Research on flow characteristics of aerostatic circular thrust bearing

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Abstract: In order to improve the pressure distribution, the aerostatic circular thrust bearing with single supply hole was studied. In the computational fluid dynamics (CFD) simulation, the laminar model, the turbulent model, the mixture model of laminar and turbulent were used simultaneously. The micro-characteristics of the gas flows were analysed based on the simulation results. One test rig was built for measuring the pressure distribution with the single test hole, and the calculated and experimental results were compared. The results showed that when the gas film clearance is small and the gas flow is subsonic completely, the whole gas flow is laminar flow, which should be calculated based on the laminar model and when the gas film thickness is large and there is supersonic flow in some region, which should be calculated according to the mixture model; at the same time, there is no surface of discontinuity for Mach number and pressure distribution, and no shock, and the pressure is recovered due to the boundary layer separation, the change of the flow state and the change of viscosity. The method for testing the pressure distributions with a single test hole is effective.

1 Introduction

Due to the inherently low viscosity of gas, aerostatic bearings with the features of low friction and small power dissipation, have attracted much attention from many domestic and foreign scholar [1–9], and have been successfully and widely applied in high-speed and high-precision machine tools, such as PrecitechVanoform700ultra [10], Toshiba USM-400B [11] and Westwind D1733 PCB spindle [12]. In addition, aerostatic bearings without the requirement of the costly, complex sealing and lubricant circulation systems may constitute the compact bearing-rotor systems with fewer parts. Furthermore, this kind of oil-free bearing eliminates process fluid contamination and is environmental friendly.

For aerostatic bearings, when the gas film thickness is large enough, especially when there is supersonic flow in it, the pressure distributions experience an undesirable pressure depression and a slight pick-up behind the gas supply hole, which decreases its load-carrying capacity and limits its use. At the same time, the gas pressure change cannot be calculated with the Reynolds equation, which limits the further research on the gas flow characteristics.

According to the gas flow of aerostatic bearings, Mori first studied the gas pressure distribution when there is a pressure depression in an aerostatic thrust bearing with a single supply hole. They assumed that the flow field could be divided into three regions [13], that is, the first region with the supersonic flow, the second region where airflow shifts from supersonic flow to subsonic flow by shocks and the pressure is recovered, and the third region with the viscous and isothermal flow [13]. The three-region theory could predict the pressure distribution to some extent, but could not explain the precise flow structure, and its results were not well agreed with its experiments [14]. Yoshimoto et al. used the finite deference method to solve the Navier-Stokes (N-S) equations [15]. The calculation pressure distributions were more consistent with the experimental ones through increasing the effective viscosity in the pressure recovery region. They concluded that the pressure recovery was caused by the flow separation at the upper wall and a decrease of air velocity behind the position of the minimum pressure, and no shock occurs when the flow changes from supersonic to subsonic, which is in a contradiction with the findings of the previous investigators. In the pressure recovery region, airflow in the bearing clearance changes from laminar to turbulent. Compared with the previous research, the pressure distributions are more consistent with the experimental ones, but the assumption that the velocity distribution at the inlet is parabolic and the settings of the effective viscosity lacks enough convinced evidences. Yu et al. calculated the flow field with CFD software based on laminar model, and the uniformity of its calculated and experimental results was proved [16]. The boundary layer theory and the change of flow states were used to explain the change of the pressure distribution. They supported that there was no shock wave in the flow. The above shortage is that the pressure recovery grad of the experiment was bigger than that of the calculation. Eleshaky used laminar and turbulent models, respectively, to calculate the flow of aerostatic bearings with single supply hole [17]. Compared with the experimental results, the results of the turbulent model were better than those of the laminar one when the gas film thickness is large. Overall, the pressure recovery grad of the turbulent model was bigger than that of the experiment in the pressure recovery region, while the pressure recovery grad of the laminar model was smaller. Based on the different calculation modes for the different regions, Wang et al. calculated the flow under large gas film thickness by using the CFD method [18]. The shock train was captured in a large gas film thickness. However, the gas film thickness was 300 μm, which exceeds the working gas film thickness range, and the flow passage no longer has the restriction effect of aerostatic bearings.

