CFD Investigation of an Aerostatic Thrust Bearing Flow Field with New Type of Throttling Structure

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Abstract

A new aerostatic thrust bearing was investigated using Computational fluid dynamic (CFD) method in this paper. The throttling structure of the aerostatic thrust bearing in this paper is an annular gap type. The CFD software FLUENT was used for solving NS equations. SST k-ω was used to serve as a turbulent flow model for the two dimensional axis fluid field. The load capacity, air flow rate at different bearing clearance and supply pressure were obtained by numerical simulation. The flow details such as pressure and mach number at different bearing clearance were discussed. The results show that, there is a stable high pressure zone of new aerodynamic thrust bearing. If the supply pressure or bearing clearance is high enough, the supersonic flow will occur in the throttle annular gap, and an oblique shock wave is produced around the end of gap.

Keywords: Aerostatic Thrust Bearing, CFD, Static Performance, Supersonic Flow.

1. Introduction

Aerostatic bearings have been successfully applied to various precision machines because of their advantages, such as high accuracy of motion and low friction, low temperature rise. A significant amount of work, both theoretical and experimental, has been published over the years on the various parameters affecting the performance of these bearings, for example, Sadek.Z[1] carried out an experiment investigation of an aerostatic bearing, the results show that as the supply pressure and film thickness increases the dimensionless load carrying capacity decreases and the lubricant mass flow rate increases. Renn[2] carried out the experimental and CFD study on the mass flow-rate characteristic through an orifice-type restrictor in aerostatic bearings, the results show that the mass flow-rate characteristic through an orifice is different from that through a nozzle. Yoshimoto[3] used CFD method studied the pressure field and shock wave distribution, their results reasoned pressure depression to the transition from laminar to turbulent flow and claimed that no shock wave is generated at the boundary between supersonic and subsonic flows. Eleshaky[4] studied two typical air thrust bearing using CFD method, the results showed that the predicted pressure distributions along the fluid film compare well with the corresponding experimental data of other investigators, and the work allowed a clear capturing of the coherent structures of the flow field in the bearing inlet region which include the coalescing of compression waves into shock waves and the region of shock boundary layer interaction (pseudo-shock).

Many investigators[5–11] have focused both theoretically and experimentally on studying the static and dynamic performance in air thrust bearing. Many studies have revealed the existence of an undesirable pressure depression for bearings operating under large bearing clearances, high air supply pressures, or high mass flow rates, in these works, a circular aerostatic thrust bearing with a single hole is always used. The speed of air plays an important role in static performance of these thrust bearing, if the air speed is supersonic, the static pressure is decreased compared with subsonic condition, so it is important to make the air thrust bearing working on a subsonic condition to hold a higher load capacity, on this point, a new orifice structure is investigated in this paper using CFD method.
Generally, the computation of radial flow in aerostatic circular thrust bearing is carried out by solving the classical Reynolds equation for compressible isothermal flows. Unfortunately, this computational approach fails to estimate the pressure distribution in the inlet region when negative pressures and flow discontinuities exist. CFD software plays an important role in bearing and lubrication simulation[12-13]. The Navier Stokes equations of air thrust bearing flow field are solved using CFD software FLUENT in this paper. The load capacity at different bearing clearance and supply pressure are calculated, the pressure and velocity field are also investigated.

2. Mathematical model

2.1 Geometry and Computational grid

The aerostatic thrust bearing analyzed in this paper is shown in Fig.1a, the thrust bearing is composed of main thrust bearing and blocking. The diameter of the bearing is 80mm, the throttling structure of the aerostatic thrust bearing in this paper is an annular gap type, the air flows through throttle annular gap under high pressure, the annular gap size is 0.2mm. In main thrust bearing part, there is a 10μm depth gap.

As the aerostatic is axially symmetrical, a 2d axial symmetry model has been assumed in this paper, and the computational grid is shown in Fig.2. The node number of bearing clearance direction is 20.

