interface of the connection structure can only bear the pressure and can't bear the tensile force, the mechanical characteristics of the connection under the action of non-determined external load are: discontinuous effective contact area of the interface, nonlinear interface stress distribution, discontinuous inter-interface angle, and interface slippage. The shift causes a bending stiffness loss and a centroid shift at the connection interface. Therefore, for a high-speed rotating rotor system, the connection structure stiffness damage coefficient and centroid offset are used to describe the mechanical characteristics of the connection structure.

Defining the stiffness damage coefficient k_p is used to describe the degree of damage of the bending stiffness of the connection structure.

$$k_p = (k_0 - k_s)/k_0 \tag{5}$$

where k_s represents the actual stiffness considering the influence of the connection interface in the rotor structural system, and k_0 represents the ideal stiffness of the rotor structure when the connection is consolidated.

As shown in Fig. 4, the flange-bolt connection is taken as an example. Under the action of large bending load, the flange edge is opened, the effective contact area is

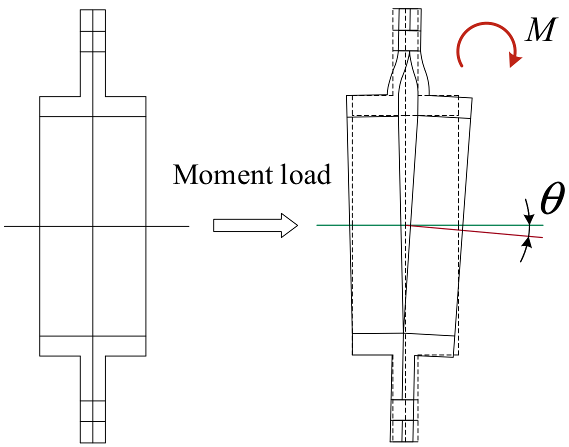


Fig. 4 Corner mutation diagram

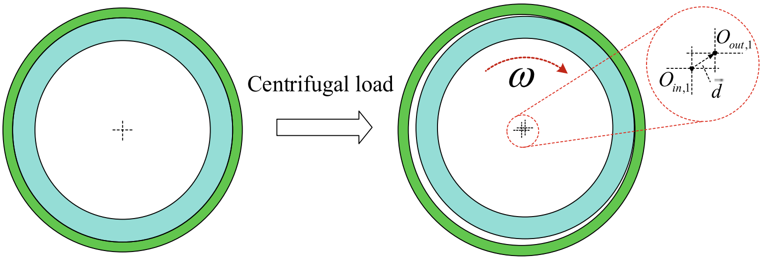


Fig. 5 Centroid offset diagram

reduced, and the corner of the connection position is abruptly changed, resulting in loss of bending rigidity of the connection structure.

The centroid offset caused by the connection structure refers to the unrecoverable deformation of the connection interface which gradually accumulates with the change of the working load. The distribution of the rotor interface deformation in the radial position of the rotor is uncoordinated, causing the rotor centroid to shift relative to the center of rotation. Radial offset $\vec{d}$ is generated for the centroids $O_{in,1}$ and $O_{out,1}$ of the corresponding section, creating an additional imbalance for the rotor structural system (Fig. 5).

The mechanical properties of the connection structure are closely related to the state of the contact interface. The connection interface can cause the deformation of the connection interface to be uncoordinated under the action of the high-speed working rotor centrifugal load. Under the action of additional constraints, the local contact interface stress may be too large or the interface may slip; under the large bending load, it may the effective contact area of the connection interface is reduced or the interface is slipped.

3.2 Contact Interface Damage Mechanism and Evaluation Parameters

Due to structural geometric parameters, assembly process parameters and load environment change with respect to design state, the change of contact state on the connection interface will cause the connection rigidity of the rotor and the change of the center of mass of the structure, which will have a significant impact on the dynamic characteristics of the rotor structural system. It is called the connection interface contact damage. The contact damage of the connection interface is the intrinsic reason for the dispersion of the mechanical properties of the connection structure. The mechanism is divided into three aspects: interface slip, interface contact stress fatigue damage, and interface friction damage. In this paper, the contact state coefficient C_{conta} of the interface, the irreversible deformation energy E of the interface, and the friction work W of the contact surface are proposed for the three aspects.

(1) **Contact interface slip Interface slip**

The sliding interface of the connecting interface means that when the connecting structure is subjected to the working load, the connecting interface is tangentially deformed to generate relative sliding deformation. When the working load is reduced or enters the parking state, a part of the connecting interface is present due to the frictional force on the connecting interface. Slip deformation is unrecoverable and may result in additional imbalances in the rotor structural system.

For the connection interface unrecoverable slip, the connection interface contact state coefficient C_{conta} is proposed to evaluate the damage degree. The contact interface is divided into four contact states according to the tightness of their mutual constraints: sticking and sliding, quasi-contact, and open, wherein only the interface is in a sticking and sliding state to transmit the load and provide rigidity. In order to ensure the stability and reliability of the connection interface under working conditions, it is required that the connection interface is viscous and the sliding area occupies a certain proportion, namely,

$$C_{conta} = \frac{A_{sticking} + A_{sliding}}{A_{total}} \times 100\% \tag{6}$$

where $A_{sticking}$ and $A_{sliding}$ are the area of the sticking state and the sliding state, respectively; A_{total} is the total area of the connection interface.

