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Research on Dynamic Characteristics of Multi-phase Flow Oil Film on Computation Fluid Dynamics Method

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Abstract

The model of multi-phase flow oil film of journal bearing was established on CFD (computation fluid dynamics) method in order to ensure the stable operation and obtain the dynamic characteristics. The radial and tangential forces of multi-flow oil film with three tiny eccentric positions were calculated, then, the stiffness and damping coefficients were reached. Compared from other results, the ones in this paper are accuracy, providing an important value on the stable and high efficient operation of journal bearings.

***Keywords**: journal bearing, oil film, dynamic characteristics, multi-flow, stiffness, damping*

1. Introductions

The instability of journal bearing is the main reason leading to oil film oscillation, and the stability of oil film is closely related to its dynamic characteristics.

The domestic and foreign scholars have done lots of studies on the dynamic characteristics on journal bearings. Yu Haomin *et. al.*, had studied the dynamic characteristics of journal bearings with radial offset and skew using numerical calculation method, then, the matrix expression of dynamic characteristics had been derived and the physical meaning of each element of the expression has been discussed[1]. Wang Fengcai *et.al.* had calculated the dynamic characteristics of bearings with the method of solving Renolds equation, and pointed out that the reasonable design parameters can make the bearings possess favorable static characteristics, dynamic characteristics and stability [2]. Wu Jianchao *et.al.* had established three dimension test model of oil film, and deducted the calculation formula of the eighteen dynamic characteristics [3]. Toshio and Zenglin Guo had calculated the pressure distribution and the eight dynamic characteristics of half-cycle oil film using computed fluid dynamic method with the software of CFX-TESCflow. Then, they pointed out that the computed fluid dynamic method had its advantage comparing to other methods [4]. Zhang Xu *et. al.*, had established multi-flow model of oil film with computed fluid dynamic method, and simulated the operating condition of real oil film [5]. Pei Zhenying *et. al.*, had analyzed the pressure distribution and vaporization ratio of multi-flow oil film with different rotation speed and eccentric rotor.

The multi-flow model of oil film is established using computed fluid dynamic method, and the oil film dynamic characteristics are calculated with tiny eccentricity in this paper.

2. The Stiffness and Damping of the Oil Film

The dynamic characteristics of oil film reveal that oil film forces will change when shaft leaves its equilibrium position and does a vertex motion around. Figure 1 is the schematic diagram of rotor whirling with the rotation speed Ω around its

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equilibrium position $O_o(e_0, \theta_0)$in bearings in cylindrical coordinates.

As shown in Figure 1, when the rotor center locates in a instant position point $O_j(e, \theta)$, the radical distance is Δe and the tangential distance is $e\Delta\theta$ from the rotor center O_j to the equilibrium position point O_o. The radical and tangential velocity is $\dot{e}$ and $e\dot{\theta}$ respectively, and the corresponding radical and tangential force are F_e and F_θ.

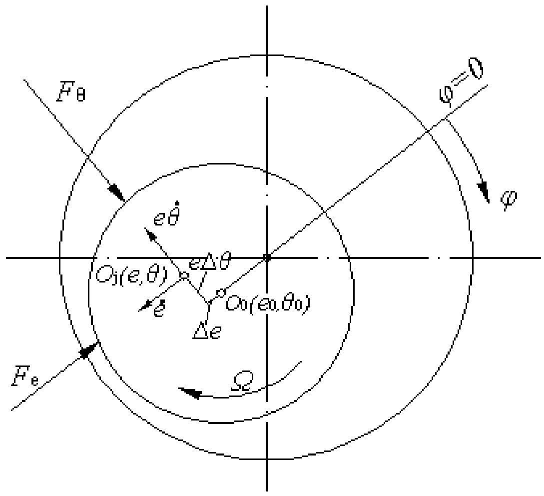

Figure 1. Rotor Whirling in Bearing

Both F_e and F_θ are the functions of coordinate position and velocity $(e, \theta, \dot{e}, \dot{\theta})$, when the rotor is in static equilibrium position, the oil film forces are:

$$\left.\begin{matrix} F_{e0} \\ F_{\theta 0} \end{matrix}\right\} = \left\{\begin{matrix} F_e(e_0, \theta_0, 0, 0) \\ F_\varphi(e_0, \theta_0, 0, 0) \end{matrix}\right. \tag{1}$$

