Numerical analysis of the static characteristic of orifice-type throttled aerostatic journal bearings

X H Zhang 1,2, C L Ke 1, N Peng 1, L Y Xiong 1,2 and L Q Liu 1,2
1 Technical Institute of Physics and Chemistry, CAS, Beijing, China
2 University of Chinese Academy of Sciences, Beijing, China

E-mail: zhangxiaohua15@mails.ucas.edu.cn
pengnan@mail.ipc.ac.cn

Abstract: The static characteristic of aerostatic journal bearing was studied by numerically simulating the state non-linear Reynolds equation. The finite difference method was used to solve Reynolds equation in MATLAB programming. The relation-ship between the static characteristics and hydrodynamic effect and hydrostatic effect were analyzed. The results show that the load capacity of bearing is directly proportional to the eccentricity ratio, the rotating speed, the air supply pressure and the diameter of orifices; increasing eccentricity ratio, the rotating speed is conducive to reduce the rotor attitude angle and improve the stability of the rotor; increasing the length diameter ratio of bearing and selecting the appropriate orifice position are beneficial to reduce the air consumption of bearing.

1. Introduction

Gas lubricated bearing is a kind of sliding bearing with gas as lubricant. It has a series of advantages, such as low friction power consumption, high motion accuracy and high and low temperature resistance. Therefore, it has been widely studied and applied in high-speed turbo expander and precision instruments [1][2].

Han[3] analyzed the influence of bearing air supply pressure on critical speed of aerostatic bearing rotor system. Li[4] carried out a numerical study on the bearing characteristics of aerostatic bearings. Li[5] carried out the simulation and experimental verification of gas bearing characteristics. Yu[6] studies the effects of aspect ratio, width of throttling slot, depth of throttling slot and thickness of gas film on static characteristics of bearing. Wang[7] simulated the flow field of the gas bearing by using the computational fluid dynamics software FLUENT, and solved the pressure distribution of the bearing gas film.

In this paper, the radial aerostatic bearing with small orifice throttling is selected as the research object. We divide it into pure dynamic pressure bearing and pure static pressure bearing. From the angle of hydrodynamic effect and hydrostatic effect, the working principle of orifice throttling hydrostatic gas bearing is clarified. Finally, how the structural parameters of bearing affect the dynamic and static pressure effects to produce static characteristic is studied.
2. Model of Aerostatic Bearing

2.1. Basic Equation of Aerostatic Bearing

For small-hole throttled aerostatic journal bearings, as shown in Figure 1 and Figure 2, the rotor is separated from the bearing under the combined action of dynamic pressure effect and orifice throttling effect, forming a frictionless gas film. Under isothermal conditions, the dimensionless form of Reynolds equation [4] for compressible gas is as follows:

\[
\frac{\partial}{\partial \phi} \left( PH \frac{\partial P}{\partial \phi} \right) + \frac{\partial}{\partial \xi} \left( PH \frac{\partial P}{\partial \xi} \right) = 2 \Lambda \frac{\partial (PH)}{\partial \tau} + \Lambda \frac{\partial (PH)}{\partial \phi}
\]

In the formula:

- \( P \) — the dimensionless film pressure
- \( H \) — the dimensionless film pressure
- \( \phi \) — the dimensionless circumferential coordinates
- \( \xi \) — the dimensionless axial coordinates
- \( \tau \) — the dimensionless time
- \( \Lambda \) — the dimensionless velocity

The boundary condition:

1. The end face of aerostatic bearing is environmental pressure:

\[ P(\phi, \xi=0) = P(\phi, \xi=L/R) = 1 \]

2. The aerostatic bearing satisfies periodic boundary conditions:

\[ P(\phi, \xi) = P(\phi + 2\pi, \xi) \]

3. The outlet pressure of orifice of aerostatic bearing is set as boundary condition:

\[ P(\phi_i, \xi_j) = P_{out} \]

![Figure 1](image1.png)  **Figure 1.** Structural diagram of bearing-rotor system.

![Figure 2](image2.png)  **Figure 2.** Position of rotor in bearing.