(2) **Contact interface fatigue damage**

Fatigue damage of the connection interface means that the connection interface bears a large normal pressure or a large normal pressure change in the assembled state and the working state, and the local region on the interface enters the plastic deformation to generate cracks or damage, and the damage mechanism is mainly the connection interface. Fretting fatigue occurs under contact stress.

For the contact fatigue damage of the connection interface, the interface contact stress and the irreversible deformation energy parameter are proposed to evaluate the damage degree. Since the interface contact stress distribution has unevenness, it is evaluated by using the maximum contact stress $\sigma_{\max}$ and the average contact stress σ_{aver}. The maximum contact stress is used to evaluate the degree of interface fatigue damage. The value should not exceed the surface micro-yield strength σ_{ms}. The average contact stress σ_{aver} is used to describe the degree of compression of the connection interface under various working conditions. The larger the value, the harder it is to loosen the connection interface, should ensure that its value is at a higher level. Based on the fatigue damage energy theory of the connection interface, the sum of the dissipative energy effects generated by each stress cycle is constant in the fatigue life. The irreversible deformation energy E represents the relative magnitude of the damage energy of each stress cycle, and the numerical transformation is used to calculate the deformation energy of the contact surface, namely,

$$E = \sum_{1}^{n} \sigma_{ai} \Delta \varepsilon_i A_i \tag{7}$$

In the formula n, σ_{ai}, $\Delta\varepsilon_i$ and A_i are number of contact unit nodes, the normal stress amplitude of the contact element node, the normal deformation of the contact element node and the contact element area, respectively. The unrecoverable deformation of the connection interface needs to meet the requirements of the connection structure during the fatigue life.

(3) **Contact interface friction damage**

Friction damage of the connection interface means that the connection interface is subjected to centrifugal and bending loads under working conditions, resulting in a relative slip direction or slip zone of the interface, which generates a large tangential friction force on the contact surface, causing damage to the interface friction damage, and its damage mechanism. Mainly the connection interface produces fretting wear under the action of friction.

For the interface friction damage, the interface friction work W is proposed to evaluate the damage degree. Due to the inverse relationship between the contact friction work and the fretting damage life, the friction work is used as the parameter to evaluate the wear of the connection interface, and the damage degree of the interface during the fretting wear process is reflected. The frictional work of the contact surface is calculated by numerical integration, namely,

$$W = \sum_{1}^{m} \mu |\sigma_{ni}| |\delta_i| A_i \tag{8}$$

In the formula m, $\sigma_{\mathrm{n}i}$, δ_i and A_i are number of contact unit nodes, the normal contact stress of the contact unit node, the relative slip amount of the contact unit node and the contact unit area, respectively. In the finite element model, the contact friction work from the assembly state to the working state cannot be directly displayed. Therefore, the friction work of the process can be expressed by the difference of the frictional work of the two states, namely,

$$W = W_2 - W_1 \tag{9}$$

In the formula, W is the friction work from the assembled state to the working state, W_1 is the friction work loaded into the assembled state, and W_2 is the friction work loaded into the working state.

3.3 Rotor Mechanical Properties Dispersion

Contact damage at the rotor connection interface changes the mechanical properties of the connection structure, which further causes changes in the dynamic characteristics of the rotor. The vibration equation of the rotor under external load excitation is

$$[M]\{\ddot{x}\} + ([G] + [C])\{\dot{x}\} + [K]\{x\} = \{p(t)\} \tag{10}$$

where $\{x\}$ is the displacement response, $\{\dot{x}\}$ is the corresponding velocity, $\{\ddot{x}\}$ is the corresponding acceleration, $[M]$ is the mass matrix, $[G]$ is the gyro moment matrix, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix, and $\{p(t)\}$ is the excitation force. Due to the loss of stiffness of the connection structure, each coefficient of the stiffness matrix has an interval distribution, which can be expressed as

$$\begin{cases} [K] = [k_i] \ (i = 1, 2, \ldots, m) \\ k_i = k_i^c + \delta k_i \in [k_i^c - \Delta k_i, k_i^c + \Delta k_i] \end{cases} \tag{11}$$

Therefore, the resonance frequency $[\lambda] = [f_{cr,i}(k, m, c)]$ and the response characteristic $\{x(k, m, c, p(t))\}$ obtained by the equation are also interval distributions. Taking the resonance frequency as an example, $f_{cr,i}(k, m, c)$ is a function of $[K]$, $[M]$, and $[C]$, and also has an undefined interval distribution.

$$\begin{aligned} f_{cr,i}(k, m, c) &= f_{cr,i}(k + \delta k, m + \delta m, c + \delta c) \\ &= f_{cr,i}(k, m, c) + \delta f_{cr,i}(k, m, c) \\ &\in [f_{cr,i} - \Delta f_{cr,i}, f_{cr,i} + \Delta f_{cr,i}] \end{aligned} \tag{12}$$

As shown in Fig. 6, the finite element model of a high-pressure rotor of an engine is taken as an example to investigate the influence of the stiffness loss on the first-order bending vibration frequency of the rotor by the finite element method. The stiffness

