Analysis on the lubrication performance of spiral-grooved journal bearing using CFD technique

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Abstract. As the main element, the lubrication characteristics of spiral-grooved journal bearing would decide the stability of mechanical systems. And, an effectivee model will represent the hydrodynamic characteristics of spiral-grooved journal bearing effectively. Based on the CFD technique, this work presents the simulation methodology for analyze the effects of spiral-grooved parameters on the lubrication performance of journal bearing. Compared with the published data, the proposed method is demonstrated effectiveness. Moreover, the influences of eccentricity ratio, groove number, spiral angle, groove width and groove depth are discussed by the orthogonal design method, which provide a reference for the optimized design of spiral-grooved journal bearing.

1. Introduction

As the development of modern industry technology, the optimized design of spiral-grooved journal bearing can change the stability of mechanical systems. As the main element, the spiral grooved geometry plays a crucial role on the hydrodynamic characteristics of spiral-grooved journal bearing [1]. A smaller variation would change the lubrication performance of spiral-grooved journal bearing, which includes load carrying capacity, attitude angle or friction torque [2-3]. Then, the effects of grooved parameters on the lubrication characteristics of spiral-grooved journal bearing are not neglected. Moreover, the complexity of spiral-grooved structure may produce a heavy workload. And, a suitable design method could improve the effectiveness of optimized design for spiral-grooved journal bearing. Then, it is necessary to discuss the analysis method of spiral-grooved parameters.

In the last few years, a lot of successful applications for journal bearing are reported in this field [4-5]. Wang [6] studied the effects of spiral groove on the nonlinear dynamic characteristics of journal bearing. With the groove structure taken into account, Chen [7] developed a stability analysis method for describing the hydrodynamic response of herringbone grooved journal bearing. The numerical results demonstrated the effectiveness of this method. Based on the multiphase flow theories and tribological equations, Meng and Yang [8] conducted the influence of textured on the lubrication behavior of journal bearing. The simulation results indicated that the cavitation would change the pressure distribution of journal bearing. A new numerical model to deal with the free boundary problems for optimizing spiral-grooved journal bearing by Chen [9]. The simulation results indicated that the
proposed method could correctly determine the pressure distribution of oil-film and improve the lubrication performance of herringbone grooved journal bearing. According to finite element method, He and Gong [10] conducted the optimization design of bearing considering the factors influence. The introduction of neural network could improve the computational effectiveness. Ma and Peng [11] established the simulation model of spiral groove gas face seal and the hydrodynamic behavior of gas face seal was conducted. The simulation results revealed that the presented model could describe the lubrication characteristics of gas face seal.

In this paper, CFD technique is employed to conduct the lubrication performance analysis of spiral-grooved journal bearing. The proposed method is verified with the published experiment data and the hydrodynamic behavior of journal bearing with rectangle-grooved and spiral-grooved is shown. Furthermore, the orthogonal design method is applied to the effects of spiral-grooved parameters on the hydrodynamic characteristics of journal bearing.

2. Theoretical and mathematical model

The type of spiral-grooved journal bearing is diagrammed in Fig. 1, which is used to show the structure characteristics of spiral-grooved journal bearing [12-13]. In the global coordinate system, the diameter of bearing is defined as D and L denotes the length of bearing. The groove width (a), groove depth (h_\text{g}) and spiral angle (\beta) are also represented. The eccentricity ratio and bearing clearance are \varepsilon and h_r, respectively. O_j and O_b are the centers of journal and bearing.

![Figure 1. The diagram of spiral-grooved journal bearing.](image)

In this paper, Navier-Stokes equations are applied to perform the hydrodynamic characteristics of spiral-grooved journal bearing [14]. Then, the governing equation should be described. The equation of mass conservational is given by:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \tag{1}
\]

Where \(\rho\) is density of fluid and \(\mathbf{v}\) is velocity vector.

