多油叶轴承油膜动力特性系数的计算方法

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摘要　刚度系数和阻尼系数是反映滑动轴承动力响应特性的重要的特性系数。对于以液体为润滑介质的多油叶轴承,本文给出了其动力特性系数的算法,采用数值方法进行了算例计算。

关键词　　多油叶轴承　动力特性系数

1 算　　法

(符号表列于文后)

取图1所示的坐标系,当轴颈中心 O_j 处于某一位置稳定工作时, O_j 偏离 O_b 某一微小偏心距 e, 偏位角为 δ, 对于每一弧轮廓面, 可以写出用轴心坐标 (x_j, y_j) 表示的膜厚函数 h_0

$$h_0 = C + e_i\cos\theta \quad (1)$$

由 $\theta_i = \theta' - \varphi_i$

(1)式可写成 $h_0 = C + e_i\cos(\theta' - \varphi_i)$ 则

$$h_0 = C - x_j\cos\theta' - y_j\sin\theta' \quad (2)$$

等温液体的动态雷诺方程为

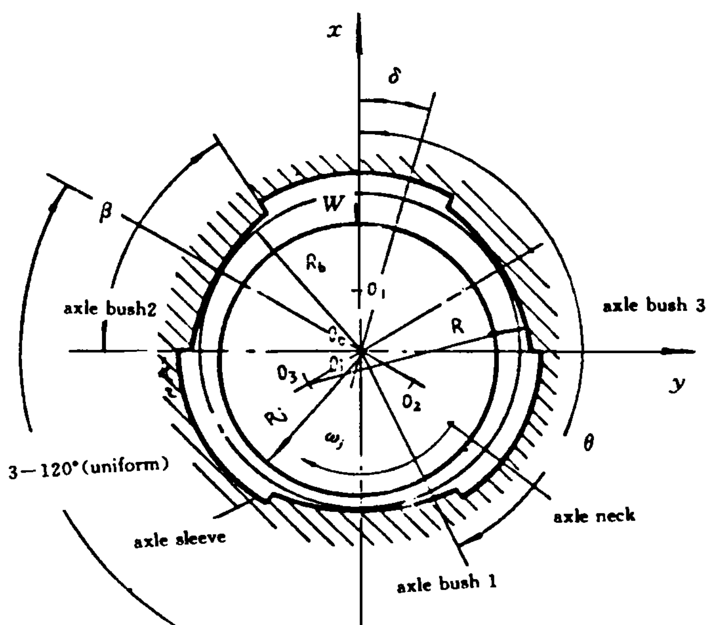

Fig. 1　Bearing structure

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$$\frac{\partial}{\partial\theta}\left(h^3\frac{\partial P}{\partial\theta}\right)+R_j^2\frac{\partial}{\partial z}\left(h^3\frac{\partial p}{\partial z}\right)=6\eta R_j^2\left(\omega_j\frac{\partial h}{\partial\theta'}+2\frac{\partial h}{\partial t}\right)\tag{3}$$

对于任意微扰 $(\Delta x_j(t),\Delta y_j(t))$，膜厚函数变为

$$h=h_0+\Delta h$$

$$\Delta h=-\Delta x_j(t)\cos\theta'-\Delta y_j(t)\sin\theta'\tag{4}$$

则有

$$h(\theta,z;x_j(t),y_j(t))=h_0(\theta,z;x_{j0},y_{j0})+\Delta h(\theta,z;\Delta x_j(t),\Delta y_j(t))\tag{5}$$

$$p(\theta,z;x_j(t),y_j(t))=p_0(\theta,z,;x_{j0},y_{j0})+\Delta p(\theta,z;\Delta x_j(t),\Delta y_j(t))\tag{6}$$

对于(3)式关于微扰 $\Delta x,\Delta y,\Delta\dot{x},\Delta\dot{y}$ 分别求偏导，并略去高阶小量，有

$$\frac{\partial}{\partial\theta}\left(h_0^3\frac{\partial P_0}{\partial\theta}\right)+R_j^2\frac{\partial}{\partial z}\left(h_0^3\frac{\partial p_0}{\partial z}\right)=12\eta R_j^2\omega\frac{\partial h_0}{\partial\theta'}\tag{7}$$

$$\frac{\partial}{\partial\theta}\left(h_0^3\frac{\partial p_x}{\partial\theta}\right)+R_j^2\frac{\partial}{\partial z}\left(h_0^3\frac{\partial p_x}{\partial z}\right)=6\eta R_j^2\omega_j\left(\sin\theta'+3\frac{\cos\theta'}{h_0}\cdot\frac{\partial h_0}{\partial\theta}\right)+3h_0^3\frac{\partial p_0}{\partial\theta'}\cdot\frac{\partial}{\partial\theta}\left(\frac{\cos\theta'}{h_0}\right)\tag{8}$$

