Research on the Fluid Excitation Force of Seal and Its Influencing Factors Based on CFD

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Abstract. The flow field of seal has been modeled by CFD method in this paper, and the effects of rotor rotational speed and eccentricity on the fluid excitation force are analyzed. In order to study the mechanism of induced vibration force in seal, the velocity field and pressure field of fluid in seal are analyzed in detail in this paper, the calculation result shows that the rotor rotation will form a spiral flow when the fluid flows into the seal, it causes the uneven pressure distribution in the seal cavity and the high pressure point is not match to the minimum clearance, thus producing a tangential exciting force perpendicular to the eccentric direction of the rotor. It’s the ultimate reason of rotor instability.

1. Introduction
The effect of fluid excitation force on rotor vibration is more and more obvious, which is directly related to the safe and reliable of turbo machineries. In recent years, many theoretical and experimental studies have shown that the tangential excitation force in the seal is the main cause of the instability of the seal rotor system [1-3]. An advantage of using CFD is its capacity to analyze a large number of complex design configurations and parameters, and the use of CFD analysis in many rotary machines has been increasing rapidly in recent years with the development of commercial software [4-6]. Because of the restriction of field test for practical annual seal, it is a valuable work to study the influence of seal fluid excitation force on rotor stability by CFD. So, in this paper considering the above experiences, we also built a CFD model of seal to study the fluid excitation force of seal and its influencing factors.

2. Calculation Model
The parameters of seal calculation model in this paper is built according to the size of actual seal on our test rig. The diagram of seal model is shown in Figure 1. There are 6 rings of seal installed in the test cylinder, the compressed gas enters from the middle of the cylinder, and then flows out through 3 rings seal on both sides, and each seal have 4 teeth. For the convenience of calculation, the model seal has been simplified to one seal ring with 12 teeth as the Figure 2 show. The specific parameters of seal calculation model are shown in Table 1. Figure 2 also shows the computational grid diagram of the sealing model in this paper, the density of the mesh increases as it gets closer to the wall and tooth tip. A grid independence test has been carried out in this paper to ensure the accuracy of the final flow field calculation results.
Figure 1. Diagram of Seal Size

Figure 2. Seal Calculation Grid

Table 1. Parameters of Seal Calculation Model

| Parameter Name     | Value            | Parameter Name     | Value            |
|--------------------|------------------|--------------------|------------------|
| Teeth Number       | 12               | Rotation Speed/rpm | 1000–6000        |
| Inlet Pressure/Mpa | 0.2–0.8          | Inlet Temperature/K| 366.7            |
| Outlet Pressure/Mpa| 0.1              | Pre-rotation Speed/m.s⁻¹ | 0       |
| Fluid Type         | Ideal Gas        | Turbulence Model   | k-ε Model        |
| Eccentricity       | 0–0.7            | Average Gap/mm     | 0.5              |

3. Calculation Results Analysis

3.1. Velocity Field Analysis

Figure 3 shows the circumferential velocity cloud map of the axial seal chamber when the rotor speed increase from 2000 r/min to 6000 r/min under the condition of no inlet prerotation. It can be clearly seen from the figure that the circumferential flow is slowly produced because the fluid is driven by the viscous friction of the rotor. When the fluid enters the seal, the circumferential velocity is almost zero. As the axial flow increases chamber by chamber, the fluid has obvious circumferential velocity in the last chamber. Also, with the increase of the rotational speed, the increasing trend of the circumferential velocity is becoming more and more obvious. The generation of circumferential flow will cause the fluid to perform complex 3D spiral flow in the sealing clearance.
3.2. Pressure Field Analysis

Figure 4 shows the circumferential pressure cloud map of one seal chamber when eccentricity $\varepsilon = 0.5$. It can be seen obviously that the pressure distribution along the circumferential direction is uneven, and the pressure value at the small seal clearance is higher than the value at the big clearance.
\[ \Delta \alpha \quad \Delta \alpha \quad \Delta \alpha \]

- **a (\(\omega=2000\text{rpm}, \varepsilon=0.5\))**
- **b (\(\omega=4000\text{rpm}, \varepsilon=0.5\))**
- **c (\(\omega=6000\text{rpm}, \varepsilon=0.5\))**

