Effects of herringbone grooves on aerodynamic journal bearings based on finite element method

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Abstract. Aerodynamic journal bearings are commonly used in high speed machines, which have weaknesses of low steady-state performance specifications. It is of great significance to study the effects of herringbone grooves on the characteristics of aerodynamic journal bearings. This paper investigates effects of herringbone grooves on functions of aerodynamic journal bearings by numerically solving the Reynolds equation based on improved finite element method. The obtained results show that the herringbone grooved aerodynamic journal bearings have a critical speed and they should run at a speed of greater than the critical speed. Ultra-high speeds and low eccentricity ratios are the suitable working conditions of the herringbone grooved aerodynamic journal bearings. The performance of aerodynamic journal bearings is enhanced with advancing groove numbers, and an optimal groove depth is existed with respect to the herringbone grooved aerodynamic journal bearing.

1. Introduction

Aerodynamic bearings have outstanding characteristics of almost no wear, few heating, no external pressurized air supply and clean operation, which are extensively applied in various engineering industries including high speed spindle, micro gas turbine engine, inertial gyroscope, laser scanner, cryogenic expander, et al. However, aerodynamic bearings have weaknesses on load capacity, stiffness and so on. Herringbone grooves had been reported to improve performance of the aerodynamic bearings.

Large quantity of papers had been published to investigate herringbone groove effects on the aerodynamic bearing. Air journal bearings with herringbone grooves were analysed by narrow groove theory (NGT) [1-3] which had an assumption of infinite groove number. However, the obtained pressure profiles had no saw-toothed ripples in the groove boarders and the smoothed pressure filed was acquired. Furthermore, the Reynolds equation was numerically calculated by finite difference method (FDM) [4, 5] or finite element method (FEM) [6-8] to analyse the effects of herringbone grooves on the aerodynamic bearing. Based on the aforementioned analyses, many papers had been published to investigate the herringbone grooved air bearings, however, few efforts had been done to comprehensively analyse herringbone groove effects on the aerodynamic journal bearing (AJB) under ultra-high-speed condition based on FEM. Therefore, this paper will numerically solve the Reynolds
equation to study herringbone groove effects on the AJB under ultra-high-speed condition with the improved FEM.

2. Herringbone grooved aerodynamic journal bearing (HGAJB)
   Figure 1 shows a typical geometry structure of a HGAJB, which has a smooth bearing bush and a herringbone grooved journal. Two groups of herringbone grooves are evenly incised around the journal surface, which are symmetric to the plane a-a of the bearing. The outer ends of the bearing bush and the herringbone grooves are aligned.

   ![Figure 1. Schematic of a HGAJB.](image)

   Figure 2 illustrates an unfolded plane of the air film in a HGAJB. $L$ is axial length of the bearing, $D$ is diameter of the bearing bore, $gl$ denotes axial herringbone groove length, $ga$ denotes the herringbone groove angle, $gd$ denotes the herringbone groove depth, $gw$ is the width of a herringbone groove, and $gt$ is the overall width of a pair of groove-ridge, $gn$ denotes groove number of one groove group. Besides, $g_{lr}$, determined by $gl/(L/2)$, denotes the ratio of groove length; $g_{wr}$, defined by $gw/gt$, denotes the ratio of groove width.

   ![Figure 2. The unfolded air film with herringbone grooves.](image)

3. Calculation model
   3.1. Mathematical equations
   Inertial effect is ignored due to the negligible mass of the lubricant gas. Besides, the current HGAJB model incorporates the following assumptions:
   (a) There are no geometric errors of the bearing bore and the journal.
   (b) There is no tilt for the displacement of the journal.
   (c) The gas viscosity is considered be constant.
   (d) Air film pressures are virtually invariable along air film thickness direction.
The dimensionless Reynolds equation for the aerodynamic journal bearing is depicted in equation (1) [9, 10]
\[
\frac{\partial}{\partial x} \left( \tilde{h}^3 \frac{\partial \tilde{p}}{\partial x} \right) + \frac{\partial}{\partial z} \left( \tilde{h}^3 \frac{\partial \tilde{p}}{\partial z} \right) = \Lambda_x \frac{\partial (\tilde{h} \tilde{p})}{\partial x} + \Lambda_z \frac{\partial (\tilde{h} \tilde{p})}{\partial z}
\]
(1)

where \( \Lambda_x \) and \( \Lambda_z \) denote the dimensionless bearing numbers, \( \tilde{x} \) and \( \tilde{z} \) denote the dimensionless Cartesian coordinates, \( \tilde{h} \) denotes the dimensionless air film thickness, \( \tilde{p} \) denotes the dimensionless air film pressure.