In this paper, for the gas flow of aerostatic bearings with single supply hole, a new model was built based on the calculation results of laminar and turbulent modes, on which both laminar and turbulent modes could be used at the same time for calculation. The single test hole was used to test the pressure distribution. The changes of the gas flow characteristics were studied through the comparison and analysis of the calculated and tested results, and the applicability of different calculation model was verified under different gas film thicknesses. The work may be as the foundation for the choice of the calculation model in the further study.

2 Calculation based on N-S equations

2.1 Physical model

The structure of the aerostatic circular thrust bearing with single supply hole is shown in Fig. 1. When the gas film thickness is h,
the pressure is constant and is equal to $P_0$. Through the restriction effect of the supply hole, the air enters the gas film clearance. At the last, the gas flows out of the gas film clearance, and its pressure drops to the atmosphere pressure $P_\infty$. In order to test the pressure distribution conveniently, the specific structure parameters are as the following: the supply hole radius $R_s = 1$ mm, the bearing radius $R_b = 30$ mm, the length of the supply hole $h_s = 3$ mm.

2.2 Simplified model and meshing

Due to the axial symmetry of the bearing structure, one two-dimension calculation model is built, as shown in Fig. 2, which is just half of the flow passage shown in Fig. 1 and can fully take the change of pressure along the gas film clearance into consideration, and compared with the three-dimension model, its calculation grid is much less. The side AKJ needs to be set as the rotating axis, and the structured grids are used. The boundary layer grids with a grid space of 0.5 μm are adopted near the up and bottom walls along the gas film clearance (AK section) to study the boundary layer well in the gas film clearance, and each boundary side has 6 layers, while the other grid space is 1 μm. The supply hole length section HG is divided into 200 segments, and the supply hole radius section HJ is 100 segments. The wall CD section is divided into 1000 segments. The region BCFG is mainly corresponding to the turbulent model was used. The length of this region is set based on the calculation results with the laminar and the turbulent models.

2.3 SST $k-\omega$ turbulent model

The shear stress transport (SST) $k-\omega$ two-equation model is a mixture model and widely used in the engineering. Near the wall, the $k-\omega$ model is still used, while the $k-\epsilon$ model is adopted far from the wall. The form of the turbulent viscosity coefficient $\mu_t$ limits the excessively high shearing stress in the boundary layer and can be well used for the transportation of shearing stress in the boundary with adverse pressure gradient, which makes the model used widely in the calculation for flow with adverse pressure gradient, aero foil, transonic shock, and so on. The static equations are written as follows:

$$\frac{\partial}{\partial x_i}(\rho k) = \frac{\partial}{\partial x_i}\left(\Gamma_k \frac{\partial k}{\partial x_i}\right) + G_k - Y_k$$  \hspace{1cm} (1)

$$\frac{\partial}{\partial x_i}(\rho \omega) = \frac{\partial}{\partial x_i}\left(\Gamma_\omega \frac{\partial \omega}{\partial x_i}\right) + G_\omega - Y_\omega + D_\omega$$  \hspace{1cm} (2)

where $\Gamma_k$ and $\Gamma_\omega$ are the effective diffusion items of $k$ and $\omega$, respectively, which are expressed as

$$\Gamma_k = \mu + \frac{\mu_t}{\sigma_k}$$  \hspace{1cm} (3)

$$\Gamma_\omega = \mu + \frac{\mu_t}{\sigma_\omega}$$

The turbulent viscosity $\mu_t$ in (3) may be gained by using (4)

$$\mu_t = \frac{\rho k}{\omega} \max \left[\left(1/\alpha^*\right), \left(\Omega F_s/\alpha_0 \omega\right)\right]$$  \hspace{1cm} (4)

where $k$ is the turbulent kinetic energy; $\omega$ is the turbulent dissipation rate; $G_k$ is the turbulent kinetic energy produced by the laminar velocity gradient; $G_\omega$ the equation of $\omega$; $Y_k$ and $Y_\omega$ are the dissipation items of $k$ and $\omega$, respectively, $D_\omega$ is the orthogonal dissipation item; $\sigma_k$ and $\sigma_\omega$ are the turbulent Brandt constant; $\Omega$ is the absolute vorticity; $F_s$ the blending function; $\alpha^*$ is the low Reynolds number correction; $\alpha_0 = 0.31$.