Minimum Clearance Point
Figure 5. Curve of Dimensionless Circumferential Pressure in No 1, 4, 7, 10 Seal Chamber

As shown in Figure 5, the dimensionless circumferential pressure distribution curves of No1, 4, 7, 10 seal chamber along the axial flow direction at rotational speed $\omega$ is 2000 r/min, 4000 r/min and 6000 r/min. The eccentricities in Figure 5a, 5b, 5c are 0.5, and the eccentricity of Figure 5d is 0.1. The dimensionless pressure can be derived from the following equation:

$$P(i) = \frac{P(i)}{P_{max}}$$

In the above equation, $P(i)$ is the calculated actual pressure distribution along the circumference of each chamber, and $P_{max}$ is the maximum of $P(i)$.

Each curve has been set evenly 72 points along the circumferential direction, and the minimum clearance at the phase angle of 180°.

In the Figure 5, $\Delta \alpha$ represents the deviation of the highest pressure in the first and tenth seal chamber. The pressure distribution of each seal chamber along the circumference is approximately cosine. With the seal fluid flows from one chamber to the next, the pressure gradient of each chamber along the circumferential direction increases, also the angle of the pressure high point deviating from the minimum clearance of each chamber is increasing.

It can be seen from the Figure 5a, 5b, 5c, the pressure high points of each seal chamber under the conditions of 2000 r/min, 4000 r/min, 6000r/min are changed, as the rotating speed increases, the $\Delta \alpha$ is gradually increased. It shows that with the increase of rotational speed, the spiral flow is becoming more and more intense, the action point of seal force deviates more and more from the minimum clearance, which leads to the increase of tangential excitation force finally.

Compared with Figure 5d and Figure 5c, under the same rotational speed, the pressure curve with small eccentricity is more flat than the big one. It means the circumferential pressure gradient decreases when the eccentricity becomes smaller. Also the $\Delta \alpha$ in Figure 5d is smaller than that in Figure 5c, it shows that with the eccentricity becoming smaller, the resulting tangential excitation force becomes smaller.

3.3. Influence Factor Analysis for Excitation Seal Force

The seal force can be obtained by integrating the rotor surface pressure along circumference direction. Figure 6 shows the variation of radial and tangential forces with rotational speed, when the rotor
eccentricity $\varepsilon = 0.6$, the inlet pressure is 0.6 Mpa, the outlet pressure is 0.1 Mpa and the rotational speed from 1000 r/min to 6000 r/min. The result shows that the amplitude of radial force and tangential force both increase with the increase of rotational speed. The increased amplitude of tangential force is bigger than that of radial force.

Figure 7 shows the variation of radial and tangential forces with eccentricity, when the rotor rotational speed is 6000 r/min, the inlet pressure is 0.6 Mpa, the outlet pressure is 0.1 Mpa and the eccentricity from 0 to 0.7. The result shows that the fluid excitation force generated in the seal is very small when the relative position of the rotor and the stator in an ideal concentric state. When the eccentricity increases gradually, the radial and tangential excitation forces increase obviously.

4. Conclusion
In this paper, the flow field of seal has been modeled by CFD method, the velocity field and pressure field of fluid in seal are analyzed in detail to study the mechanism of flow induced vibration force in seal. From the above analysis, it can be seen that because the rotor eccentricity produces wedge clearance, the fluid pressure near the minimum clearance in the direction of rotation increases intensely. An apparent fluid flow excitation force opposite to the eccentric direction of the rotor has been generated. Due to the spiral flow of the seal flow driven by the rotor, the high point of the fluid pressure along the flow direction deviates gradually from the minimum clearance, which forms the tangential excitation force perpendicular to the eccentric direction of the rotor, and this force is the important cause of rotor instability.

Finally, the effects of rotor rotational speed and eccentricity on the fluid excitation force are analyzed. The result shows that the amplitude of radial force and tangential force both increase with the increase of rotational speed. The increased amplitude of tangential force is bigger than that of radial force. The result also shows that the fluid excitation force in the seal is very small when the relative position of the rotor and the stator in an ideal concentric state. But when the eccentricity increases gradually, the radial and tangential excitation forces increase obviously.
Figure 7. Seal Forces with Eccentricity

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