Expand the forces of F_e and F_θ around their equilibrium position with the method of Taylor series and retain the linear team, the result is:

$$\left.\begin{matrix} F_e \\ F_\theta \end{matrix}\right\} = \left\{\begin{matrix} F_{e0} + \left(\frac{\partial F_e}{\partial e}\right)_0 \Delta e + \left(\frac{\partial F_e}{e\partial \theta}\right)_0 e\Delta\theta + \left(\frac{\partial F_e}{\partial \dot{e}}\right)_0 \dot{e} + \left(\frac{\partial F_e}{e\partial \dot{\theta}}\right)_0 e\dot{\theta} \\ F_{\theta 0} + \left(\frac{\partial F_\theta}{\partial e}\right)_0 \Delta e + \left(\frac{\partial F_\theta}{e\partial \theta}\right)_0 e\Delta\theta + \left(\frac{\partial F_\theta}{\partial \dot{e}}\right)_0 \dot{e} + \left(\frac{\partial F_\theta}{e\partial \dot{\theta}}\right)_0 e\dot{\theta} \end{matrix}\right. \tag{2}$$

Where the subscript 0 represents derivation around the equilibrium position. The number of the derivatives of oil film force on the displacement of rotor center is four, possessing stiffness characteristic, consequently, they are called stiffness coefficient and expressed with the symbol k_{ij}, where the first subscript i represents the force increasing direction and the second subscript j represents the displacement increasing direction. They are shown as below:

$$k_{ee} = \left(\frac{\partial F_e}{\partial e}\right)_0 ; k_{e\theta} = \left(\frac{1}{e}\frac{\partial F_e}{\partial \theta}\right)_0 ; k_{\theta e} = \left(\frac{\partial F_\theta}{\partial e}\right)_0 ; k_{\theta\theta} = \left(\frac{1}{e}\frac{\partial F_\theta}{\partial \theta}\right)_0 \tag{3}$$

The derivatives (four) of oil film force on the velocity of rotor center possess damping characteristic, consequently, they are called damping coefficient and expressed with the symbol b_{ij}, where the first subscript i represents the force increasing direction and the second subscript j represents the displacement increasing direction. They are shown as below:

$$b_{ee} = \left(\frac{\partial F_e}{\partial \dot{e}} \right)_0 ; b_{e\theta} = \left(\frac{1}{e} \frac{\partial F_e}{\partial \dot{\theta}} \right)_0 ; b_{\theta e} = \left(\frac{\partial F_\theta}{\partial \dot{e}} \right)_0 ; b_{\theta\theta} = \left(\frac{1}{e} \frac{\partial F_\theta}{\partial \dot{\theta}} \right)_0 \tag{4}$$

The four stiffness and damping coefficients are usually called the eight dynamic characteristic coefficients of oil film.

When the rotor center has a tiny displacement around its static equilibrium position, the increment of oil film force can be expressed linearly as below:

$$\begin{aligned} \Delta F_e &= F_e - F_{e0} = k_{ee}\Delta e + k_{e\theta} e \Delta \theta + b_{ee}\dot{e} + b_{e\theta} e \Delta \dot{\theta} \\ \Delta F_\theta &= F_\theta - F_{\theta 0} = k_{\theta e}\Delta e + k_{\theta\theta} e \Delta \theta + b_{\theta e}\dot{e} + b_{\theta\theta} e \Delta \dot{\theta} \end{aligned} \tag{5}$$

The oil film force is composition of its pressure, consequently, the dynamic characteristic (the derivatives of oil film force on the velocity and displacement disturbance) is depending on the disturbance of the pressure (the derivatives of oil film pressure on the velocity and displacement disturbance).

