Analysis of Gas-Solid-Thermal Coupling on Micro-Vibration of Aerostatic Bearing at Micron-Scale

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Abstract. Based on gas lubrication theory and rarefied gas dynamics, combined with boundary slip and gas-solid-thermal coupling analysis technology, the local deformation of aerostatic bearing gas film caused by temperature change and the effect on gas-vortex and micro-vibration are studied. The results show that the maximum deformation of the gas-film increases linearly with the increase of temperature. The move speed of gas-vortex motion considering thermal coupling is much less than that obtained by traditional numerical analysis method. Considering the gas-solid-thermal coupling condition, the influence of different working temperatures on the micro-vibration of aerostatic bearing is also different. According to the experiments available, with the increase of temperature, the micro-vibration intensity decreased gradually, but the temperature does not change its natural frequency.

1. Introduction
Aerostatic bearings with high precision, low friction power consumption and non-polluting advantages, are widely used in high-precision testing equipment, ultra-precision machining machine tools and aircraft flight testing and other fields [1]. Along with the changing working environment, all kinds of precision instruments are more and more demanding on the reliability and working stability of bearing, not only to ensure the normal work in the range of (-250~315) °C, but also to ensure the stability of the spindle during the rotation and the bearing seat, and to relieve the impact and vibration between them. On the macroscopic scale, based on the isothermal assumption, ignoring the temperature change can satisfy the work requirement. However, with the decreasing of the gas film thickness and the continuous improvement of the precision, the flow form of the gas film in the micro-scale will present the transition from the layer to the slip flow [2].

Domestic and foreign scholars have analyzed the dynamic and static characteristics of aerostatic bearing. CHEN, et al [3] and KONG, et al [4] analyzed the micro-vibration characteristics of the aerostatic bearing, observed the gas-vortex phenomenon and put forward a numerical analysis method of gas-solid coupling. LI, et al [5] based on the large eddy simulation of aerostatic bearing self-excited micro-vibration characteristics of the analysis, observed the generation of gas-vortex. Although the existing mechanical models have made many assumptions about the flow characteristics of gases in
tiny gaps and throttles, the influence of temperature on their internal microscopic properties is ignored. This will not only affect the shape and thickness of the lubricating gas film, but also further change the flow characteristics and amplitude frequency characteristics of the gas film through the way of thermal coupling, which will lead to a larger deviation between the numerical simulation results and the experimental data. Therefore, it is necessary to study the effect of the gas-solid-thermal coupling on the temperature sensitivity and the micro-vibration on the micro-scale gas film. The design calculation method of the aerostatic bearing is effectively supplemented, which provides technical support for the development of the ultra-precision shaft system and related engineering application.

2. Working principle and mathematical model

In this paper, the disc type central gas supply small hole throttle static thrust bearing with a diameter of $D=50$ mm is selected as the research object. Bearing structure schematic diagram as shown in Fig. 1 solid line outline, gas hole diameter $d_0=0.2$ mm, gas cavity depth $\delta=0.2$ mm, gas cavity diameter $d_1=3$ mm.

Ps - the gas pressure of the throttle hole, $\Delta h$ - the maximum deformation of the gas film, $h_0$ - the average thickness of gas film, $P_a$ - atmospheric pressure

![Fig. 1 Gas-solid-thermal coupling model](image)

Under the condition of normal temperature, the effect of thermal coupling and velocity slip is not considered. Based on the principle of aerostatic lubrication, the motion law of the flow field in the gas film can be expressed as Navier-Stokes (N-S) equation.

The momentum equation in the $X$ direction:

$$\frac{\partial p}{\partial x} = \mu \frac{\partial^2 u}{\partial y^2}$$

The momentum equation in the $Z$ direction:

$$\frac{\partial p}{\partial z} = 0$$

The momentum equation in the $Y$ direction:

$$\frac{\partial p}{\partial y} = \mu \frac{\partial^2 w}{\partial y^2}$$

Gas State equation:

$$p = \rho RT$$

Continuity equation:

$$\frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} + \frac{\partial \rho}{\partial t} = 0$$
In the form: $\rho$ - gas density, $\mu$ - dynamic viscosity of gas, $p$ - gas pressure, $u, v, w$ - velocity component in $x, y, z$ direction, $T$ - temperature.