Defining dimensionless parameters:
\[ P = \frac{P}{P_a} \quad ; \quad H = \frac{h}{Cr} = 1 + \varepsilon \cos \varphi \quad ; \quad \Phi = \frac{x}{R} \]

\[ \xi = \frac{z}{R} \quad ; \quad \tau = \omega t \quad ; \quad A = \frac{6\mu R^2 \omega}{P_a Cr^2} \quad ; \quad P_s = \frac{P_s}{P_a} \]

In the formula:
- \( P \) — the film pressure
- \( P_s \) — the air supply pressure
- \( h \) — the film thickness
- \( C_r \) — the gas film gap
- \( e \) — the eccentricity
- \( \varepsilon \) — the eccentricity ratio \((\varepsilon = e/Cr)\)
- \( \omega \) — the rotor angular velocity
- \( t \) — time
- \( \mu \) — the viscosity of lubricant
- \( R \) — the rotor radius
- \( x \) — the circumferential coordinates
- \( z \) — the axial coordinates

### 2.2. Static Characteristics of Aerostatic Bearing

By solving Reynolds equation (1), the distribution of film pressure in the gas film gap can be obtained. As shown in Figure 2. Through the mechanical equilibrium conditions\[8\][9], \( F_n \) is the bearing loading capacity in the eccentric direction and \( F_t \) is the bearing loading capacity in the vertical eccentric direction:

\[ F_n = \int_0^L \int_0^{2\pi} (P - 1) \cos \varphi \, d\varphi d\xi \]

\[ F_t = \int_0^L \int_0^{2\pi} (P - 1) \sin \varphi \, d\varphi d\xi \]

The total bearing capacity of aerostatic bearing:

\[ F = (F_n^2 + F_t^2)^{1/2} \]  

The deflection angle of rotor:

\[ \theta = \tan \left( \frac{F_t}{F_n} \right) \]

The static stiffness of gas film:

\[ k = \frac{dF}{d\varepsilon} \]

### 3. Solution of Reynolds for Aerostatic Bearing

The outlet pressure \( P_{ij} \) of the orifice is treated as the boundary condition, which is helpful to simplify the Reynolds equation. According to the conservation of mass, the mass flow rate into the
orifice is $Q_{in}$ is equal to the mass flow rate $Q_{out}$ out of the orifice. The boundary condition $P_{out}$ can be solved. Finally, the distribution of gas film pressure $P_{ij}$ is obtained by using the over relaxation iterative method (SOR). The flow chart$^{[10][11]}$ of solving Reynolds equation for gas lubrication is shown in Figure 3.

![Flow chart of film pressure solution.](image)

**Figure 3.** Flow chart of film pressure solution.

**Table 1.** Basic structural parameters of aerostatic bearing.

| Name              | Symbol / Unit | Value |
|-------------------|---------------|-------|
| Length            | $L$ / (mm)    | 32    |
| Diameter          | $D$ / (mm)    | 16    |
| Gas Film Gap      | $Cr$ / (μm)   | 20    |
| Orifice Position  | $L_1$ / (mm)  | 8     |
| Orifice Diameter  | $d$ / (mm)    | 0.3   |
| Number of Orifices| $n$           | 8*2   |
| Air Supply Pressure| $P_s$ / (MPa) | 0.5   |
| Environmental Pressure | $P_e$ / (MPa) | 0.1   |
| Environmental Temperature | $T$ / (K) | 300   |

4. Operating Principle of Aerostatic Bearing

For pure dynamic pressure gas bearing, under the action of gas viscosity, the high-speed rotating rotor will draw the bearing gas into the wedge-shaped gap, forming a high-pressure area, as shown in Figure 4; the low-pressure area is formed at the position where the bearing gas was continuously transported to the wedge-shaped clearance$^{[12][13]}$, and the bearing capacity is formed under the interaction of high and low film pressure.
In the pure hydrostatic gas bearing, the rotor speed is 0, the eccentricity is 0, and the gas film pressure is distributed symmetrically along the radial direction, as shown in Figure 5, the bearing capacity is 0; When the rotor has unbalanced mass, resulting in the rotor eccentricity in the bearing, the gas film pressure has a negative correlation with the gas film thickness, and is axially symmetrically distributed along the dividing line. As shown in Figure 6, the bearing capacity of pure hydrostatic gas bearing is formed under the effect of pressure difference.