3. CFD Multi-Flow Model of Oil Film

3.1. Computation Model

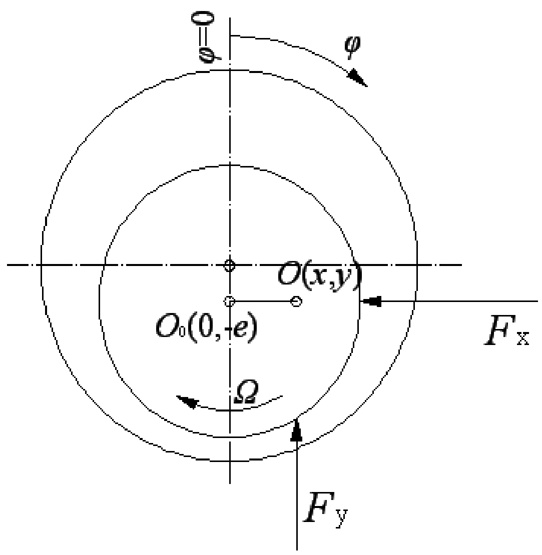

Figure 2. Calculation Model of Oil Film

As shown in Figure 2, the equilibrium position coordinates of the rotor is $O_0(0，-e)$. When the rotor has a tiny whirling around its equilibrium position, at a certain instant position $O(x, y)$, if the whirling rotation speed is zero, the forces on the rotor inducing by the oil film are F_x and F_y.

The oil film forces with a tiny x/c and y/c displacement of 0.01、0.005 and 0.002 are calculated respectively, obtaining the stiffness coefficients.

Table 1. Geometric Size of Model

Geometric size of the model	value
Bearing radius *R*	25mm
Rotor radius *r*	24.95mm
Bearing width *l*	25mm
The inlet angle of lubrication oil α	2.5°
Eccentricity *e*	0.025mm
Eccentric ratio ε	0.5

3.2. Calculation Condition

The calculation grid division of the model is referred in reference [5].

The solver setting: the segregated and implicit solver is adapted, the three dimension stable laminar calculation model is selected, and the model is multiphase one with two phases.

The material setting: a material is hu-20, with the density ρ = 876Kg/m^3, the kinematic viscosity μ = 0.0125Pa·s. The other material is lubrication oil in gaseous condition. The density of the air and the lubrication in gaseous condition is quite small compared to the one of the lubrication in liquid condition, so it will be very accurate to replace the lubrication oil in gaseous condition with the air. The parameters of the air come from the database of FLUENT.

Each phase setting: set hu-20 as the main phase and the air as the secondary phase. The vaporization pressure of the oil film is 0 Pa.

The boundary setting: set the mixture as the calculation fluid. The inlet pressure is 1.5MPa; the volume fraction of gaseous lubrication oil is 0 in inlet position; the outlet pressure is 1MPa; the backflow volume fraction of gaseous lubrication is 0; the wall rotation speed is 9550rpm.

(1) x/c = 0.01 and y/c = 0, the starting point coordinate of rotor is x = 0.005, y = -0.025 and z = 0, the rotation axis keeps parallel with z axis positive, the rotor rotates around its centre line and the whirling rotation speed is zero. x/c = 0 and y/c = 0.01, the starting point coordinate of rotor is x = 0, y = -0.0255 and z = 0, the rotation axis keeps parallel with z axis positive, the rotor rotates around its centre line and the whirling rotation speed is zero.

(2) x/c = 0.005 and y/c = 0, the starting point coordinate of rotor is x = 0.0025, y = -0.025 and z = 0, the rotation axis keeps parallel with z axis positive, the rotor rotates around its centre line and the whirling rotation speed is zero. x/c = 0 and y/c = 0.01, the starting point coordinate of rotor is x = 0, y = -0.02525 and z = 0, the rotation axis keeps parallel with z axis positive, the rotor rotates around its centre line and the whirling rotation speed is zero.

(3) x/c = 0.002 and y/c = 0, the starting point coordinate of rotor is x = 0.001, y = -0.025 and z = 0, the rotation axis keeps parallel with z axis positive, the rotor rotates around its centre line and the whirling rotation speed is zero. x/c = 0 and y/c = 0.002, the starting point coordinate of rotor is x = 0, y = -0.0251 and z = 0, the rotation axis keeps parallel with z axis positive, the rotor rotates around its centre line and the whirling rotation speed is zero.

