Research on Creep Relaxation Non-uniformity and Effect on Performance of Combined Rotor

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Abstract: The combined rotor of gas turbine is connected by a certain number of rod bolts. It works in the high temperature environment for a long time, and the rod bolts will creep and relax. Under the influence of elastic interaction, the loss of pretightening force of rod bolts at different positions is non-uniform, which will cause the connection of the combined rotor to be out of tune. In this paper, the creep relaxation non-uniformity model for a class F heavy duty gas turbine is established. On the basis of this, the performance degradation and structural strength change of combined rotor resulting from creep relaxation non-uniformity of rod bolts are studied. The results show that the ratio of preload mistuning increases with time and then converges, and there is a threshold inflection point in about seven thousand hours.

1. Introduction
The combined rotor of gas turbine is divided into three parts: compressor, connecting section and turbine. The compressor is composed of 17 stage discs, and is compressed by 12 long rod bolts. The turbine section is composed of 5 stage discs, and is clamped by 12 short rod bolts, as shown in Figure 1. Combined rotor of gas turbine serve in high temperature, high pressure and high speed conditions, due to the impact of micro crack \cite{1} \cite{2} \cite{3} , rod unwinding relaxation \cite{4}, creep relaxation of rod \cite{5}, slip of discs \cite{6} and other factors, which will cause performance degradation and structural strength reduction of combined rotor. Under high temperature conditions, the creep of rod bolts will cause the reduction of preload, resulting in lower connection stiffness and severe vibration of rotor system. Therefore, it is important to study the creep relaxation of rod bolts.

Some scholars have studied the creep relaxation of rotor system at high temperature. Y Sun \cite{7} studied the creep characteristics of the rotor under bending residual stress. It was found that the creep relaxation alone was not enough to lead to the bending of the rotor during the start-up stage. Y Su \cite{8} carried out the stiffness equivalent treatment on the contact interface of combined rotor. The results show that the creep relaxation of the rod bolts will cause the natural frequency drift of the combined rotor.

H Zhang \cite{9} analyzed the creep of the rotor disk. It was found that the creep rate of the 1 stage disk is
the fastest, and the more the number of rod bolts, the greater the frequency drift. H Liu [10] studied the effect of creep on the fatigue of turbine rotors. It was found that the creep changed the steady strain of the rotor.

To sum up, scholars have studied the creep relaxation related mechanism of the rotor and single rod bolt, but there is little research on the creep relaxation mechanism of rod bolts group. Therefore, in this paper, rod bolts group of a gas turbine is taken as the object of study, and the influence factors of creep relaxation non-uniformity of the bolts are analyzed.

2. Mechanism of Creep Relaxation Non-uniformity of Rod Bolts

To ensure the relative uniformity of the force, the two cycle pre tightening method is adopted in the actual loading stage, and two rod bolts in the diagonal position stretch simultaneously. In order to describe the influence of the interaction between the rod bolts in different positions of the combined rotor, the elastic interaction stiffness \( K_{m,n} \) is introduced. The interaction stiffness \( K_{m,n} \) indicates that when the rod bolt \( n \) is stretched, the disc at the rod bolt \( m \) has the capability of resisting the elastic deformation, as shown in Figure 2.

After completion of loading, the preload variation can be expressed as:

\[
\begin{align*}
\Delta F_{x,3} + \Delta F_{x,9} &= -F(K_{x,3}^{-1} + K_{x,9}^{-1})(K_{3}^{-1} + K_{9}^{-1})^{-1} \\
\Delta F_{x,4} + \Delta F_{x,8} &= -F(K_{x,4}^{-1} + K_{x,8}^{-1})(K_{4}^{-1} + K_{8}^{-1})^{-1} \\
\Delta F_{x,5} + \Delta F_{x,10} &= -F(K_{x,5}^{-1} + K_{x,10}^{-1})(K_{5}^{-1} + K_{10}^{-1})^{-1} \\
\Delta F_{x,3} + \Delta F_{x,9} &= -F(K_{x,3}^{-1} + K_{x,9}^{-1})(K_{3}^{-1} + K_{9}^{-1})^{-1} \\
\Delta F_{x,6} + \Delta F_{x,10} &= -F(K_{x,6}^{-1} + K_{x,10}^{-1})(K_{6}^{-1} + K_{10}^{-1})^{-1}
\end{align*}
\]

The general expression of the high temperature creep model is:

\[\delta_{bcr} = L_C \sigma^{1/\epsilon} e^{\frac{\tau}{1+\epsilon}} \]