In this study, aforementioned dimensionless Reynolds equation has the following boundary conditions.
1. Pressure at the outer border of the bearing: \( p = p_{\infty} \), \( p_a \) is ambient pressure;
2. Pressure at the symmetric boundary: \( \frac{\partial \tilde{p}}{\partial n} = 0 \), \( n \) is the normal direction of the symmetric boundary.

The numerical solution of the Reynolds equation is calculated by FEM with the triangular element, and the finite element formula of the Reynolds equation for aerodynamic journal bearings is deduced as follows
\[
\sum_{c \in A} \int_{A} (N^c \phi)^T d{x} d{z} \left( c_i c^T + b_i b^T \right) \Phi^e \frac{1}{(2\Delta e)^2} \left( \int_{A} \sum_{c \in A} \lambda_i (u_i + b_i \omega_i) \phi^T d{x} d{z} \right) = 0
\]
(2)

where \( N^e \) is the shape function, \( \phi^e \) is the column matrix of the node thickness, \( c_i \) and \( b_i \) are the coefficients of the interpolation function, \( c^T \) and \( b^T \) are the coefficient matrixes of the interpolation function, \( \Phi^e \) is the column matrix of dimensionless node pressure square, \( \bar{u} \) and \( \bar{\omega} \) are the dimensionless velocities, \( \lambda \) is the bearing coefficient.

Iteration method is applied to solve the finite element formula and the unknown nodes’ pressures are obtained. Furthermore, properties of the aerodynamic journal bearing, such as load capacity, attitude angle and stiffness, can be calculated (the detailed mathematical equations are published in reference [9]).

3.2. Computational domain

In this study, the computational domain of aerodynamic journal bearing is determined by half of the fluid zone which is symmetric to plane a-a depicted in figure 1. The air film of the AJB is unfolded into a plane along the direction of A-B-C-D illustrated in figure 2. Figure 3 depicts the meshed computational domain with triangle elements and boundary conditions. Plane k-k locates at middle position in the AJB along the axial direction, and plane m-m is positioned at the inside end of the groove. It should be noted that the groove node thicknesses are superposed by the ridge node thicknesses and the groove depth. Thickness discontinuity of the air film locates in the transition boundaries between the ridge zone and the groove zone. In this study, the node thickness depends on the corresponding elements to which the node belongs [11].

Grid independence test is conducted to determine the computation grid size. Scheme A: 5 segments are uniformly meshed in each groove zone and ridge zone along peripheral direction. Scheme B: 10 segments are uniformly meshed in each groove zone and ridge zone along peripheral direction. Identical grids are meshed for schemes A and B in the axial direction. Geometrical parameters and working conditions of the bearings for schemes A and B are also identical. Difference of the
calculated load capacities between scheme A and scheme B is 0.23%, manifesting that the performance parameters of the aerodynamic journal bearings are almost identical calculated by the two meshing schemes. Less grid quantity needs less computational time, so meshing scheme A is used to determine the grid size.

![Diagram of grids and boundary conditions for the HGAJB.](image)

**Figure 3.** Schematic diagram of grids and boundary conditions for the HGAJB.

3.3. Experimental verification

It is exceedingly hard to test the effects of the herringbone groove on the property specifications of the AJB. Gao et al. [11] employed a round-about way to verify the improved FEM simulation method for analysing the effects of herringbone grooves on the property behaviors of ultra-high-speed aerostatic journal bearings. Equation (1) of reference [11] for aerostatic bearings can be transformed into equation (1) of this paper for aerodynamic bearings by ignoring the mass flow factor. Hence, the proposed calculational method of this paper is also indirectly verified based on the reference [11].

4. Results and discussions

There are many geometrical parameters of herringbone grooves, and the parameters of groove number and groove depth are selected as the variables to research herringbone groove effects on performance of aerodynamic journal bearing under various running conditions. An analysing procedure is developed by MATLAB. The nonlinear equations are numerical solved by the ‘fsolve’ function with the termination tolerance of 1e-20. Pressure distribution, load capacity, attitude angle and air film stiffness of aerodynamic journal bearings are thoroughly studied at various speeds (n) and eccentricity ratios (ε).