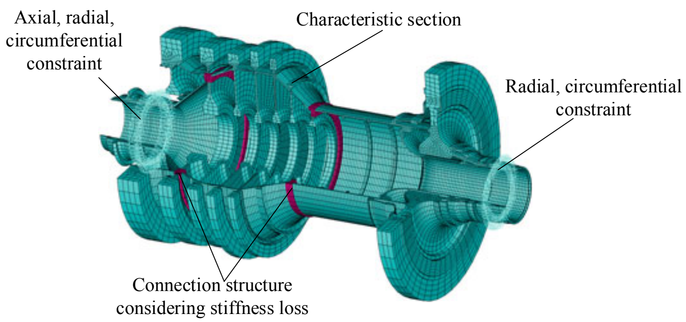


Fig. 6 Rotor finite element model

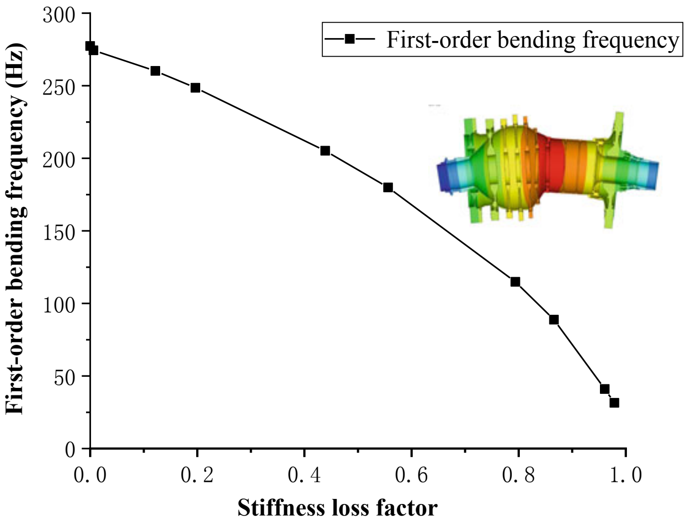


Fig. 7 First-order bending frequency is deformed with loss of stiffness

loss is simulated by modifying the elastic modulus of the connection structure. Adjust the elastic modulus of the two joint structural materials in Fig. 6. Consider the original support mode of the rotor, the left ball bearing applies a simplified full constraint, and the radial and circumferential constraints are applied to the right ball bearing. The equivalent stiffness of the rotor is loaded with lateral load at the characteristic section, and the corresponding lateral displacement is calculated. The ratio of force to displacement is the equivalent stiffness.

The stiffness loss coefficient is the equivalent stiffness considering the stiffness loss and the equivalent stiffness ratio without considering the stiffness loss. As shown in Fig. 7, in order to calculate the influence curve of the connection stiffness loss coefficient on the first-order bending frequency of the rotational speed, it can be seen that after considering the stiffness loss, the first-order natural frequency increases with the increase of the stiffness loss coefficient.

4 Robust Design of the Connection Structure

Rotor connection structure robustness refers to the ability of the mechanical properties of the rotor connection structure to be insensitive to changes in assembly conditions and load environment during operation. That is, within the allowable range, the connection structure is required to have as small a stiffness damage factor and centroid, and the bending stiffness remains stable as the working state changes and does not change in the dynamic characteristics of the rotor.

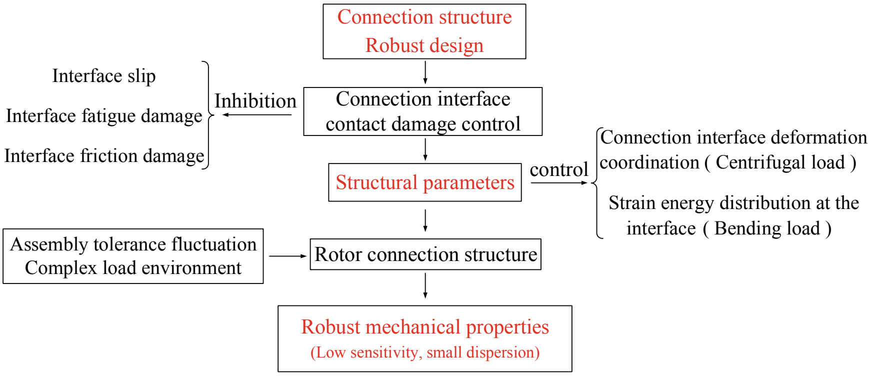


Fig. 8 Robust design idea of rotor connection structure

According to the cause of the dispersion of the mechanical characteristics of the connection structure and the interface damage mechanism, the robust design of the high-speed rotor connection structure should be designed and optimized from the contact damage control of the connection interface. In the specific structural design, the connection structure parameters can be rationally designed to control the connection interface deformation coordination and reduce the strain energy distribution of the connection structure, thereby controlling the interface damage and improving the robustness of the connection structure, as shown in Fig. 8, which is the rotor connection structure robust design ideas.

4.1 Connection Interface Contact Damage Control Method

Connection interface contact damage control design is a multi-parameter, multi-objective robust design to achieve effective control of interface contact conditions and damage. The following connection interface damage control design model is proposed as follows:

$$\begin{cases} \min F[Y_{conta}(G, A, L)] \\ s.t.\ g_j\left(Y_{joint}\right) \le 0\ j = 1, 2, \cdots, l \end{cases} \tag{13}$$

where Y_{conta} represents the contact parameters of the connection interface, G, A, and L represent the geometric parameters of the connection structure, the assembly process parameters, and the work load parameters, and Y_{joint} represents the mechanical characteristics of the connection structure.