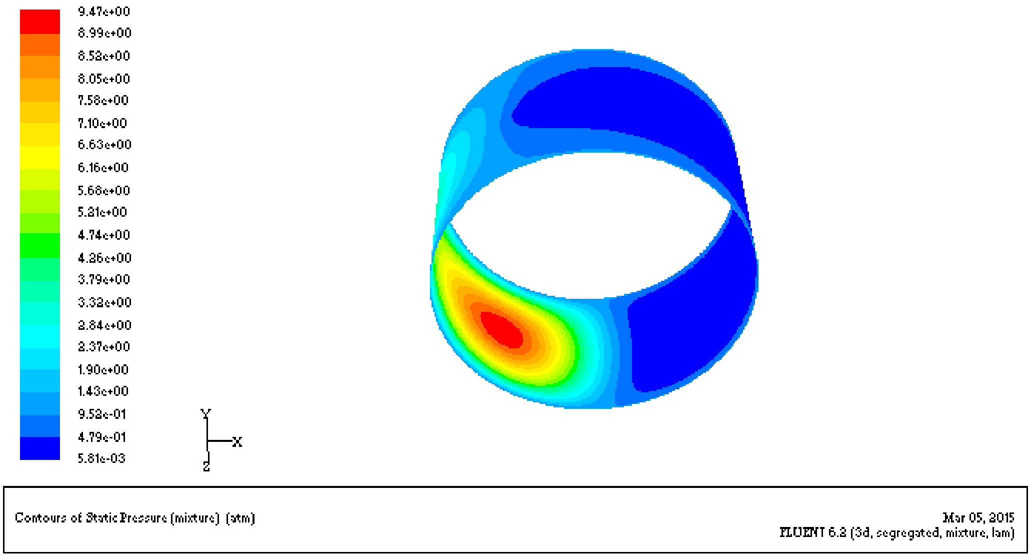

Figure 3. Oil Film Pressure Distribution with X/C = 0.005 and Y/C = 0

4. The Stiffness Coefficient of the Oil Film

4.1. Calculation Method

Figure 3 shows the pressure distribution with rotor displacement x/c = 0.005 and y/c = 0.

Make the rotor have a tiny displacement on radial and tangential direction in the cylindrical bearing shown in Figure 2, the oil film force increment can be expressed in formula 6:

$$\Delta F_t = k_{xx} x + k_{xy} y + c_{xx} \dot{x} + c_{xy} \dot{y}$$
$$\Delta F_r = k_{yx} x + k_{yy} y + c_{yx} \dot{x} + c_{yy} \dot{y} \quad (6)$$

Where $k_{ij}(i, j = x, y)$ and $c_{ij}(i, j = x, y)$ represent the stiffness and damping coefficients of the bearing respectively; x and y represent the tiny rotor displacement on radial and tangential direction respectively; $\dot{x}, \dot{y}$ represents the rotor velocity on radial and tangential direction respectively.

$\dot{x} = 0, \dot{y} = 0$, give a tiny displacement (x, 0)on the tangential direction, calculate the force ΔF_t and ΔF_r using computed fluid dynamic method, obtain the stiffness coefficients k_{xx} and k_{yx} solving the equations.

$\dot{x} = 0, \dot{y} = 0$, give a tiny displacement (0, y)on the radial direction, calculate the force ΔF_t and ΔF_r using computed fluid dynamic method, obtain the stiffness coefficients k_{xy} and k_{yy} solving the equations.

In real condition, the tiny rotor displacement scope is between 0.001～0.01 with x/c and y/c. This paper select the tiny rotor displacement is 0.01、0.005 and 0.002.

4.2. The Results

The oil film forces are calculated with the FLUENT software using computed fluid dynamic method as shown in Table 2.

Table 2. Radial and Tangential Force on Oil Film

x/c	y/c	F_t/tangential force(N)	F_r/radial force(N)
0	0	431.8	280.7
0.01	0	448.7	274.8
0	lt0.01	408.8	266.1
0.005	0	437.1	277.7
0	0.005	420.4	273.5
0.002	0	433.8	279.5
0	0.002	427.2	277.7

Bring the forces into formula (6), then, the stiffness coefficients can be obtained, the results are compared to the ones in reference [4]. They are shown in Table 3.