In this paper, the principle size parameters of the bearing are defined as follows: L=34.813mm, D=19.01mm, h_m=10μm, where h_m is the air film thickness with no grooves and no eccentricity. The groove angle, ga, is fixed at 30°, the groove length ratio, glr, is 1/3 and the groove width ratio, gwr, is 1/2. The atmospheric pressure (p_a) is 101,325Pa, and the reference air film pressure (p_r) is 0.6MPa. The atmospheric air density (ρ_a) is 1.205kg/m³, and the atmospheric air dynamic viscosity (η) is 1.81e-5Pa·s.

4.1. Groove number

In this section, the groove depth, gd, is fixed at 10μm. Figure 4 depicts three-dimensional dimensionless air film pressure profiles for variable groove numbers under conditions of n of 200,000r/min and ε of 0.3. It can be seen from figure 4 that major changes of air film pressures are occurred in the groove-ridge zones, presenting a zigzag profile of the air film pressure. Herringbone grooves pump outside gas into the bearing film, leading to the increased pressure of the air film, shown in figure 4 (a) and (b). Furthermore, pressure fluctuation amplitudes of the air film in adjacent groove zones and ridge zones ease up with enhancing groove numbers.
**Figure 4.** Dimensionless pressure profiles of the aerodynamic bearing films with variable groove numbers. (a) groove number is 0. (b) groove number is 8. (c) groove number is 12. (d) groove number is 16.

**Figure 5.** Dimensionless air film pressures corresponding to diverse groove numbers. (a) Plane $k$-$k$. (b) Plane $m$-$m$.

Dimensionless pressures of the air film at cross-sections $k$-$k$ and $m$-$m$ with respect to diverse groove numbers are illustrated in figure 5. Figure 5 depicts that herringbone grooves significantly increase air film pressures, and air film pressure increases with enhancing groove numbers. However, the increasing amplitude of the air film pressure is not obvious from $gn$ of 8 to 16. It can be also found that the negative pressure appears when $gn$ of 0 and disappears when $gn$ of 8 or more. When there is no groove in the aerodynamic journal bearing, the external air is pumped into the air film in negative pressure zone, and the inner air is pumped out of the air film in positive pressure zone. When the herringbone groove number reaches 8 or more, only positive pressure appears in the bearing film,
which presses the inner gas out of the air gap meanwhile the herringbone grooves pump the external gas into bearing film.

Figure 6 depicts property data of the AJB corresponding to diverse groove numbers under conditions of different eccentricities and speeds. The load capacity is reduced by herringbone grooves at speed of lower than 50,000r/min, as shown in figure 6(a). However, progressive enhancement of the aerodynamic effect resulted from herringbone grooves occurs corresponding to enhancing speeds. The load capacities with herringbone grooves are larger than those with non-grooves at speed of greater than 50,000r/min. Hence, the HGAJB has a critical speed which should be lower than its running speed. Besides, the grooved load capacity increases with enhancing groove numbers. The load capacity is increased by 107.25% from gn of 0 to 16 at speed of 400,000r/min and eccentricity of 0.3.

Figure 6. Performance parameters of the AJB corresponding to diverse groove numbers. (a) ε=0.3. (b) n=200,000r/min. (c) n=200,000r/min. (d) n=200,000r/min.

Figure 6 (b) illustrates that the load capacities with herringbone grooves are larger than those with non-grooves with various eccentricities and n of 200,000r/min. Figure 6 (c) and (d) present that herringbone grooves can improve air film stiffness with eccentricity ratio of lower than 0.7 and the attitude angle is declined with ε of less than 0.5 at n=200,000r/min. However, air film stiffnesses are decreased and attitude angles are increased by herringbone grooves with ε > 0.7 at n=200,000r/min. Besides, load capacities and air film stiffnesses increase with enhancing groove numbers, and attitude angles decrease with enhancing groove numbers. Based on aforementioned analysis results, ultra-high speeds and low eccentricity ratios are optimum operating conditions for herringbone grooved aerodynamic journal bearings. The performance parameters of HGAJB are advanced with enhancing groove numbers.
4.2. Groove depth
In this section, the groove number, \( g_n \), is fixed at 16. Figure 7 depicts property data of the AJB corresponding to diverse groove depths under conditions of different eccentricities and speeds. Figure 7 (a) illustrates that the load capacity with \( gd \) of 20μm increases with increasing speeds and is greater than those of other groove depths when the speed reaches 240,000r/min or more. The load capacity with \( gd \) of 5μm is larger than those of other groove depths at speed of \( n\leq40,000\)r/min and becomes the lowest at speed of \( n>200,000\)r/min. The load capacity with \( \varepsilon \) of 0.3 for various groove depths has the following relation \( W_{gd=20\mu m}>W_{gd=10\mu m}>W_{gd=30\mu m}>W_{gd=5\mu m} \) at speed of \( n\geq240,000\)r/min.