According to the deformation coordination of the contact surface, the change of the contact position is consistent with the creep extension of the rod bolts. The general model of creep relaxation Non-uniformity is as follows:

\[\Delta F^r = -K^\top \delta_{bcr} \]

Where

\[
K = \begin{bmatrix}
K_{1,1}^{-1} & K_{1,2}^{-1} & K_{1,3}^{-1} & \cdots & \cdots & K_{1,12}^{-1} \\
K_{2,1}^{-1} & K_{2,2}^{-1} & K_{2,3}^{-1} & \cdots & \cdots & K_{2,12}^{-1} \\
K_{3,1}^{-1} & K_{3,2}^{-1} & K_{3,3}^{-1} & \cdots & \cdots & K_{3,12}^{-1} \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
K_{12,1}^{-1} & K_{12,2}^{-1} & K_{12,3}^{-1} & \cdots & \cdots & K_{12,12}^{-1}
\end{bmatrix}
\]

3. Creep Relaxation Non-uniformity Analysis of Rod Bolts

3.1 The Mistuning Ratio Under Different Initial Preload Conditions

When the initial pretension is exactly the same, because of the elastic interaction between the bolts at different positions, the variation of preload will be uneven, which will cause the rotor to be out of tune. The ratio of preload mistuning of rod bolt set is changed [11], as shown in Figure 3. The ratio of preload mistuning of rod bolt set is 1.19% at the end of the simulation.
Figure 3. When the initial preload is tuned, mistuning ratio changes with time.

According to the formula of elastic interaction at the pre tightening stage, the ratio of initial preload is less than 1%. Therefore, the simulation of creep relaxation is carried out with the initial mistuning ratio of 1%, and the simulation time is 50,000 hours, as shown in the Figure 4. The mistuning ratio first diverges and then converges, and there is a threshold for the mistuning curve of rod bolts. When the combined rotor works for 7000 hours, the mistuning threshold is 1.29%.

During the assembly process, the initial mistuning ratio is limited to less than 5%. Under the condition of initial mistuning ratio of 5%, mistuning ratio changes with time, as shown in the Figure 5. At the end of the 50000th hour, the mistuning ratio of the rod bolts is reduced to 1.18%.

Figure 5. Mistuning ratio versus time under the condition of initial mistuning ratio of 5%.

3.2. The Mistuning Ratio Under Different Initial Different Rotating Speeds and Temperature

The combined rotor has different working conditions, such as speed, temperature, etc., which affect the connection stiffness caused by the unevenness of the creep relaxation of the rod bolt set. The simulation is carried out for two speed conditions, 3000 rpm and 1500 rpm, respectively. In the simulation process, The ratio of preload mistuning of rod bolt set is changed, as shown in Figure 6. When the speed is large, the mistuning ratio becomes larger, and the time required to reach the threshold is relatively short.

Figure 6. The mistuning ratio versus time under different rotating speeds.
Under the condition of initial detuning 1%, the combined rotors with operating temperature of 500 °C and 580 °C are simulated respectively, as shown in Figure 7. The higher the temperature is, the higher the mistuning ratio is, and the relatively short time it takes to reach the threshold.

3.3. Effect of Creep Relaxation on Structural Strength

For the combined rotor, the maximum contact stress is on the rod bolts, so it is necessary to study the contact stress between the rod bolts and the disk holes. In contrast to no creep relaxation, the variation of contact stress considering creep relaxation is different, as shown in Figure 8. The contact stress on the contact surface between the rod bolt and the disk hole is uneven in the axial direction. Under the influence of the centrifugal force generated by the high-speed rotation, the contact stress is a positive and negative change.

Figure 9. Turbine section model of combined rotor

Due to the lack of preload, the structural strength of the contact surface of the discs is reduced and micro slip occurs. Therefore, it is necessary to study the contact shear stress of disks contact surfaces, as shown in Figure 9 and Figure 10.

The contact stress between the discs of the combined rotor turbine has a transient decrease, and then increases gradually. After the threshold of mistuning ratio, the mistuning ratio decreases gradually and tends to converge.

4. Summary

From the above analysis, we can draw the following conclusions.

1. Under the influence of elastic interaction, the loss of pretightening force of rod bolts at different positions is non-uniform, which will cause the connection of the combined rotor to be out of tune.
2. The mistuning ratio first diverges and then converges, and there is a threshold for the mistuning curve of rod bolts.

3. When the speed is large, the mistuning ratio of rod bolts becomes larger, and the time required to reach the threshold is relatively short. At different temperatures, there is the same trend. As the preload decreases, the structural strength of the combined rotor decreases.

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