In engineering, the joint coordination design of the joint interface and the strain energy distribution design of the joint structure are proposed to control the joint interface damage. The load on the connection structure is complex and variable.

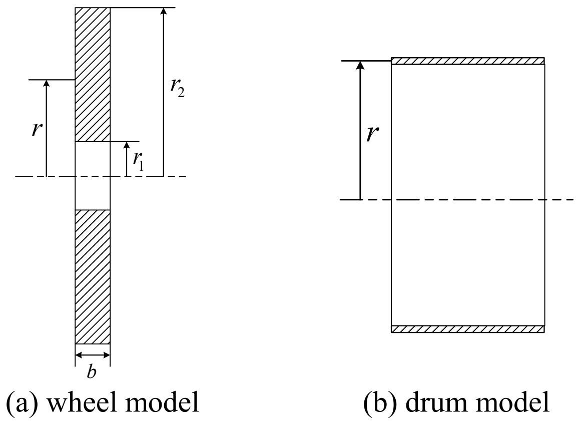


Fig. 9 Schematic diagram of radial deformation model

If the deformation of the connection interface is not coordinated, under the action of additional constraints, excessive stress will be generated locally at the connection interface, causing stress damage. Taking the drum-wheel connection structure design as an example, the radial deformation formula of the equal-thickness wheel is calculated by the displacement method [15].

Taking the wheel-drum connection structure as an example, the equal-thickness wheel and drum model as shown in Fig. 9 is established, and the radial deformation formula (14) of the equal-thickness disk under centrifugal load is derived.

$$u_d = \rho\omega^2 \frac{r}{E} \frac{(1-\mu)(3+\mu)}{8} \left(r_1^2 + r_2^2 + \frac{1+\mu}{1-\mu} \frac{r_1^2 r_2^2}{r^2} - \frac{1+\mu}{3+\mu} r^2 \right) \tag{14}$$

where r is the radial position, r_1 wheel inner diameter, r_2 wheel outer diameter, u_d is the radial deformation of the wheel r position, w is the rotational speed, μ is Poisson's ratio, ρ is the density, and E is the elastic modulus. It can be seen that the radial deformation u_d of the wheel is independent of the thickness b.

For the solid disk $r_1 = 0$, the radial deformation from (14) is

$$u_d = \rho\omega^2 \frac{r}{E} \frac{(1-\mu)(3+\mu)}{8} \left(r_2^2 - \frac{1+\mu}{3+\mu} r^2 \right) \tag{15}$$

The drum can be approximated as a special wheel of $r_1 \approx r_2 \approx r$. The approximate radial deformation u_c under the centrifugal load of the drum is

$$u_c \approx \rho\omega^2 \frac{r}{E} \frac{(1-\mu)(3+\mu)}{8} \left(2r^2 + \frac{1+\mu}{1-\mu} r^2 - \frac{1+\mu}{3+\mu} r^2 \right) = \frac{\rho\omega^2}{E} r^3 \tag{16}$$

In Eqs. (15) and (16), the radial deformation of the disk and the radius are in a cubic polynomial function relationship. The radial deformation of the drum is in a cubic relationship with the radius. The radial deformation curve is drawn at a given

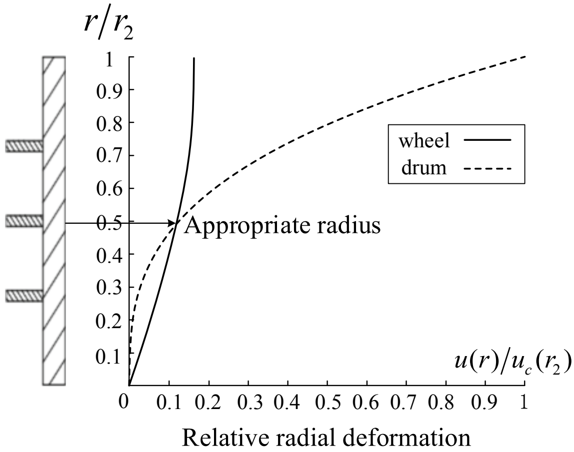


Fig. 10 Rotary drum radial deformation curve (given speed)

speed as shown in Fig. 10. The abscissa is the relative radial deformation (ratio of the radial deformation r_2 to the outer diameter of the drum), the ordinate is the relative radial position (ratio to the outer diameter $u_c(r_2)$ of the wheel), and the radial position of the drum and the wheel When the radial deformation of the interface is changed, the law of variation is different. The same position of radial deformation is called the proper radius.

Let $u_d = u_c$, from (15) and (16), assuming different material parameters, Poisson's ratio μ is the same, r_{cr} is the proper radius, then there is

$$\rho_d \omega^2 \frac{r_{cr}}{E_d} \frac{(1-\mu)(3+\mu)}{8} \left(r_2^2 - \frac{1+\mu}{3+\mu} r_{cr}^2 \right) = \frac{\rho_c \omega^2 r_{cr}^3}{E_c} \tag{17}$$

Finished

$$\frac{r_{cr}}{r_2} = \sqrt{\frac{\rho_d E_c}{\rho_c E_d} \frac{1-\mu}{3-\mu}} \tag{18}$$

where E_d is the disk elastic modulus, E_c is the drum elastic modulus, ρ_d is the disk density, ω is the rotational speed, ρ_c is the drum density, r_a is the wheel rim radius, and μ is Poisson's ratio of the material. It can be seen from (18) that the value of the proper radius is independent of the rotational speed and is only related to the material parameters of the wheel and drum.