The momentum conservation equation would be expressed as:

\[
\begin{align*}
\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho u \mathbf{v}) &= -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \\
\frac{\partial (\rho v)}{\partial t} + \nabla \cdot (\rho v \mathbf{v}) &= -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho f_y \\
\frac{\partial (\rho w)}{\partial t} + \nabla \cdot (\rho w \mathbf{v}) &= -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z
\end{align*} \tag{2}
\]

Where \(p\) is pressure, \(\tau_{ij}\) is the deviator stress component and \(f\) denotes the quality force component. u, v, w define the velocity components, respectively.
Meanwhile, the energy equation could provide the solution of temperature variation of oil-film, which can is described by:

\[
\rho c_p \left( \frac{\partial T}{\partial x} + w \frac{\partial T}{\partial z} \right) = \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \mu \left( \frac{\partial u}{\partial y} \right)^2 + \left( \frac{\partial w}{\partial y} \right)^2
\]  

(3)

The term on left side of Eq. (3) is energy transfer, which is caused by the convection. The terms on the right side of Eq. (3) denote the energy transfer due to conduction and dissipation, respectively.

In addition, the cavitation is also considered in the lubrication characteristics of journal bearing and the Singhal-et-al cavitation model is employed to describe the multiphase flow characteristics [15-16]. The liquid-vapor mass transfer is defined as:

\[
\frac{\partial}{\partial t}(\rho_m f) + \nabla(\rho_m \vec{v}_v f) = -\nabla(\gamma \nabla f) + R_e - R_c
\]

(4)

Where

\[
R_e = \frac{\rho_c V_{ch}}{\rho_1 \mu} \sqrt{\frac{2(P_{sat} - P)}{3 \rho_1}} (1 - f)
\]

(5)

\[
R_c = \frac{C_c V_{ch}}{\sigma} \rho_1 \rho_v \sqrt{\frac{2(P - P_{sat})}{3 \rho_1}} f
\]

(6)

Where \( \rho_m \) and \( \vec{v}_v \) are the mixture density and velocity vector of vapor phase. \( f \) denotes the vapor mass fraction and \( \gamma \) represents the effective exchange coefficient. \( R_e \) and \( R_c \) represent vapor generation and condensation rate, respectively.

3. Simulation results discussion

3.1. Validation study

In order to obtain the accuracy of the presented method, the model in Ref. [17] is used to study the hydrodynamic behavior of journal bearing. The rotational speed is 600 rpm and the velocity residual is \( 10^{-5} \). The SIMPLE algorithm of pressure-velocity couple is chosen. The relative difference between mass flow inlet and mass flow is given 1%. The pressure distribution of journal bearing with different external loads is shown in Fig. 2. Although the deviation between the simulation results and experimental data, it is clear shown that the proposed methodology could represent the hydrodynamic characteristics of journal bearing effectively.

[Figure 2. Comparison between present model and experiment data: (a) external load is 6 kN, (b) external load is 8 kN.]
3.2. Application case

The influence of groove parameters on the hydrodynamic response of journal bearing are conducted. Due to improve the accuracy and efficiency of computation, the hexahedron mesh is applied to simulation model and the groove depth is divided 10 layers. The simulation parameters is listed in Tab. 1.

| Parameters                  | value       |
|-----------------------------|-------------|
| Bearing width \( L \) (mm)  | 60          |
| Clearance \( h_r \) (mm)    | 0.04        |
| Groove width ratio \( \lambda \) | 0.6, 0.8, 1, 1.2 |
| Groove depth \( h_g \) (mm) | 0.02, 0.04, 0.06, 0.08 |
| Groove angle \( \beta \) (°) | 15, 30, 45, 60 |
| Eccentricity ratio \( \varepsilon \) | 0.4, 0.5, 0.6, 0.7 |
| Groove number \( N \)       | 6, 8, 10, 12 |
| Rotation speed \( \omega \) (rpm) | 2000 |
| Bearing diameter \( D \) (mm) | 80          |
| Lubricant density \( \rho \) (kg/m\(^3\)) | 890         |
| Lubricant viscosity \( \nu \) at 20°C (Pa·s) | 0.068       |
| Lubricant viscosity \( \nu \) at 100°C (Pa·s) | 0.008       |
| Thermal conductivity (W/(m·k)) | 0.13        |
| Lubricant specific heat (J/(kg·k)) | 2000 |