Table 3. Stiffness Coefficients of Oil Film (106N/M)

Calculation method	k_{xx}	k_{xy}	k_{yx}	k_{yy}
VT-FAST	40.0	-19.4	87.2	59.1
DyRoBeS-BePerf	38.0	-15.2	84.8	65.2
VT-EXPRESS	33.9	-13.1	85.3	65.0
CFX-TASCflow ($x/c = y/c = 0.01$)	41.2	-21.9	88.0	56.0
CFX-TASCflow ($x/c = y/c = 0.005$)	41.1	-22.1	88.0	56.0
CFX-TASCflow ($x/c = y/c = 0.002$)	38.9	-21.3	85.0	55.0
FLUENT ($x/c = y/c = 0.01$)	42.3	-23.5	92.0	58.3
FLUENT ($x/c = y/c = 0.005$)	42.7	-23.9	91.3	57.9
FLUENT ($x/c = y/c = 0.002$)	40.5	-23.4	92.4	59.2

The comparison of the rotor displacement $x/c = y/c = 0.05$ using CFD method with others is shown in Table 4.

Table 4. Comparison with other Results with X/C = Y/C = 0.005

comparison	k_{xx}	k_{xy}	k_{yx}	k_{yy}
VT-FAST	6.3%	18.8%	4.5%	12.1%
DyRoBeS-BePerf	11.2%	36.4%	7.1%	12.6%
VT-EXPRESS	20.6%	45.2%	6.6%	12.3%
CFX-TASCflow ($x/c = y/c = 0.01$)	2.1%	8.4%	3.6%	3.3%
CFX-TASCflow ($x/c = y/c = 0.005$)	3.7%	7.5%	3.6%	3.3%
CFX-TASCflow ($x/c = y/c = 0.002$)	8.9%	10.9%	6.9%	7.1%

Knew from Table 4, the difference of the example is little with the ones from CFX-TASCflow, only the parameter k_{xy} is a little bigger than 10%. Compared with other results, the difference of k_{xy} is the most obvious, with the maximum value

45.2%. Because the first three software obtain the stiffness coefficients solving Reynolds equation instead of N-S equation used in this paper, the difference may be large.

5. The Damping Coefficient of the Oil Film

5.1. The Calculation Model

The moving grid setting: set that the grid nodes around rotor neck are constituted with moving node, whereas, the nodes around bearing are constituted with static node. The whirling rotation speed is 4775 rpm.

(1) x/c = 0.01 and y/c = 0, the starting point coordinate of rotor is x = 0.005, y = -0.025 and z = 0, the rotation axis keeps parallel with z axis positive, the rotor rotates around its centre line and at the same time, the rotor neck has a whirling rotation at the speed of 4775 rpm around the axis x = 0, y = -0.025 and z = 0, and $\frac{\dot{x}}{c\Omega} = 0, \frac{\dot{y}}{c\Omega} = 0.01$. x/c = 0 and y/c = 0.01, the starting point coordinate of rotor is x = 0, y = -0.0255 and z = 0, the rotation axis keeps parallel with z axis positive, the rotor rotates around its centre line and at the same time, the rotor neck has a whirling rotation at the speed of 4775 rpm around the axis x = 0, y = -0.025 and z = 0, and $\frac{\dot{x}}{c\Omega} = 0.01, \frac{\dot{y}}{c\Omega} = 0$.

(2) x/c = 0.005 and y/c = 0, the starting point coordinate of rotor is x = 0.0025, y = -0.025 and z = 0, the rotation axis keeps parallel with z axis positive, the rotor rotates around its centre line and at the same time, the rotor neck has a whirling rotation at the speed of 4775 rpm around the axis x = 0， y = -0.025, z = 0, and $\frac{\dot{x}}{c\Omega} = 0, \frac{\dot{y}}{c\Omega} = 0.005$. x/c = 0 and y/c = 0.005, the starting point coordinate of rotor is x = 0, y = -0.02525 and z = 0, the rotation axis keeps parallel with z axis positive, the rotor rotates around its centre line and at the same time, the rotor neck has a whirling rotation at the speed of 4775 rpm around the axis x = 0, y = -0.025 and z = 0, and $\frac{\dot{x}}{c\Omega} = 0.005, \frac{\dot{y}}{c\Omega} = 0$.