$$\frac{\partial}{\partial\theta}\left(h_0^3\frac{\partial p_y}{\partial\theta}\right)+R_j^2\frac{\partial}{\partial z}\left(h_0^3\frac{\partial p_y}{\partial z}\right)=-6\eta R_j^2\omega\left(\cos\theta'-3\frac{\sin\theta'}{h_0}\cdot\frac{\partial h_0}{\partial\theta}\right)+3h_0^3\frac{\partial p_0}{\partial\theta'}\cdot\frac{\partial}{\partial\theta}\left(\frac{\sin\theta'}{h_0}\right)\tag{9}$$

$$\frac{\partial}{\partial\theta}\left(h_0^3\frac{\partial p_{\dot{x}}}{\partial\theta}\right)+R_j^2\frac{\partial}{\partial z}\left(h_0^3\frac{\partial p_{\dot{x}}}{\partial z}\right)=-12\eta R_j^2\cos\theta'\tag{10}$$

$$\frac{\partial}{\partial\theta}\left(h_0^3\frac{\partial p_{\dot{y}}}{\partial\theta}\right)+R_j^2\frac{\partial}{\partial z}\left(h_0^3\frac{\partial p_{\dot{y}}}{\partial z}\right)=-12\eta R_j^2\sin\theta'\tag{11}$$

由(7)、(8)、(9)、(10)和(11)解出 p_0、p_x、p_y、$p_{\dot{x}}$ 和 $p_{\dot{y}}$，油膜承载力分量为

$$\left.\begin{aligned}F_x&=-\int_{-l/2}^{l/2}\int_{\theta_1^j}^{\theta_2^j}p_0\cos\theta' R_j d\theta' dz\\F_y&=-\int_{-l/2}^{l/2}\int_{\theta_1^j}^{\theta_2^j}p_0\sin\theta' R_j d\theta' dz\end{aligned}\right\}\tag{12}$$

则刚度系数和阻尼系数按下式计算

$$\left.\begin{aligned}\begin{Bmatrix}K_{xx}\\K_{yx}\end{Bmatrix}&=\int_{-l/2}^{l/2}\int_{\theta_1^j}^{\theta_2^j}p_x\begin{Bmatrix}\cos\theta'\\\sin\theta'\end{Bmatrix}R_j d\theta' dz\\\begin{Bmatrix}K_{xy}\\K_{yy}\end{Bmatrix}&=\int_{-l/2}^{l/2}\int_{\theta_1^j}^{\theta_2^j}p_y\begin{Bmatrix}\cos\theta'\\\sin\theta'\end{Bmatrix}R_j d\theta' dz\end{aligned}\right\}\tag{13}$$

$$\left.\begin{aligned}\begin{Bmatrix}d_{xx}\\d_{yx}\end{Bmatrix}&=\int_{-l/2}^{l/2}\int_{\theta_1^j}^{\theta_2^j}p_{\dot{x}}\begin{Bmatrix}\cos\theta'\\\sin\theta'\end{Bmatrix}R_j d\theta' dz\\\begin{Bmatrix}d_{xy}\\d_{yy}\end{Bmatrix}&=\int_{-l/2}^{l/2}\int_{\theta_1^j}^{\theta_2^j}p_{\dot{y}}\begin{Bmatrix}\cos\theta'\\\sin\theta'\end{Bmatrix}R_j d\theta' dz\end{aligned}\right\}\tag{14}$$

求出各个油叶的刚度系数和阻尼系数后,对所有油叶的动力特性系数进行矢量运算,就可得到整个轴承的刚度系数和阻尼系数。

2　算　例

对应参数进行无量纲化 $\bar{h}_0 = \frac{h_0}{C}, P_0 = \frac{p_0}{p_s}, \overline{p_x} = \frac{p_x}{p_s/C}, \overline{p_y} = \frac{p_y}{p_s/C}, \overline{p_{\dot{x}}} = \frac{p_{\dot{x}}}{\frac{p_s}{C\omega}}, \overline{p_{\dot{y}}} = \frac{p_{\dot{y}}}{\frac{p_s}{C\omega}}$, $z = \frac{z}{\frac{l}{2}}, \overline{K_{xx}} = \frac{C}{W}K_{xx}, \overline{K_{yx}} = \frac{C}{W}K_{yx}, \overline{K_{xy}} = \frac{C}{W}K_{xy}, \overline{K_{yy}} = \frac{C}{W}K_{yy}, \overline{d_{xx}} = \frac{C\omega}{W}d_{xx}, \overline{d_{yx}} = \frac{C\omega}{W}d_{yx}, \overline{d_{xy}} = \frac{C\omega}{W}d_{xy}, \overline{d_{yy}} = \frac{C\omega}{W}d_{yy}$,其中 $p_s = \frac{2\eta\omega}{\psi^2}$