Strain energy refers to the work done by external force on deformation displacement when the structure is deformed by external force. These work are stored in the form of energy inside the structure, so it is called strain energy, which can be used to quantitatively describe the damage of the structure under external force [15]. In the case, the strain energy is expressed as U_0, where the σ and ε distributions represent the normal and positive strains of the element, and τ and γ are the shear stress and the shear strain, respectively.

$$U_0 = \frac{1}{2}(\sigma_x\varepsilon_x + \sigma_y\varepsilon_y + \sigma_z\varepsilon_z + \tau_{xy}\gamma_{xy} + \tau_{xz}\gamma_{xz} + \tau_{yz}\gamma_{yz}) \tag{19}$$

Strain energy characterizes the potential energy stored in the object in the form of strain and stress. The strain energy indicates that the joint interface is prone to friction–fatigue damage. Therefore, reducing the strain energy distribution of the joint structure can effectively control the contact interface damage, thereby reducing the influence of the joint interface on the dynamic characteristics of the rotor system.

4.2 Robust Design of Rotor Connection Structure

(1) **Connection interface deformation coordination design**

The centrifugal load that mainly rotates the rotor at high speed will affect the deformation and coordination design of the connection interface. The interface deformation coordination mentioned here includes two aspects: one is the radial deformation coordination of the contact interface, and the other is the angular deformation coordination of the contact interface. We studied the drum-wheel connection structure design and the cone-rotor connection structure design by finite element method.

The main influencing factor of drum-wheel connection structure design is the radial deformation coordination of the contact interface. As shown in Fig. 11, two wheel-drum flange-bolt models of A and B are selected. The difference between the

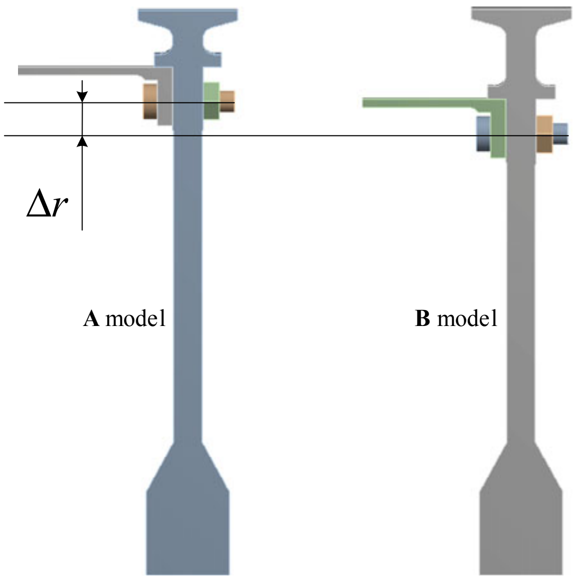


Fig. 11 Drum-wheel connection model

two models is B model. The bolt connection position radius is lower than the A model by Δr (20 mm), and the other conditions are the same. Given the same rotational speed (10,000 r/min), as shown in Fig. 12, the radial deformation difference of the centering cylindrical surface of the A and B models is 0.554 mm and 0.295 mm, respectively, and the radial deformation incompatibility of the B model is 46.8% smaller than that of the A model (Tables 1 and 2).

Apply the same bolt preload force 10 kN and speed 10,000 r/min to the A and B models and calculate the contact interface contact state and contact stress as shown in Fig. 13. Comparing the calculation data of the two models in the table, it can be clearly seen that the interface contact state of the B model under the working load is better, because the radial deformation inconsistency of the B model is smaller than that of the A model.

The simulation results of the two models show that the radial deformation coordination of the connection interface has a great influence on the interface contact state and the contact stress. Therefore, in the design of the connection structure, the uncoordinated connection interface should be reduced as much as possible.

The deformation coordination of the shell-wheel connection structure can be divided into two aspects: radial deformation coordination and angular deformation coordination, as shown in Fig. 14, $\Delta\theta$ in the figure represents the angular deformation uncoordinated quantity, and Δr represents the amount of radial deformation uncoordinated. The robust design of the radial deformation coordination is similar to the drum-wheel connection structure, the difference is that the radial deformation of the cone shell is affected by the radial dimension of the flange (represented by the circle of the indexing circle) R_u and the half cone Angle α is controlled by two parameters.

Different from the drum-wheel connection structure, in the robust design of the shell-wheel connection structure, the radial deformation coordination cannot guarantee the angular deformation of the flange end face and the wheel end face. Considering the centrifugal load, the deflection angle of the connection interface of the wheel is zero, so it is only necessary to consider the deflection angle of the flange edge of the cone. Under the action of centrifugal load, due to the characteristics of its own structure, the angle of the taper shell angle is enlarged, and the deformation of the cone shell and the flange edge at the joint is not coordinated, resulting in the deflection angle of the end face of the flange shell flange. This has an effect on the contact characteristics of the journal and the end face of the wheel end.

