In this paper, a calculation model of the dynamic characteristic coefficient of labyrinth seal is established, the influence of rotor rotating speed and inlet and outlet pressure on the dynamic characteristic of labyrinth seal is numerically analyzed. The calculation results show that the cross stiffness and main damping are important factors affecting the stability of the seal rotor system; the increase of speed and pressure between inlet and outlet are not conducive to the stability of the system. On the basis of numerical analysis, a research device for air flow excitation test is set up to study the influence of rotor speed, pressure and other parameters on the vibration characteristics of the rotating subsystem. The experimental results show that the flow induced force increases the deformation degree of the flexible rotor, makes the stiffness of the rotor system change and changes the critical speed of the system. The flow of gas in the steam seal promotes the whirling of the rotor and makes the running track of the rotor more chaotic.

Keywords: labyrinth seal, flow induced force, dynamic coefficient, rotordynamic

1. Introduction

The air flow induced by labyrinth seal is the main reason for the instability of the turbine compressor unit, so it is significance to study the influence factors of the dynamic characteristics of the labyrinth seal to reduce the exciting force of the air flow and improve the stability of the system. The research on the exciting mechanism of labyrinth seals began in the 1960s. Alford flow model, spiral flow model and three-dimensional flow model were successively established. In recent years, with the development of computational fluid dynamics (CFD) technology, scholars have gradually started the mutual verification of numerical analysis and experimental research on sealed gas force[1-4].
In this paper, a calculation model of the dynamic characteristic coefficient of labyrinth seal is set up, and the influence of rotor rotate speed and pressure on the dynamic characteristics of labyrinth seal is numerically analyzed. On this basis, an experimental device for airflow excitation is set up, and the rotor speed and pressure difference are tested and studied on the vibration of the rotor system.

2. Numerical Calculation of Dynamic Characteristic Coefficient

2.1 Calculation Method

When the rotor moves in a small trajectory vortex at an eccentric position, the flow induced force can be represented by the linear relationship between the 8 dynamic characteristic coefficients and the displacement, velocity of the rotor[1]:

\[
\begin{bmatrix}
F_r(t) \\
F_r(t)
\end{bmatrix} =
\begin{bmatrix}
k_{xx} & k_{xy} \\
k_{yx} & k_{yy}
\end{bmatrix}
\begin{bmatrix}
x(t) \\
y(t)
\end{bmatrix} +
\begin{bmatrix}
c_{xx} & c_{xy} \\
c_{yx} & c_{yy}
\end{bmatrix}
\begin{bmatrix}
x(t) \\
y(t)
\end{bmatrix}.
\]

(1)

Where: \(F_r\) and \(F_r\) are the tangential and radial components of the flow induced force. \(k_{xx}\) and \(k_{yy}\) are main stiffness, \(k_{xy}\) and \(k_{yx}\) are cross stiffness; \(c_{xx}\) and \(c_{yy}\) are main damping, \(c_{xy}\) and \(c_{yx}\) are cross damping.

In actual calculation, the static eccentricity of the rotor is 0, the simplified linear relationship between flow induced force and gap, vortex motion speed, dynamic coefficients is as follow[1]:

\[
F_r / \delta = k - C \Omega
\]

\[
F_r / \delta = K - c \Omega
\]

(2)

Where: \(K\) is main stiffness, \(k\) is cross stiffness, \(C\) is main damping, \(c\) is cross damping.

In order to determine the dynamic characteristic coefficient of the labyrinth seal, the pressure distribution of the rotor wall in the steam seal must be calculated under certain boundary conditions and \(F_r\) and \(F_r\) should be obtained by integrating. Two groups of \(F_r\) and \(F_r\) are calculated under two different vortex velocity boundary conditions, and then the equations are solved jointly. Four unknown dynamic characteristic coefficients can be obtained.

In this paper, \(F_r\) and \(F_r\) under different conditions are calculated, and the dynamic characteristic coefficient of the seal is obtained. In the simulation the rotor rotating speed range is 2000 to 10000 r/min, the eccentricity is 0.5 times the seal gap, the pressure range is 0.05 to 0.35 MPa. The geometric parameters of labyrinth seals are as follows:

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameters</th>
<th>Item</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tooth Number</td>
<td>8</td>
<td>Tooth Depth (mm)</td>
<td>4.3</td>
</tr>
<tr>
<td>Seal Gap (mm)</td>
<td>0.2</td>
<td>Shaft Diameter (mm)</td>
<td>50</td>
</tr>
<tr>
<td>Outlet Pressure (MPa)</td>
<td>0.1</td>
<td>Inlet Pressure (MPa)</td>
<td>0.65</td>
</tr>
<tr>
<td>Fluid State</td>
<td>Ideal Gas</td>
<td>Inlet Temperature (K)</td>
<td>300</td>
</tr>
</tbody>
</table>
2.2 Influence of Rotating Speed on Dynamic Characteristic Coefficient

The following conclusions can be drawn: (1) the magnitude of the stiffness coefficient of the seal structure is about $10^5$, which is quite different from oil film stiffness coefficient, and the influence of the dynamic coefficient of the seal on the stability of the whole shafting is limited. (2) The numerical values of the main stiffness and the cross stiffness increase with the increase of rotating speed. The calculated values of stiffness are all negative, and the negative cross stiffness is beneficial to the stability of the rotor, but the negative main stiffness increases the eccentricity of the rotor, which is not conducive to the stability of the system. (3) The main damping and cross damping decrease with the increase of rotational speed, the increase of rotation speed is not conducive to the stability of the system from the damping coefficient.