Combined with Figures 4, 6 and 7, the film pressure produced by the orifice-type radial aerostatic bearing not only has the hydrodynamic pressure effect produced by the hydrodynamic gas bearing, but also has the throttling effect of the hydrostatic gas bearing. As shown in Figure 7, the peak value of film pressure has deviated to the left from the center of symmetry. At this time, the position of the rotor in the bearing can be determined by the eccentricity \(\varepsilon\) and the attitude angle \(\theta\).

The essence of the orifice-type radial aerostatic bearing is the coupling bearing of the pure hydrodynamic pressure bearing and the orifice-type pure hydrostatic gas bearing. Therefore, the structure parameters such as the rotor eccentricity \(\varepsilon\), bearing number \(\Lambda\), air supply pressure \(P_s\), orifice diameter \(d\) can have an important influence on the static characteristics of the orifice-type aerostatic bearing.
5. Influence of System Parameters on Static Characteristics of Bearing

In order to verify the accuracy of the program results, the calculation results are compared with reference\textsuperscript{[4]}\textsuperscript{[4]}. Under the conditions of rotating speed $\omega = 0$, gas supply pressure of 0.5MPa, and the same bearing structure, the comparison results are shown in Figure 8. The two methods have good trend consistency, and the maximum error is less than 7%, which can inferred the correctness of the calculation results in this paper.

![Figure 8. Comparison of calculation results.](image1)

**Eccentricity Ratio**

The eccentricity ratio represents the ratio of eccentricity to gas film gap. As shown in Figures 9, 10 and 11, the bearing capacity increases with the increase of eccentricity, and the slope $k = \frac{dF}{de}$ of the bearing capacity also increases, which indicates that increasing the eccentricity of the rotor not only increases the bearing capacity, but also improves the static stiffness of the gas film.

As shown in Figure 9, with the increase of eccentricity ratio, the attitude angle of the rotor decreases, the ratio of $F_t/F_n$ decreases. The bearing capacity $F_t$ in the vertical eccentric direction is the main factor causing the rotor whirl\textsuperscript{[14]}\textsuperscript{[4]}. Therefore, increasing the eccentricity ratio increases the bearing loading capacity and improves the stability of the rotor.

![Figure 9. Influence of eccentricity on bearing capacity and attitude angle.](image2)

**Figure 10. Influence of eccentricity on bearing capacity under different bearing numbers.**

**Figure 11. Influence of eccentricity on bearing capacity under different pressures.**

![Figure 10](image3)

![Figure 11](image4)
Number of bearings

The number of bearings is the dimensionless form of rotor angular velocity. As shown in Figure 12, the bearing capacity increases with the increase of the number of bearings. With the increase of rotor speed, the attitude angle increases first and then decreases, which indicates that the bearing capacity in the vertical eccentric direction increases the instability of the rotor under the condition of small rotating speed. With the increase of rotating speed, the dynamic pressure effect becomes more and more important, and the stability of the rotor is improved continuously.

![Figure 12. Influence of bearing number on bearing capacity and attitude angle.](image)

![Figure 13. Influence of bearing number on bearing capacity under different eccentricity.](image)

![Figure 14. Influence of bearing number on bearing capacity under different air supply pressure.](image)

Figure 13 and Figure 14 show the influence of bearing number on bearing capacity under different eccentricity and gas supply pressure. It can be seen from the figure that the radial bearing capacity of the bearing increases with the number of bearings, but the slope decreases gradually. The results show that to a certain extent, increasing the rotor speed is an effective means to improve the bearing capacity, and the dynamic pressure effect of the bearing is gradually weakened under the condition of too high rotating speed. At this time, the radial bearing capacity of the bearing can be increased by increasing the eccentricity and gas supply pressure.