2.4 Dynamic viscosity

Since the pressure changes a lot when the gas film clearance is large or the supply pressure is high, the local temperature will change under the supersonic flow, and the dynamic viscosity $\mu$ of air is estimated by using the Sutherland equation, as shown in (5)

$$\mu = \frac{\mu_\infty}{\left(\frac{T}{T_\infty}\right)^{\nu_2} + 1 + S/T_\infty}$$  \hspace{1cm} (5)

where $T$ is the temperature; $\mu_\infty = 1.716 \times 10^{-5}$ Pa S; $T_\infty = 273.11$ K; and $S = 110.56$ K.

2.5 Boundary conditions

The calculations mentioned above are based on the following two assumptions: (i) the wall is smooth, and the effect of surface roughness and non-slip boundary are not considered. (ii) the working medium is ideal gas.

Based on the above assumptions, the settings of boundaries are as follows:

(i) The ambient pressure $P_a = 0.1$ MPa, and the ambient temperature $T_a = 300$ K. (ii) At the pressure inlet, the supply pressure $P_s = 0.6$ MPa, and the gas supply temperature $T_s = 300$ K. At the outlet, the pressure is equal to $P_\infty$, and the outlet temperature is equal to the ambient temperature $T_\infty$.

2.6 Discretisation and solution of equations

Several discretisation schemes provided by the FLUENT can be chosen. In this paper, the second-order upwind scheme is chosen for the pressure and density items, which is more suitable for compressible flow with shocks. The first-order upwind scheme is chosen for the other, which has a good stability and can guarantee the calculation convergence. It can be seen from the results that the first-order upwind scheme can satisfy the calculation accuracy. The SIMPLE algorithm is used for solving equations, which is the most widely used algorithm in the calculation of fluid engineering. The pressure and the velocity may be solved simultaneously, and the above algorithm is a kind of pressure-correction method. Its basic idea is as the following: for the flow field of one given pressure, which may be assumed or the last iteration results, the momentum equation can be solved, and the velocity may be also derived. As the given pressure is assumed or not precise, the velocity derived from it cannot satisfy the continuity equation, and the pressure needs correction. The solving process is shown in Fig. 3.
3 Experiment system

The schematic diagram of experiment system is shown in Fig. 4, which consists of fixed support 1, Vernier knob 2, pressure test board 3, test bearing 4, steel ball 5, force sensor 6, gas cylinder 7, direction valve 8, precision pneumatic pressure regulators 9 and 10, pressure sensor 11. The load of test bearings is exerted by gas cylinder 7, and its force can be adjusted sleeplessly with a precision pneumatic pressure regulator in the range of the load capacity of test bearings. In order to avoid the unbalanced load and make the load on test bearings and the gas film clearance uniform, the point contact loading method is adopted. The force is transported from the gas cylinder to test bearing through a steel ball 5. The gas film will be automatically adjusted with its self-balancing effect. The contact inductance micrometer is used to measure the gas film clearance. A force sensor at the end of the cylinder rod is used for measuring the exerted force.

The single test hole is used to test the pressure distribution in the gas film clearance, which can minimise the influence of the test hole on the flow characteristics and help to capture the inflection point of pressure [19]. There is a test hole with a diameter of 0.4 mm in the pressure test board 3. The pressure on the lower wall of the gas film is transferred to the pressure sensor through the test hole. The change of the position of the test hole can be done by screwing the Vernier knob, and the pressures of different positions can be obtained. If the knob rotates a scale, the moving distance of the test board is 0.03 mm, which will guarantee to capture the inflection point of pressure in the flow.

4 Comparison and analysis of results

4.1 Analysis of pressure distributions

The pressure distributions obtained from calculations and experiments under four different gas film clearances are shown in Figs. 5–8. In Fig. 5a, when the gas film clearance is merely 20 μm, the pressure still has a small depression and recovery. With the increase of the gas film clearances in Figs. 6–8, the depression becomes gradually larger, while the pressure recovery becomes gradually smaller. The position of minimum pressure moves away from the axis of test bearings, and its reasons have been analysed in detail in Reference [16].

From Fig. 5b, which is the partial enlarged drawing of Fig. 5a, it is found that the results from laminar and mixture models coincide with each other and agree well with the experimental results. The results from turbulent model are higher than the experimental ones in the pressure recovery region, and the deviation is larger. It is drawn that the flow is laminar in this gas film clearance, and the laminar should be chosen for calculation.