2.3 Influence of Pressure on Dynamic Characteristic Coefficient

The following conclusions can be drawn: (1) The relationship between stiffness and the differential pressure is nonlinear, main stiffness and cross stiffness value increases with the increase of the pressure. This cause the increase of the air flow excitation force, which makes the stability of the system change. The increase of pressure difference between inlet and outlet is not conducive to the stability of the system. (2) Both the main damping and the cross damping decrease with the increase of pressure; when the pressure changed from 0.05 MPa to 0.15MPa, the main damping value decreased rapidly. When the pressure difference reached a certain value, the main damping value decreased gradually. (3) The main damping has a great influence on the system. From the perspective of the main damping, the increase of pressure is not conducive to the stability of the system.
3. Experimental Study on Airflow Excitation

3.1 Introduction on Test Device

In order to study the influence of the dynamic characteristics in the seal, an experimental device of the airflow excitation is designed. The device is mainly composed of variable frequency motor, support bearing, simulated cylinder and elastic support system. The device has the following characteristics: (1) The seal is easy to install and disassemble, and it is convenient to study the vibration characteristics of the airflow excited vibration and its influence on the dynamic characteristics; (2) The adjustable elastic support is adopted between the cylinder and the base to separate the seal from the whole system, and the influence of rotating speed, inlet pressure, inlet mode and other factors on vibration can be considered separately; (3) The device has an independent oil supply system to ensure stable operation of sliding bearings and gear boxes. By calculation, the theoretical value of critical rotor speed of the system is 3702r/min.

![System Diagram](image1)

(1) System Diagram

![Real Figure](image2)

(2) Real Figure

Figure 3: Experimental Device of the Air Flow Excitation.

3.2 Influence of Rotating Speed on Shaft Vibration

![Graph 1](image3)

(1) Front Bearing Seat

![Graph 2](image4)

(2) Rear Bearing Seat

Figure 4: Influence of Rotating Speed on Shaft Vibration.

It can be seen from figure 4: (1) When the pressure reaches 0.15MPa, the peak of the rotor vibration displacement is reduced from 3400r/min to 3200r/min. It is because the radial force increase the deformation of flexible rotor, which cause the stiffness of the rotor system change, and cause the critical speed of the system changed. (2) Under the restriction of the structural form of the system, the vibration of the front bearing is obviously larger than that of the rear bearing. This is because the front bearing connects with gear box; the bearing capacity is larger than the rear bearing. For bearings with larger capacity, the stiffness changes greatly, and the shaft vibration is obviously affected by the stiffness.
3.3 Effect of Pressure on Shaft Vibration

As can be seen from figure 5, the shaft vibration increases with the increase of the pressure, indicating that the direction of the gas pressure in the steam seal is the same as that of the rotor under the experimental pressure, which reduces the stiffness and damping of the rotor system and increases the vibration of the rotating shaft.

3.4 Analysis of Axis Orbit

When the operating speed is 2000r/min, the axis orbit of the rotor under different pressure is shown in the figure below.

Figure 6: Axis Orbit at Different Pressures.

Due to the limitation of the balance precision of the rotor and the difference of bending stiffness and supporting stiffness in different directions, the axis trajectory of the rotor as a whole is oval. When the pressure increased from 0 to 0.1MPa, the shape of the rotor's axis trajectory did not change significantly, the airflow force only increased the amplitude of the rotor. When the pressure increases to 0.2MPa, the effect of airflow force on the stiffness of the system begins to appear. The axis trajectory of the rotor starts to become regular circular, indicating that the airflow force makes the anisotropic stiffness of the system tend to be consistent.

4. Conclusion

The following conclusions can be drawn:

(1) The cross stiffness and main damping are important factors that affect the stability of the seal rotor system, but the influence is limited. The dynamic coefficient of the seal has limited influence on the overall stability of the system.

(2) The increase of speed and pressure not conducive to the stability of the system.
(3) The flow induced force aggravates the deformation of the flexible rotor, changes the stiffness of the system. The flow of gas in the seal accelerates the rotor's eddy motion, which makes the rotor's running track more disordered.

(4) Optimizing the seal structure form, increasing the main damping of the seal structure, can reduce the absolute value of the cross stiffness and the flow induced force, and increase the stability of the system.

REFERENCES