For the typical conical shell-wheel connection structure, the structure shown in Fig. 15a is used as a reference, and the axial span of the conical shell is kept constant, and the angle of the conical shell is reduced to form the structures shown in (b) and (c). The finite element model is used to calculate and analyze the variation law of the joint interface deflection angle with the rotation speed. It can be seen from the figure that the different cone angles and the deflection angle of the contact interface are different. Therefore, the angular deformation coordination of the contact interface should also be considered in the design. Measures such as local reinforcement can be used to ensure angular deformation coordination.

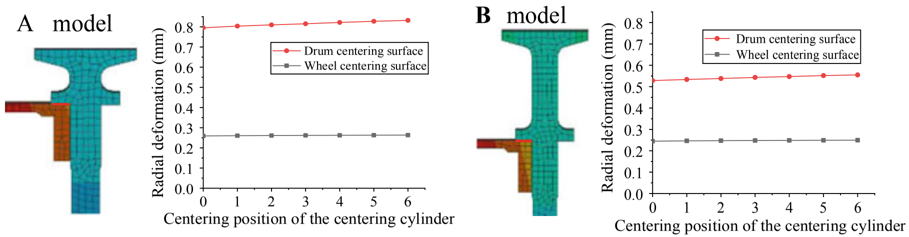


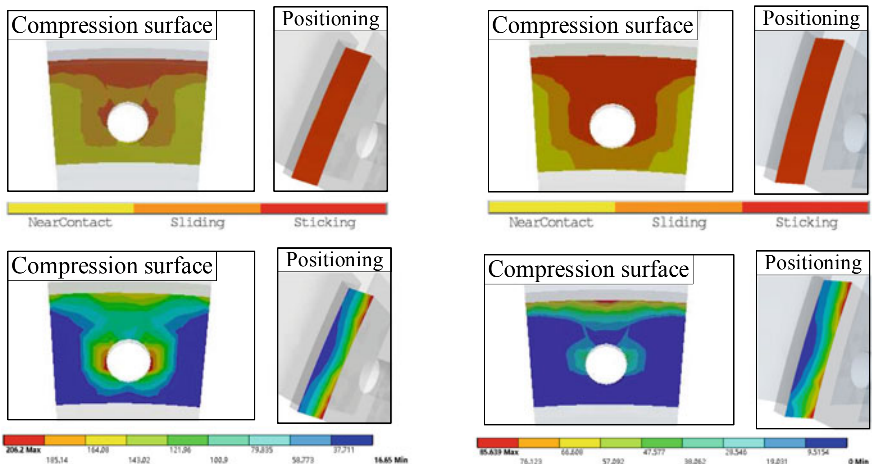
Fig. 12 Radial deformation of the positioning surface

Table 1 A model contact state and contact stress value

Interface	Sticking contact (%)	Sliding contact	Near contact	Max contact stress (MPa)	Aver contact stress (MPa)
Positioning surface	100.0	–	–	206	89
Compression surface	26.5	32.7%	40.8%	86	36

Table 2 B model contact state and contact stress value

Interface	Sticking contact (%)	Sliding contact	Near contact	Max contact stress (MPa)	Aver contact stress (MPa)
Positioning surface	100.0	–	–	121	63
Compression surface	62.7	21.5%	15.8%	52	30



(a) A model (b) B model

Fig. 13 Interface contact state and contact stress

(2) **Optimizing the design of strain energy distribution of rotor structure**

Interfacial friction–fatigue damage is fretting wear due to interface contact force. The working load cannot be accurately given in the design stage. Therefore, in the engineering, the strain energy distribution of the rotor structure can be optimized. As shown in Fig. 16, it is a three-stage axial flow compressor tester rotor structure. The rotor adopts a large-span two-point support and has a plurality of joint structures. From the bending vibration mode and strain energy distribution of the rotor in Fig. 17,