When the gas film clearances are 40, 60, and 80 μm, respectively, the results obtained from mixture model agree better with the experimental ones in the pressure recovery region, and the deviation is larger. It is drawn that the flow is laminar in the most of the flow field and the turbulent flow coexists in the small part of the flow field. The turbulent flow mainly locates in the pressure recovery region, and the mixture model should be used, while different model is used in different region at the same time.

It is found that if the range of the turbulent region is set properly, the calculation results almost coincide with the experimental ones. However, the range of the region changes with the gas film clearance, and the building of calculation models is merely based on the calculation results from laminar and turbulent models, which has to be done repeatedly due to no rule to follow and needing further study.
Clearance.

local flow field from calculation results with the mixture models to the wall. At the position of 0.041, the flow state basically fits the number locates in the range from 0.034 to 0.036, which is not at range from 0.036 to 0.038. The distribution of Mach number field. In the following, the flow states for the gas film clearances of 0.033 to 0.07 (dimensionless distance) behind the entrance of gas film (0.033). The position of minimum pressure locates in the range from 0.034 to 0.036, which is not at the entrance of the gas film clearance and indicates that the throat of the whole flow passage is behind the entrance of the gas film. The whole flow passage can be seen as a Laval nozzle, and after the subsonic flow flows through its throat, the velocity of the flow decreases and the pressure increases [20]. It is also found that the positions of the minimum pressure and the maximum Mach number do not coincide and the positions of the minimum pressure is lagged behind that of the maximum Mach number, the reason of which needs further study. The changes of viscosity are shown in Fig. 10. It is necessary to point out that the flow in the boundary layer separation near each wall almost correspond to that of the supersonic flow. The velocity behind the maximum Mach number gradually decreases, and the equipotential lines of Mach number form closed loops near the upper and lower walls, which indicates that there is boundary layer separation. Combined with the velocity vector distribution in Fig. 10d and the stream line distribution in Fig. 10e, the arrows of vectors towards the right and the stream lines also form closed loops, and the results illustrate that there is boundary layer separation. The positions of the boundary layer separation near each wall almost correspond to each other at about 0.154. The direction of backflow after the boundary layer separation is opposite to that of the supersonic flow. For the outward supersonic flow, the whole flow passage can be seen as a Laval nozzle, as shown in Fig. 11. The supersonic flow flows through a Laval nozzle and becomes subsonic, and the kinetic energy turns into the pressure energy and the pressure increases.

4.2 Analysis of micro-characteristics

Based on the above analysis, there are two flow states, that is, laminar flow, and the flow being laminar in the most of the flow field and the turbulent flow coexisting in the small part of the flow field. In the following, the flow states for the gas film clearances of 0 and 80 μm are taken as examples for analysing the micro-characteristics near the point of minimum pressure.

For the gas film clearance of 20 μm, the micro-characteristics of local flow field is shown in Fig. 9. It can be seen that the process of the pressure depression and recovery occurs in the range from 0.033 to 0.07 (dimensionless distance) behind the entrance of gas film (0.033). The position of minimum pressure locates in the range from 0.036 to 0.038. The distribution of Mach number corresponding to Fig. 9a is shown in Fig. 9b, and it is found that the velocity in the whole region is subsonic and the maximum Mach number is about 0.7. The position of the maximum Mach number locates in the range from 0.034 to 0.036, which is not at the entrance of the gas film clearance and indicates that the throat of the whole flow passage is behind the entrance of the gas film. From Figs. 10a and b, it is found that the pressure continues to increase when the flow is subsonic. In Fig. 10d, the flow state is gradually turning from chaotic to be order. In calculation, the turbulent model is used in this region, and behind this region, the laminar model is used, so the flow changes from turbulent to laminar in this region. The inertial force of the high-speed flow turns into viscous force, and the pressure increases. At the same time, the viscosity in this region as shown in Fig. 10c increases, and its change is obvious, the rate of which exceeds 40%. With the increase of viscosity, the flow resistance and the pressure increase, and the velocity decreases. The impact of viscosity can not be ignored under this condition.
(iii) The position of the minimum pressure lags behind that of the maximum Mach number in the flow.
(iv) When the gas film clearance is in the working range of aerostatic bearings, there is no shock in the flow.
(v) The method with a single test hole for testing the pressure distributions is effective, and has no impact on the flow characteristics.

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7 References

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