Air Supply Pressure

Figure 15 shows the effect of orifice supply pressure on bearing loading capacity, rotor attitude and bearing air consumption. With the increase of air supply pressure, the bearing capacity and mass
flow rate of the bearing are improved. It shows that increasing the air supply pressure increases the bearing radial bearing capacity and increases the air consumption of the bearing.

It can be seen from the figure that increasing the air supply pressure of the bearing leads to the increase of the rotor attitude angle. When the rotor is eccentric, the static pressure effect makes \( F_t \) and \( F_n \) increase, and the ratio of \( F_t/F_n \) increases, which reduces the stability of the rotor system.

![Figure 15](image)

**Figure 15.** Effect of air supply pressure on bearing capacity, attitude angle and mass flow rate.

### Aspect Ratio

It can be seen from Figure 16 that with the increase of length diameter ratio, the bearing capacity increases and the mass flow rate decreases. By increasing the length diameter ratio of the bearing, the high pressure area between the two rows of orifices is increased, and the flow resistance from the orifice to the end face of the bearing is increased. Therefore, the radial bearing capacity of the aerostatic bearing is improved, the air consumption of the bearing is reduced and the cost is saved. Therefore, the bearing with high aspect ratio is more suitable.

![Figure 16](image)

**Figure 16.** Effect of aspect ratio on bearing capacity, attitude angle and mass flow rate.

### Orifice Diameter

Figure 17 shows the effect of orifice diameter on the static characteristics of aerostatic bearings. The bearing capacity is improved by increasing the orifice diameter, but the air consumption and rotor attitude angle are increased at the same time.
Figure 17. Effect of orifice diameter on bearing capacity, attitude angle and mass flow rate.

Under the condition of keeping the orifice diameter unchanged, the bearing capacity and gas consumption of the bearing can be greatly increased by increasing the air supply pressure of the orifice as shown in Figure 18 and Figure 19. When the orifice diameter is large, the bearing gas consumption is huge, but the bearing capacity increase is small, which is uneconomical. Therefore, the orifice diameter of gas bearing should not be too large.

Figure 18. Influence of orifice diameter on bearing capacity under different gas supply pressure.

Figure 19. Effect of orifice diameter on mass flow rate under different gas supply pressure.

Orifice Position

The position of the orifice indicates the ratio of the distance $L_1$ of the orifice to the total length of the bearing L. As shown in Figure 20, the closer the orifice position is to the bearing end face, the more bearing gas leakage, resulting in the smaller bearing capacity; with the increase of the distance from the orifice to the bearing end face, the bearing gas leakage resistance increases, and the bearing gas consumption decreases continuously; as the high pressure area between the exhaust orifices decreases, the bearing capacity begins to decrease at 0.35 of the orifice position.
6. Conclusion

1. The orifice-type throttled aerostatic journal bearing is actually a kind of hybrid bearing \(^{[15]}\). The hydrodynamic pressure effect and the hydrostatic throttling effect are coupled together to form the gas film pressure, which makes the rotor rotate at high speed in suspension state. The average pressure produced by hydrostatic throttling effect is greater than that by hydrodynamic pressure effect in the orifice-type aerostatic bearing.

2. The results of numerical analysis show that the bearing capacity of the journal aerostatic bearing with orifice throttling can be improved by increasing the eccentricity of rotor, rotating speed and air supply pressure, adopting large length diameter ratio, large orifice diameter and reasonably arranging orifice position.

3. Bearing capacity in vertical eccentric direction \(F_t\) is the main factor causing whirl \(^{[14]}\). The results of numerical analysis show that increasing the eccentricity and rotating speed can reduce the rotor attitude angle. It is not recommended to use too large orifice diameter, and too large orifice position.

4. Gas consumption is one of the important indexes to evaluate the performance of gas bearing. The calculation results show that the air consumption and operation cost will be increased by increasing the air supply pressure and orifice diameter. The leakage of bearing gas can be reduced and the cost can be saved by selecting the proper position of orifice and the ratio of length to diameter of bearing.

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