Figure 1. Aerostatic thrust bearing structure drawing: 1 main thrust bearing part, 2 blocking
2.2 Governing equations

In this paper, the conservation form of the Navier–Stokes equations for steady, compressible flow is being solved for the turbulent flow cases. The indicial notation form of these equations in the Cartesian coordinates is written as [3]:

Continuity equation
\[ \frac{\partial (\rho u_i)}{\partial x_i} = 0 \]

Momentum equation
\[ \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial P}{\partial x_j} + \frac{\partial P}{\partial x_i} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_l}{\partial x_l} \right) \right] - \frac{\partial}{\partial x_j} \left( \rho u_i u_j \right) \]

\( u_i \) is the time averaged Cartesian velocity components in the three coordinate directions. The Reynolds stress tensor \( \rho u_i u_j \) is written as:

\[ \rho u_i u_j = \frac{2}{3} (\rho k + \mu_\tau) \delta_{ij} - \mu_\tau \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \]

where \( \mu_\tau \) is the turbulent eddy-viscosity, \( \delta_{ij} \) is the Kronecker delta symbol which is equal to unity when \( i=j \) and zero when \( i \neq j \), and \( k \) is the turbulent kinetic energy \( \frac{1}{2} u_i u_i \). In order to close the equations, two more equations are required to determine \( \mu_\tau \) and \( k \).

In this paper the Stand \( k-\omega \) turbulent model [13] is used.

\[ \frac{\partial}{\partial x_i} \left( \rho k \frac{\partial u_i}{\partial x_j} \right) = \frac{\partial}{\partial x_j} \left( \Gamma_k \frac{\partial k}{\partial x_j} \right) + G_k - Y_k \]

\[ \frac{\partial}{\partial x_i} \left( \rho \omega \frac{\partial u_i}{\partial x_j} \right) = \frac{\partial}{\partial x_j} \left( \Gamma_\omega \frac{\partial \omega}{\partial x_j} \right) + G_\omega - Y_\omega \]

Where \( G_k \) represents the generation of turbulence kinetic energy due to mean velocity gradients. \( G_\omega \) represents the generation of \( \omega \). \( \Gamma_k \) and \( \Gamma_\omega \) represent the effective diffusivity of \( k \) and \( \omega \), respectively. \( Y_k \) and \( Y_\omega \) represent the dissipation of \( k \) and \( \omega \) due to turbulence. All of the above terms are calculated as described below.

Energy equation
\[ \frac{\partial}{\partial x_j} \left( \rho u_j (\sigma + P) \right) = \frac{\partial}{\partial x_j} \left[ \kappa_{\omega} \frac{\partial T}{\partial x_j} + u_j (\mu + \mu_\tau) \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_l}{\partial x_l} \right) \right] \]

The total energy, \( e \), and the effective thermal conductivity, \( \kappa_{\omega} \), are written as:
Where $\kappa$ is the thermal conductivity and $Pr_t$ is the Prandtl number taken for air is 0.85.

The molecular viscosity of the air is calculated from the Surherland’s law given by:

$$\mu' = \frac{\mu}{(T/T^*)^{1/2} (T^* + S)/T + S}, \quad \mu' = 1.716 \times 10^{-5}\text{Pa.s}, \quad S = 110.55\text{K}, \quad \text{and} \quad T^* = 273.11\text{K}.$$
3.2 Flow details in aerostatic thrust bearing

Fig. 7–8 show the pressure distribution along the radial direction, when supply pressure or bearing clearance is lower, the speed of air is subsonic. As the supply pressure or bearing clearance increased, the velocity field of aerostatic thrust bearing will achieve supersonic, and shock wave occurs. Fig. 7 gives five typical subsonic results and Fig. 8 gives three supersonic results with supply pressure 0.5MPa, it can be seen that the pressure field is divided into three parts according to distance of R, the first zone is R 0–15.75mm (the end of throttle annular gap), the second zone is R 15.75–35mm (the end of plane gap), and the third zone is R 35–40mm. In first zone, the static pressure remain unchanged as R increased in both subsonic and supersonic conditions, this feature makes the aerostatic thrust bearing a higher load capacity. In second zone, the speed increases for expansion of the air, because of this, the static pressure has declined markedly, but when bearing clearance is higher enough, there is a pressure jump at the end of annular gap, this is because the shock wave occurs. The air keeps on expanding in third zone and the static pressure continues to drop.