In order to represent the groove characteristics, the pressure distributions of journal bearing with rectangle-grooved and spiral-grooved are shown in Fig. 3. In the same operation condition, the results show that the maximum pressures of oil-film for rectangle-grooved journal bearing and spiral-grooved journal bearing are 4.45 MPa and 5.37 MPa. And, the load carrying capacity are 8162.85 N and 8425.55 N. The difference of hydrodynamic behavior between rectangle-grooved and spiral-grooved may be the velocity gradient of oil-film is changed by structural characteristics of groove. Meanwhile, the attitude angle of rectangle-grooved journal bearing is 63.38° and the value of spiral-grooved journal bearing is 67.03°. Then, it is easily to seen that the spiral-grooved can present a larger load carrying capacity and the spiral-grooved parameter plays the curial element on the hydrodynamic response of journal bearing.

![Figure 3. The pressure distribution of journal bearing: (a) rectangle-grooved; (b) spiral-grooved.](image)

The effects of spiral-grooved parameters on the lubrication characteristics of spiral-grooved journal bearing are discussed. The eccentricity ratio, groove number, spiral angle, groove width ratio and groove depth are chosen to the variable and the each parameter has 4 factors. If all cases of spiral-grooved journal bearing are considered and the case number is 4\(^5\) times, which has a heavy workload. And, the orthogonal design method is employed to analyze the influence of spiral-grooved parameter. \( L_n (r^{mn}) \) represents the form of orthogonal table, which includes the simulation number (n=16), the factor level number (r=4), factor number (m=5). The orthogonal design table is shown in Tab. 2. The load carrying capacity (LCC), oil-film stiffness (ST) and attitude angle (AT) are selected to the evaluative objective (EOB). \( A_i \) is the eccentricity ratio and the values (0.4 0.5 0.6 0.7) are correspond to \( i=1, 2, 3, 4 \). In the same way, \( B_i \) represents groove number and \( C_i \) denotes spiral angle. \( D_i \) and \( E_i \) are the groove width ratio and groove depth, respectively. Moreover, R is the extreme value of average value (\( K_i \)) at the same level number, which is written as:
\[ K_i = \sum A_i \ (i = 1,2,3,A) \]  
\[ R = \max\{K_1,K_2,K_3,K_4\} - \min\{K_1,K_2,K_3,K_4\} \]  

**Table 2.** The orthogonal design method and results.

| Case number | \( A_i \) | \( B_i \) | \( C_i \) | \( D_i \) | \( E_i \) | LCC (N) | ST (N/m) | AT (°) |
|-------------|------------|------------|------------|------------|------------|---------|----------|-------|
| 1           | 1          | 1          | 1          | 1          | 1          | 5992.61 | 13468750 | 76.58 |
| 2           | 1          | 2          | 2          | 2          | 2          | 6938.36 | 12784375 | 67.41 |
| 3           | 1          | 3          | 3          | 3          | 3          | 5789.42 | 89587500 | 63.09 |
| 4           | 1          | 4          | 4          | 4          | 4          | 3624.62 | 26965625 | 66.09 |
| 5           | 2          | 1          | 2          | 3          | 4          | 5647.21 | 33856250 | 62.19 |
| 6           | 2          | 2          | 1          | 4          | 3          | 6086.9  | 58296875 | 71.84 |
| 7           | 2          | 3          | 4          | 1          | 2          | 7258.18 | 54708125 | 62.36 |
| 8           | 2          | 4          | 3          | 2          | 1          | 9968.22 | 17621250 | 66.71 |
| 9           | 3          | 1          | 3          | 4          | 2          | 6922.88 | 71500000 | 59.54 |
| 10          | 3          | 2          | 4          | 3          | 1          | 11351.8 | 10262500 | 62.84 |
| 11          | 3          | 3          | 1          | 2          | 4          | 5016.83 | 21975000 | 69.38 |
| 12          | 3          | 4          | 2          | 1          | 3          | 7766.05 | 95912500 | 58.91 |
| 13          | 4          | 1          | 4          | 2          | 3          | 6802.89 | 27381250 | 56.51 |
| 14          | 4          | 2          | 3          | 1          | 4          | 6080.88 | 17131250 | 53.49 |
| 15          | 4          | 3          | 2          | 4          | 1          | 13819.5 | 80312500 | 61.36 |
| 16          | 4          | 4          | 1          | 3          | 2          | 8425.55 | 25378125 | 67.03 |