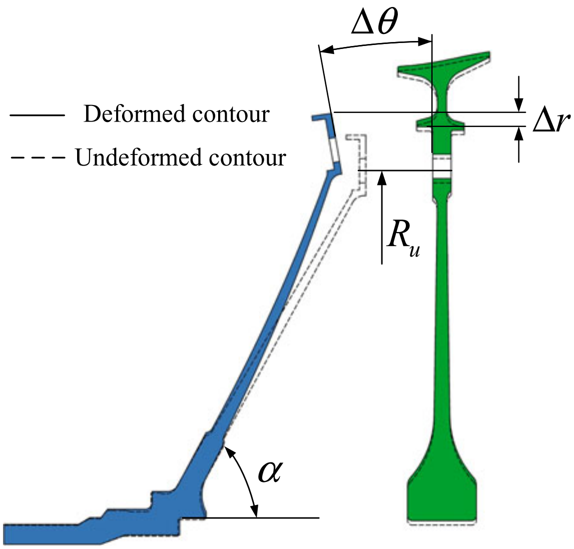


Fig. 14 Cone shell and wheel deformation under centrifugal load

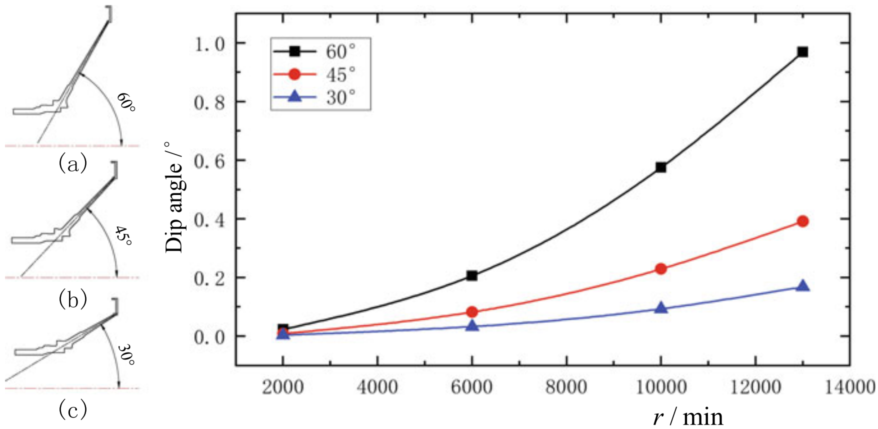


Fig. 15 Angle-dependent deformation of end face of different angles of cone shell with rotation speed

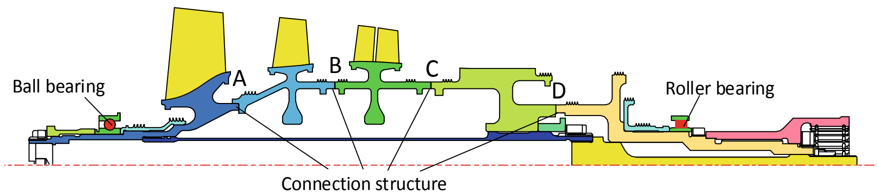
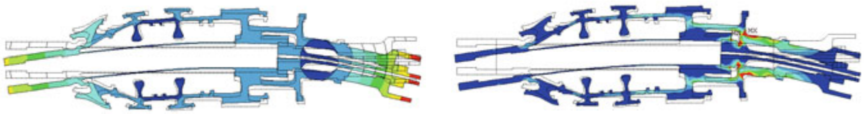


Fig. 16 Three-stage axial flow compressor tester rotor structure diagram



(a) Bending mode (b) Strain energy distribution

Fig. 17 Rotor bending mode and strain energy distribution

Table 3 Effect of stiffness loss of joint structure on critical speed of rotor system (r/min)

	Translational vibration mode	Rate of change	Pitching vibration mode	Rate of change	Bending mode	Rate of change
Regardless of stiffness loss	8640		16140		55020	
Consider stiffness loss	8460	↓ 2%	15720	↓ 3%	42915	↓ 22%

it can be seen that when the rotor has bending deformation, the strain energy near the joint structure of the joint is large, and the influence of the stiffness loss cannot be ignored.

The method of correcting the elastic modulus is used to consider the influence of the joint structure stiffness loss on the vibration characteristics of the rotor system [9]. The calculation results are shown in Table 3. The results show that the stiffness loss of the joint structure has little effect on the critical speed (translation and pitch) of the rigid body vibration mode and has a great influence on the critical speed of bending. The loss of stiffness of the joint structure can reduce the critical speed of the rotor bending by about 22%.

In order to reduce the stiffness loss of the joint structure and its influence on the critical speed of the rotor bending mode, the strain energy distribution at the joint structure under the bending mode should be reduced. According to the correlation between the vibration characteristics of the rotor system and the support stiffness, the support stiffness can be adjusted to optimize the strain energy distribution. Figure 18 shows the effect of the change in the stiffness of the front fulcrum on the strain energy of the joint structure. The reason for selecting the front fulcrum is that the front fulcrum is far from the node of the bending mode of the rotor, and the strain energy distribution of the connecting structure is sensitive to the change of the bearing stiffness.

It can be seen from Fig. 8 that after the support stiffness of the front fulcrum is appropriately increased (twice), the strain energy at the joint structure is reduced by more than 20%, and the influence of the joint structure stiffness loss on the vibration characteristics of the rotor system is calculated, as shown in Table 4.

It shows that by reducing the strain energy ratio of the rotor joint structure by 20%, the influence of the stiffness loss on the critical speed of the rotor system is reduced, while the rotor resonance safety margin is improved. In order to ensure the rotor vibration characteristics of multiple connection interfaces, the strain energy distribution under the bending mode of the rotor is optimized by adjusting the support

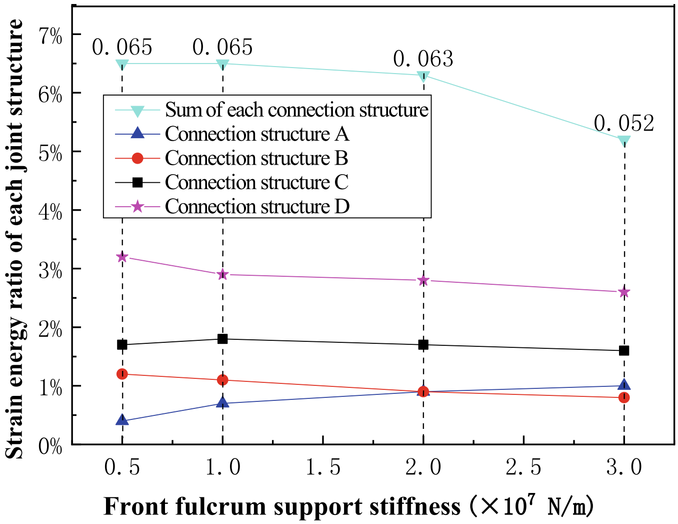


Fig. 18 The variation of the strain energy of the joint structure in the bending mode with the support stiffness of the front fulcrum

Table 4 Effect of stiffness loss on critical speed after optimization (r/min)

	Translational vibration mode	Rate of change	Pitching vibration mode	Rate of change	Bending mode	Rate of change
Initial support stiffness	8460		15720		42915	
Optimized support stiffness	9581	↑ 13%	17728	↑ 13%	54436	↑ 27%

stiffness, and the strain energy at the joint structure is reduced, which can effectively suppress the stiffness loss at the joint structure under bending deformation and reduce. The sensitivity of the bending critical speed of the rotor system to the stiffness loss ensures the robustness of the vibration characteristics of the rotor system.