![Figure 7. Static pressure distribution against bearing radius](image)

![Figure 6. Mass flow rate at different bearing clearance (0.5MPa)](image)

![Figure 5. Mass flow rate at different supply pressure](image)
Fig. 8. Mass flow rate at different bearing clearance

Fig. 9 gives the mach number details around throttle annular gap and Fig. 10 gives the mach number distribution against radial direction at bearing clearance 40μm. From Fig. 9–10 it can be seen that in lower bearing clearance cases, when the air flows into corner of throttle annular gap, the speed of the air first increases, then decreases as shown in Fig. 9a, the maximum mach number around the corner is about 0.18, and it can be seen that there is a separation bubble in the corner. As the air flows from the end of throttle annular gap into the working space, the speed is increased, because this is an expansion, for example, when the bearing clearance is 40μm, the mach number increased to 0.38 at the end of the gap (Fig. 9b). When the air flow into the end of step, the speed increases as the flow area is decreased, but its mach number is still less than 1 (Fig. 9c).

Fig. 9. Mach number distribution details of subsonic case: (a) in throttle annular gap, (b) around the end of gap, (c) around the step.
Figure 10. Mach number distribution against bearing radius (h=20~40μm)

Figure 11. Mach number distribution against bearing radius (h=200μm)

Fig.11~12 show the mach number distribution and flow details at bearing clearance 200μm, it is different from lower bearing clearance case. At the corner of throttle annular gap, the air reach supersonic speeds and there is a normal shock around the gap as shown in Fig.12a, there is also a separation bubble around throttle annular gap likes lower bearing clearance condition. The air will be compressed when it flow pass the end of annular gap, so there is an oblique shock wave near the end of throttle annular gap as shown in Fig.12b. The air speed is dropped when it flow pass the end of the step as Fig.12c shows. Because of the oblique shock wave, there is a pressure jump around the end of gap as Fig.12d shows. It also can be concluded that the flow around the end of gap is shock-wave/boundary-layer interaction including boundary layer separation as Fig.12e shows, there is an obvious separation bubble in transonic flow compared with subsonic conditions (Fig.9b).
Figure 12. Flow details of supersonic case (h=200 μm):

(a) mach number in throttle annular gap, (b) mach number around the end of gap, (c) mach number around the step, (d) Static pressure around the end of gap, (e) Velocity around the end of gap

Generally speaking, for the traditional aerostatic thrust bearing the static pressure will decline sharply if the bearing clearance or supply pressure is very high, and the pressure will rise again in the location far away from the inlet, then it decline again until flow out the bearing. Compare with subsonic and supersonic conditions, it could be found that whatever the air maximum speed, the pressure in zone 1 is always a high value, this characteristic makes the aerostatic thrust bearing be different from other types of gas bearing, because of the high pressure in zone 1, the new aerostatic thrust bearing could working with high load capacity both in high or low bearing clearance.

4. Conclusion

A new aerostatic thrust bearing is studied using CFD software FLUENT, NS equations has been solved for compressed flow field. The static performance and flow details have been discussed. The numerical result shows that there is high pressure zone which makes the aerostatic thrust bearing work at a high load capacity. Other conclusion is as follows:

1. As the supply pressure or bearing clearance is increased, the air flow rate is increased, but if the flow is critical, the flow rate is unchanged.

2. The pressure field is divided into three parts according to distance of R, In first zone, the static pressure remain unchanged as R increased in both subsonic and supersonic conditions, this feature makes the aerostatic thrust bearing a higher load capacity.
3 If the supply pressure or bearing clearance is high enough, the supersonic flow will occur in the throttle annular gap and there is an oblique shock wave near the end of throttle annular gap.

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Nomenclature

P-Pressure, Pa,
T-Temperature, K,
ρ-Density, kg/m$^3$,
μ-Dynamic viscosity, Pa.S,
u-Flow field velocity, m/s,
h- Aerostatic thrust bearing clearance, μm,
R-Radius of aerostatic thrust bearing, mm.

6. References