However, when the gas film thickness of the aerostatic bearing is in the micron-scale or even below, due to the small scale of the fluid characteristic, the Kn number will increase, which makes the gas at the micro scale have the same characteristics as the rarefied gas. The flow pattern of supporting gas film is in the transition stage of slip flow or laminar flow slip flow. The traditional N-S equation will not well reflect the characteristics of boundary slip flow and micro vibration. No slip boundary conditions will no longer apply to micro-scale flow analysis. Based on the influence of the boundary slip on the [6] and the gas stratification theory [7], the velocity slip boundary conditions need to be supplemented at this time:

$$ z = 0 \frac{1}{2}, \quad u = U + l' \frac{\partial u}{\partial z}, \quad v = l' \frac{\partial w}{\partial z}, \quad w = 0 $$  \hspace{1cm} (6)

$$ z = h \frac{1}{2}, \quad u = -l' \frac{\partial u}{\partial z}, \quad v = -l' \frac{\partial w}{\partial z}, \quad w = u \frac{\partial h}{\partial x} + v \frac{\partial h}{\partial y} $$  \hspace{1cm} (7)

The above formula (1), (2), (3) is brought into the formula (6), (7) to solve the $u, v, w$ and into the formula (4), (5) the micro-scale of the Reynolds equation can be simplified as:

$$ \frac{\partial}{\partial x} \left( ph^3 \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left( ph^3 \frac{\partial p}{\partial y} \right) = \frac{6 \mu U}{1 + 6k_w} \frac{\partial (ph)}{\partial x} + \frac{12 \mu}{1 + 6k_w} \frac{\partial (ph)}{\partial t}, \quad k'_w = 2 - \frac{\sigma_v}{\sigma_r} $$  \hspace{1cm} (8)

In the form: $\sigma_v$ - molecular tangential momentum adjustment coefficient.

In actual work, with the increase of ambient temperature and bearing local temperature, the uneven thermal deformation of the bearing in height direction and the expansion of gas inside the gas film lead to the change of the flow field inside the flat supporting gas film, as shown in Fig. 1, the outline of the dashed line. At this time, the gas film is deformed in the vertical height direction, and the deformation amount is $\Delta h$. The deformation of the edge of the gas cavity is the largest. It is recorded as $\Delta h_{\text{max}}$ and is nonlinear decreasing to the radius direction. The change of gas film thickness can be expressed by the formula as follows.

$$ h = \begin{cases} h_0 + \Delta h + \delta h, r = \left(0, \frac{d_i}{2}\right), \\ h_0 + \Delta h, r > d_i \end{cases} $$

$$ \delta_i = \begin{cases} 1, \sqrt{x^2 + y^2} < \frac{d_i}{2} \\ 0, \frac{d_i}{2} < \sqrt{x^2 + y^2} < D \end{cases} $$  \hspace{1cm} (9)

In the form: $P$ - the pressure of gas supply, $h$ - the effective gas film thickness, $h_0$ - the average thickness of gas film, $d_i$ - Kronecker delta, $\eta$ - the viscosity of gas after pressurization, $u, v$ - the velocity of $x, y$ in the gas film, respectively, $r$ - distance along the flow direction.

The formula (9) is brought into the formula (8), and the formula of Reynolds equation after the gas film deformation is obtained.

$$ \frac{\partial}{\partial x} \left( p (h_0 + \Delta h)^3 \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left( p (h_0 + \Delta h)^3 \frac{\partial p}{\partial y} \right) = \frac{6 \mu U}{1 + 6k_w} \frac{\partial (p h_0 + \Delta h)}{\partial x} + \frac{12 \mu}{1 + 6k_w} \frac{\partial (p h_0 + \Delta h)}{\partial t} $$  \hspace{1cm} (10)

3. Temperature sensitivity and gas-vortex phenomenon of gas film

In this paper, a two-way gas-solid-thermal coupling model of aerostatic bearing is established. The Fluent and Static Structural modules in Ansys Workbench are used to initialize the fluid domain and solid domain respectively. The setting mainly includes the boundary condition, the gas-solid-thermal coupling surface, the solution model and the monitoring setting, and the convective temperature should be set in the boundary condition. It needs special description that in the Static Structural module, the three-dimensional flow field in the micro gas film gap of the Fluent module can be
coupled to the aerostatic bearing in the solid domain, and then the maximum deformation of the aerostatic bearing under certain working conditions can be obtained. The large eddy simulation (LES) should be used in the analysis of the fluid domain model, because it can better calculate the flow characteristics of gas in the gas film. The grid distortion is 0.05, which satisfies the calculation precision. The bearing material is aluminum alloy.

The maximum deformation $\Delta h_{\text{max}}$ of the gas film height direction is obtained, and the variation rule shown in Fig. 2 is obtained.

As shown in Fig. 2, as the temperature increases, the gas film maximum deformation overall increases, but the increasing amplitude decreases with the increase of the gas film thickness. Before 25$^\circ$C, the maximum deformation of 5$\mu$m gas film is the smallest, and the maximum deformation of (10–20) $\mu$m gas film is very similarity. After 25$^\circ$C, with the increase of gas film thickness, the maximum deformation of 5$\mu$m gas film rapidly increased, and the maximum deformation of (10–20)$\mu$m gas film began to widen. The bigger the gas film thickness, the smaller the maximum deformation is causes. Especially at 25$^\circ$C, when the gas film thickness is (5–20) $\mu$m, the maximum deformation $\Delta h_{\text{max}}$ of the gas film is maintained at about 1$\mu$m.