(3) x/c = 0.002 and y/c = 0, the starting point coordinate of rotor is x = 0.001, y = -0.025 and z = 0, the rotation axis keeps parallel with z axis positive, the rotor rotates around its centre line and at the same time, the rotor neck has a whirling rotation at the speed of 4775 rpm around the axis x = 0, y = -0.025 and z = 0, and $\frac{\dot{x}}{c\Omega} = 0, \frac{\dot{y}}{c\Omega} = 0.002$. x/c = 0 and y/c = 0.002, the starting point coordinate of rotor is x = 0, y = -0.0251 and z = 0, the rotation axis keeps parallel with z axis positive, the rotor rotates around its centre line and at the same time, the rotor neck has a whirling rotation at the speed of 4775 rpm around the axis x = 0, y = -0.025 and z = 0, and $\frac{\dot{x}}{c\Omega} = 0.002, \frac{\dot{y}}{c\Omega} = 0$。

5.2. The Results

Calculate the stiffness coefficient using the method above, and compare the results with ones in the reference written by Zenglin Guo, Toshio Hirano and R Gordon Kirk, the results are shown in Table 5.

Table 5. Damping Coefficients of Oil Film (104Ns/m)

methods	c_{xx}	c_{xy}	c_{yx}	c_{yy}
VT-FAST	5.75	4.93	5.41	16.7
DyRoBeS-BePerf	4.86	4.29	4.29	16.1
VT-EXPRESS	4.38	3.87	4.50	15.9
CFX-TASCflow ($v_x/c\Omega$, $v_y/c\Omega$=0.01)	6.92	5.90	6.60	18.2
CFX-TASCflow ($v_x/c\Omega$, $v_y/c\Omega$=0.005)	7.16	5.92	6.40	18.4
CFX-TASCflow ($v_x/c\Omega$, $v_y/c\Omega$=0.002)	6.86	5.82	6.50	18.0
FLUENT ($v_x/c\Omega$, $v_y/c\Omega$=0.01)	7.04	6.08	6.82	19.1
FLUENT ($v_x/c\Omega$, $v_y/c\Omega$=0.005)	7.23	5.99	6.73	19.7
FLUENT ($v_x/c\Omega$, $v_y/c\Omega$=0.002)	7.05	5.99	6.64	18.9

The comparison of tiny whirling $v_x/c\Omega$ and $v_x/c\Omega$ = 0.005 using CFD method with other computation results is shown is Table 6.

Table 6. Comparison with other Results with x/c = y/c = 0.005

comparison	c_{xx}	c_{xy}	c_{yx}	c_{yy}
VT-FAST	20.5%	17.7%	19.6%	15.2%
DyRoBeS-BePerf	32.8%	28.4%	36.3%	18.3%
VT-EXPRESS	39.4%	35.4%	33.1%	19.3%
CFX-TASCflow ($v_x/c\Omega$, $v_y/c\Omega$=0.01)	4.3%	1.5%	1.9%	7.6%
CFX-TASCflow ($v_x/c\Omega$, $v_y/c\Omega$=0.005)	1.0%	1.2%	1.9%	7.6%
CFX-TASCflow ($v_x/c\Omega$, $v_y/c\Omega$=0.002)	5.1%	2.8%	3.4%	8.6%

It is known that the results in this paper differ a little from the ones from CFX-TASC flow, with 10% error, but the difference with other results is more significant. The oil damping coefficients from the first there computation methods are obtained using Reynolds equation, ignoring many items, but the ones from the paper and CFX-TASCflow are reached using N-S equation, containing the ignorance.

6. Conclusions

The computation formula of oil film dynamic characteristic coefficients was induced in this paper. The stiffness coefficients of multi-flow oil film were obtained, using CFD methods and FLUENT software, and the damping coefficients of multi-flow oil film were obtained with the addition function of moving grid in FLUENT.

The comparison of the stiffness and damping coefficient with the results in reference 5 was done, and the difference was little, illustrating that the results in this paper was accurate. The computation methods had the accurate dynamic coefficients and would provide important values for the sable operation of the oil film.

Acknowledgment

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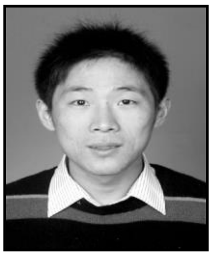

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