5 Conclusion

This paper takes a typical engine high-pressure rotor as an example to analyze its structural discontinuity. Due to the limitations of rotor machining, assembly, materials, etc., it must have a connection structure. The mechanical model of the contact structure of the connection structure is established. The contact interface of the connection structure is analyzed from the load condition, and the change of the working load environment is obtained. The coordination state and mechanical characteristics of the connection interface have certain dispersion, and the robust design requirements are non-deterministic. Under load, the connection structure is least sensitive to changes in external loads. It is pointed out that the damage of the connection interface will cause the bending stiffness of the connection structure to decrease and the rotor centroid to shift, which will further increase the unbalance of the rotor system. The interface damage mechanism of the rotor connection structure is revealed, and the interface damage evaluation parameters of the connection interface state coefficient, interface deformation energy and interface friction work are proposed.

According to the mechanism of interface damage, this paper proposes a robust design method for controlling the interface damage and ensuring the low dispersion of the mechanical properties of the joint structure. The joint structure should be designed in the position where the interface deformation is coordinated, reduce the interface contact damage caused by the unbalanced deformation of the joint interface due to the centrifugal load, and move the position with large deformation from the joint interface to the continuous structure to optimize the bending strain energy. Distribution, reducing friction-fatigue damage caused by bending load on the joint interface. Taking the robust design of the typical connection structure as an example, it is concluded that the coordination position of the drum and the wheel is not related to the rotational speed and is related to the material parameters, and the higher the interface deformation coordination degree, the better the connection interface has a good contact state and Contact stress distribution; optimize the support stiffness to optimize the strain energy distribution under the bending mode of the rotor, reduce the strain energy at the joint structure, effectively suppress the stiffness loss at the joint structure under bending deformation, and reduce the sensitivity of the bending critical speed of the rotor system to the stiffness loss. Degree to ensure the robustness of the vibration characteristics of the rotor system.

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References

1. Chen M, Ma YH, Liu GS et al (2007) Rotor dynamics analysis of finite element model of aeroengine. J Beijing Univ Aeronaut Astronaut 33(9):1013–1016 (in Chinese)
2. Ma Y, Liang Z, Chen M et al (2013) Interval analysis of rotor dynamic response with uncertain parameters. J Sound Vib 332(16):3869–3880
3. Wang C, Zhang D, Zhu X et al (2014) Study on the stiffness loss and the dynamic influence on rotor system of the bolted flange connection. In: ASME Turbo Expo 2014: turbine technical conference and exposition. American Society of Mechanical Engineers, 2014:V07AT31A020
4. Jing H, Liu JX, Zhang DY et al (2018) Mechanical models of influence of interface deformation on rotor dynamic characteristics. J Beijing Univ Aeronaut Astronaut 44(6):1294–1302 (in Chinese)
5. Truman CE, Booker JD (2007) Analysis of a shrink-fit failure on a gear hub/shaft assembly. Eng Fail Anal 14(4):557–572

6. Qin Z, Han Q, Chu F (2014) Analytical model of bolted disk drum connections and its application to dynamic analysis of connectioned rotor. Proc Inst Mech Eng: Part C J Mech Eng Sci 228(4):646–663
7. Qin Z, Cui D, Yan S et al (2016) Hysteresis modeling of clamp band connection with macro-slip. Mech Syst Signal Process 66/67(1):89–110
8. Eriten M, Lee C, Polycarpou AA (2012) Measurements of tangential stiffness and damping of mechanical connections: direct versus indirect contact resonance methods. Tribol Int 50(4):35–44
9. Hong J, Xu XR, Su ZM, Ma Y (2019) Joint stiffness loss and vibration characteristics of high-speed rotor. J Beijing Univ Aeronaut Astronaut 45(1):18–25 (in Chinese)
10. Chen LZ (2000) Robust design. China Machine Press, Beijing (in Chinese)
11. Hasenkamp T, Arvidsson M, Gremyr I (2009) A review of practices for robust design methodology. J Eng Des 20(6):645–657
12. Hong J, Xu XL, Liang TY et al (2018) Interface failure analysis and robust design method in rotor structural system. J Aerosp Power 33(3):649–656 (in Chinese)
13. Wang HW, Ma JS, Nan JM et al (1991) Relationship between surface microscopic yield strength and fatigue limit. J Metals Metall 27(5):49–53
14. Song Z (1988) Strength design of aviation gas turbine engine. Beijing Aviation Academy Press, Beijing (in Chinese)
15. Dan HZ (2009) Material mechanics. Higher Education Press, Beijing (in Chinese)