It is necessary to point out that when the gas film thickness is 20$\mu$m, the deformation amount is between (1–1.5) $\mu$m with the increase of temperature. This is mainly because the gas film is in a fully developed laminar state when the gas film thickness is 20$\mu$m or above. The sensitivity of the gas film to temperature is reduced. The internal flow can be described by the traditional N-S equation. At that time, the sensitivity of the gas film to temperature is very low. Therefore, the maximum deformation $\Delta h_{\text{max}}$ is lower than that of other gas film thickness. In contrast, when the gas film thickness is reduced to 5$\mu$m or below, by the gas stratification theory, slip zone proportion increases, resulting in the N-S equation and the laminar flow hypothesis is not the traditional well reflect the internal flow characteristics. So it is necessary to use the thin layer flow velocity slip conditions, the gas film in large deformation in the range of temperature increase linearly. The flow state and pressure distribution of the gas film shows the work inside will have a temperature sensitive characteristic strongly, the flow characteristics and pressure distribution in the gas film will change.

From the above analysis, it can be seen that for the aerostatic bearing with micro scale gas film, the change of temperature will cause the gas film to deform in the direction of height, resulting in the change of the gas flow characteristics. Thus, the change of the position and size of the gas-vortex in the gas cavity will be affected, and then the micro-vibration will be affected. On this basis, the gas flow characteristics of the gas film are studied.
Under \( p_s=0.4\text{MPa}, h=10\mu m, T=-40\, ^\circ\text{C} \) conditions, the turbulent vortex structure near the orifice exit presents complex three-dimensional characteristics, the scale of the vortex structure and the process of motion development become irregular, as shown in Fig. 3-a), Fig. 3-b), Fig. 3-c). The location, size and intensity of the gas-vortex are not fixed, but with the passage of time, the position of the gas-vortex gradually moves to the edge of the gas cavity. This is mainly due to the impact of high velocity gas flow into the gas cavity. The gas streamline is sharply bent. Due to the limited space and the large gas kinetic energy, the gas-vortex energy is very high and the momentum is large. Gradually forming an annular large scale gas-vortex. Then, in the wall of the gas-vortex appeared under the influence of continuous fluctuation, the gas-vortex scale increases gradually and moves in the radial direction. After a certain stage of development, because the flow cross-sectional area of the larger, quickly rupture under the action of convection, gas-vortex is divided into a large number of irregular small scale vortex. Then the velocity of gas-vortex decreases gradually, and finally dissipates gradually under the action of gas viscosity.

As shown in Fig. 4, under \( p_s=0.4\text{MPa}, h=10\mu m, T=-40\, ^\circ\text{C} \) conditions, the gas film pressure of the aerostatic bearing in the gas cavity and near the throttle hole shows an alternating upward and downward trend, resulting in the alternating variation of wave peaks and troughs. This results in micro-vibration of the aerostatic bearing. In addition, when observing the location of gas-vortex from the center of the gas cavity to the radius of 0.64 mm, the intensity of gas-vortex decreases gradually and the amplitude fluctuation is small, which proves that the location, size and intensity of the gas-vortex are not fixed. Based on this, the comparison between ideal condition and gas-solid-thermal coupling condition is made at different times, and the intensity of micro-vibration is analyzed by comparing the position of gas-vortex and the size of pressure drop in gas cavity. It will provide theoretical support and technical help for effectively suppressing or reducing micro-vibration.
a) The gas-vortex position at different time  b) The gas-vortex position at different temperatures

Fig. 5 The gas-vortex position in gas cavity under ideal and gas-solid-thermal coupling conditions

As shown in Fig. 5-a), under \( p_s=0.4\text{MPa}, h=10\mu\text{m} \) conditions, \( T=-40^\circ\text{C}, 25^\circ\text{C} \) and \( 250^\circ\text{C} \) were chosen as the research objects according to the different operating temperature of the aerostatic bearing. Under the ideal condition, the position of the gas-vortex is gradually spread to the periphery along the radius direction of the gas cavity with time. Under different temperature conditions, the position of the gas-vortex is approximately the same. This is mainly due to the ideal condition of no damping and viscosity. Without taking into account the error factors, the gas flow will become unhindered, and the velocity of gas-vortex will be similar. However, when the gas-solid-thermal coupling is applied, the position of the gas-vortex still moves outward along the radius of the gas cavity, but with the increase of temperature, the movement speed of the gas-vortex gradually decreases. Combined with Fig. 5-b), under the ideal conditions of \( t=20\text{ms} \), the position of the gas-vortex in the gas cavity of the aerostatic bearing is \((0.37\sim0.39)\text{mm}\). This may be due to the fact that, with the increase of temperature, the thermal motion of the gas molecules intensifies, the collisions between molecules become more frequent, and the gas in the gas film tends to move irregularly. Gradually counteracting with the direction of gas-vortex rotation, the gas viscosity gradually increases, which results in the decrease of gas-vortex velocity.