\[ \begin{align*}
\text{Load capacity (N)} & \quad \text{Speed (×10^4 r/min)} \\
0 & \quad 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \\
0 & \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \quad 60 \quad 70 \quad 80 \\
\text{Eccentricity ratios} & \quad \text{Eccentricity ratios} \\
\text{gd=5μm} & \quad \text{gd=20μm} \\
\text{gd=10μm} & \quad \text{gd=30μm} \\
\text{gd=20μm} & \quad \text{gd=30μm} \\
\end{align*} \]

\[ \begin{align*}
\text{Air film stiffness (N/μm)} & \quad \text{Eccentricity ratios} \\
0 & \quad 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \\
0 & \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \quad 60 \quad 70 \quad 80 \\
\text{Eccentricity ratios} & \quad \text{Eccentricity ratios} \\
\text{gd=5μm} & \quad \text{gd=20μm} \\
\text{gd=10μm} & \quad \text{gd=30μm} \\
\text{gd=20μm} & \quad \text{gd=30μm} \\
\end{align*} \]

\[ \begin{align*}
\text{Attitude angle (°)} & \quad \text{Eccentricity ratios} \\
0 & \quad 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \\
0 & \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \quad 12 \\
\text{Eccentricity ratios} & \quad \text{Eccentricity ratios} \\
\text{gd=5μm} & \quad \text{gd=20μm} \\
\text{gd=10μm} & \quad \text{gd=30μm} \\
\text{gd=20μm} & \quad \text{gd=30μm} \\
\end{align*} \]

**Figure 7.** Performance parameters of the AJB corresponding to diverse groove depths. (a) \( \varepsilon=0.3 \). (b) \( n=200,000\)r/min. (c) \( n=200,000\)r/min. (d) \( n=200,000\)r/min.

Figure 7 (b) describes that the load capacity with \( gd \) of 10μm is greater than others at \( 0.2\leq\varepsilon\leq0.8 \) and \( n=200,000\)r/min. Figure 7 (c) presents that the air film stiffness with \( gd \) of 10μm is greater than others at \( 0.1\leq\varepsilon\leq0.6 \) and \( n=200,000\)r/min, and the air film stiffness with \( gd \) of 5μm becomes the greatest one at \( \varepsilon>0.6 \) and \( n=200,000\)r/min. Figure 7 (d) depicts that the attitude angles decrease with increasing eccentricity ratios for various groove depths at \( n=200,000\)r/min, and the attitude angle with \( gd \) of 30μm has the highest value at \( \varepsilon<0.8 \), and the attitude angle with \( gd \) of 5μm becomes the smallest one at \( \varepsilon>0.4 \). In conclusion, too big or too small groove depth is hard to improve performance characteristics of HGAJB, and an optimal groove depth exists in the HGAJB with ultra-high speeds and low eccentricity ratios.

5. Conclusions
Effects of herringbone grooves on properties of the AJB are investigated by numerically solving the Reynolds equation based on FEM, and air film pressure, bearing load capacity, bearing attitude angle and air film stiffness are obtained under different operating conditions. Based on the aforementioned analysis results, the conclusions are as follows
(1) The HGAJB has a critical speed which should be lower than its running speed.
(2) Ultra-high speeds and low eccentricity ratios are optimum operating conditions for herringbone grooved aerodynamic journal bearings. The performance parameters of HGAJB are advanced with enhancing groove numbers.
(3) Too big or too small groove depth is hard to improve performance characteristics of HGAJB, and an optimal groove depth exists in the HGAJB with ultra-high speeds and low eccentricity ratios.

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