**Table 3.** Simulation results analysis.

| LCC (N) | \( A_i \) | \( B_i \) | \( C_i \) | \( D_i \) | \( E_i \) |
|---------|------------|------------|------------|------------|------------|
| \( k_1 \) | 5586.2525  | 7016.3975  | 6380.4725  | 6774.43    | 10283.0325 |
| \( k_2 \) | 7240.1275  | 7614.485   | 8542.78    | 7181.575   | 8061.2425  |
| \( k_3 \) | 8439.39    | 7970.9825  | 7865.35    | 7803.495   | 6611.315   |
| \( k_4 \) | 8782.205   | 7446.11    | 7259.3725  | 8288.475   | 5092.385   |
| R        | 3195.9525  | 954.585    | 2162.3075  | 1514.045   | 5190.6475  |

| ST (N/m) | \( A_i \) | \( B_i \) | \( C_i \) | \( D_i \) | \( E_i \) |
|----------|------------|------------|------------|------------|------------|
| \( k_1 \) | 64466406.25| 36614062.5| 29779687.5| 168398437.5| 93154687.5 |
| \( k_2 \) | 203861718.8| 76474218.75| 84481250 | 88353125 | 193013281.25 |
| \( k_3 \) | 73055782.15| 18117187.5| 87043281.25| 62861718.75| 67794531.25 |
| \( k_4 \) | 337550781.25| 14812500 | 146233593.75| 109067187.5| 168031250 |
| R        | 166310937.55| 14812500 | 146233593.75| 109067187.5| 168031250 |

According to the simulation results, the effects of parameter and extreme value are shown in Tab. 3. The primary and secondary of factors (PSF) could reflect the influence of each parameter on the lubrication characteristics of spiral-grooved journal bearing. And, the optimization design scheme (ODS) is also presented. It is clear to show that \( A_i \) and \( E_i \) are the key elements of load carrying capacity, oil-film stiffness and attitude angle. According to the results, \( A_4 \) and \( E_1 \) are chosen to the optimal parameters. \( C_3 \) is a better value of spiral angle. Meanwhile, groove width ratio and groove number are \( D_1 \) and \( B_3 \),
respectively. The simulation results reveal that the structural characteristics (E1A4C3D1B3) would provide a better hydrodynamic behavior of spiral-grooved journal bearing.

4. Conclusion
This paper proposes a general methodology for modelling and evaluating the lubrication characteristics of spiral-grooved journal bearing. Considering the cavitation effects, the lubrication performance analysis model of spiral-grooved journal bearing is established by CFD. Meanwhile, the simulation results are compared with the published data, which demonstrate the effectiveness of the proposed method. The higher lubrication performance is the design objective of spiral-grooved journal bearing. Then, the eccentricity ratio, groove number, spiral angle, groove width ratio and groove depth are chosen to the factors for structure design of spiral-grooved journal bearing. Based on the orthogonal design method, the effects of spiral-grooved parameters on the hydrodynamic characteristics of spiral-grooved journal bearing are obtained, which could provide a better evaluation in the design of journal bearing.

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