From the above analysis, it is known that the increase of temperature will cause the reduction of the velocity of the gas-vortex. Based on this, the size of the pressure drop in the gas cavity at different temperatures is studied, as shown in Fig. 6.

Fig. 6 Pressure distribution in gas cavity under different temperature conditions

As shown in Fig. 6, under the condition of \( p_s=0.4\text{MPa}, h=10\mu\text{m}, t=16\text{ms} \), There is a phenomenon of pressure drop in the gas film inside the gas cavity. When \( T=-40^\circ\text{C} \), the moving velocity of the gas-vortex in the gas cavity is fast, and the pressure drop is large. However, at \( T=25^\circ\text{C} \), the moving velocity of the gas-vortex in the gas cavity changed little, but the pressure drop in the pressure distribution was lower than that at \( T=-40^\circ\text{C} \). At \( T=250^\circ\text{C} \), the moving velocity and the pressure drop of
the gas-vortex in the gas cavity are decreased greatly. This is mainly due to the increase of temperature leading to the increase of the distance between the gas molecules and the gradual decrease of the interaction force. But the energy of the gas increases, the gas molecules are more inclined to do irregular motion and gradually replace the trajectories of the gas-vortex, thus reducing the velocity and the micro-vibration of the gas-vortex.

4. Design and Test Scheme
The phenomenon of gas-vortex in the gas film causes micro-vibration. An experimental set-up is constructed which makes it possible to measure the micro-vibration, the schematic drawing and test set-up are shown in Fig. 7 respectively.

![Micro-vibration test schematic diagram](image1)

![Micro-vibration test equipment](image2)

1. Air source 2. Air source filtrating equipment 3. Space heater 4. SMC precision pressure regulating valve 5. Pressure regulating valve 6. Cylinder 7. PCB acceleration sensor 8. Aerostatic bearing 9. Marble platform 10. LMS dynamic monitor 11. Personal computer 12. Pressure transducer 13. Micro-displacement measuring instrument

Fig. 7 Micro-vibration test

The temperature is measured by the standard glass mercury thermometer in the experiment, the measuring range is (-30~300) °C, with the zero scale. Using dry ice to make low temperature environment. All the measurement procedures are instantaneous values.

5. Results and Analysis
Based on the above experiments, the effect of gas-solid-heat coupling on the micro-vibration of aerostatic bearing is analyzed. As is shown in Fig. 8 respectively.

![Time-domain signals](image3)

![Frequency-domain signals](image4)

Fig. 8 Time-domain signals of aerostatic bearings at different temperatures
As shown in Fig. 8-a), under the condition of h=10μm, ps=0.4MPa, the influence of temperature on the micro-vibration of the aerostatic bearing is analyzed when the working temperature is T=0℃, T=25℃ and T=100℃ respectively. It is obvious that with the increase of temperature, the micro-vibration amplitude of the aerostatic bearing is the highest at T=0℃, which is about (1.1~2) times the thickness of the initial gas film. As the temperature rises to T=100℃, the micro-vibration amplitude of the aerostatic bearing is the lowest, the amplitude range is (4~7)μm fluctuation, it is (0.4~0.7) times of the initial gas film thickness. As a result, the micro-vibration amplitude of the aerostatic bearing decreases with increasing temperature, so that the micro-vibration intensity can be reduced as the temperature increases. As shown in Fig. 8-b), the temperature increase does not alter its natural frequency. In addition, it can be seen from the figure that there is a large peak at frequencies of 2601Hz and 6015Hz. This is mainly caused by the system resonance due to the load of the aerostatic bearing and the influence of the environmental factors.

6. Conclusion

By comparing the above numerical analysis and experimental results, we can draw the conclusion that when the working temperature of aerostatic bearing increases gradually, the gas-vortex will gradually weaken, and the flow characteristics of gas film will be close to laminar flow. However, when the operating temperature is below a certain critical value, the flow characteristics of the gas film are closer to the turbulent, and the intensity of the gas-vortex increases gradually, which leads to the increase of the micro-vibration intensity. Mainly reflected in the gas vortex volume and time domain signal fluctuation amplitude value. Therefore, it is necessary to select suitable working parameters according to different working conditions in order to weaken the micro-vibration, and to avoid the occurrence of resonance phenomenon according to the frequency-domain signal graph.

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