则得无量纲形式的雷诺方程为

$$\frac{\partial}{\partial\theta}\left(\bar{h}_0^3\frac{\partial}{\partial\theta}\right) + \left(\frac{d}{l}\right)^2\frac{\partial}{\partial z}\left(\bar{h}_0^3\frac{\partial}{\partial z}\right) = \begin{Bmatrix}\bar{p}_0\\ \bar{p}_x\\ \bar{p}_y\\ \bar{p}_{\dot{x}}\\ \bar{p}_{\dot{y}}\end{Bmatrix} = \begin{cases}\frac{6\eta\omega}{\psi^2 p_s}\cdot\frac{\partial\bar{h}_0}{\partial\theta'}\\ \frac{6\eta\omega}{\psi^2 p_s}\left(\sin\theta' + 3\frac{\cos\theta'}{\bar{h}_0}\frac{\partial\bar{h}_0}{\partial\theta}\right) + 3\bar{h}_0^3\frac{\partial\bar{p}_0}{\partial\theta'}\frac{\partial}{\partial\theta}\left(\frac{\cos\theta'}{\bar{h}_0}\right)\\ -\frac{6\eta\omega}{\psi^2 p_s}\left(\cos\theta' - 3\frac{\sin\theta'}{\bar{h}_0}\frac{\partial\bar{h}_0}{\partial\theta}\right) + 3\bar{h}_0^3\frac{\partial\bar{p}_0}{\partial\theta'}\frac{\partial}{\partial\theta}\left(\frac{\sin\theta'}{\bar{h}_0}\right)\\ -\frac{12\eta\omega}{\psi^2 p_s}\cos\theta'\\ -\frac{12\eta\omega}{\psi^2 p_s}\sin\theta'\end{cases} \tag{15}$$

由式(15)解得 $\bar{p}_0, \bar{p}_x, \bar{p}_y, \bar{p}_{\dot{x}}$ 和 $\bar{p}_{\dot{y}}$ 则有

$$\begin{Bmatrix}\begin{Bmatrix}\bar{K}_{xx}\\ \bar{K}_{yx}\end{Bmatrix} = \frac{1}{2S_0}\int_{-1}^{1}\int_{\theta_1}^{\theta_2}\bar{p}_x\begin{Bmatrix}\cos\theta'\\ \sin\theta'\end{Bmatrix}d\theta' dz\\ \begin{Bmatrix}\bar{K}_{xy}\\ \bar{K}_{yy}\end{Bmatrix} = \frac{1}{2S_0}\int_{-1}^{1}\int_{\theta_1}^{\theta_2}\bar{p}_y\begin{Bmatrix}\cos\theta'\\ \sin\theta'\end{Bmatrix}d\theta' dz\end{Bmatrix} \tag{16}$$

$$\begin{Bmatrix}\begin{Bmatrix}\bar{d}_{xx}\\ \bar{d}_{yx}\end{Bmatrix} = \frac{1}{2S_0}\int_{-1}^{1}\int_{\theta_1}^{\theta_2}\bar{p}_{\dot{x}}\begin{Bmatrix}\cos\theta'\\ \sin\theta'\end{Bmatrix}d\theta' dz\\ \begin{Bmatrix}\bar{d}_{xy}\\ \bar{d}_{yy}\end{Bmatrix} = \frac{1}{2S_0}\int_{-1}^{1}\int_{\theta_1}^{\theta_2}\bar{p}_{\dot{y}}\begin{Bmatrix}\cos\theta'\\ \sin\theta'\end{Bmatrix}d\theta' dz\end{Bmatrix} \tag{17}$$

由式(16)、(17)可解得轴承的无量纲刚度系数和阻尼系数。

对于轴承结构参数, $R_j = 30\text{mm}$, $n = 3$, $\beta = 60°$, $R = 30.00931\text{mm}$, $e_p = 8.21\mu\text{m}$,按照上述方法和式(15)、(16)、(17)求得的 $\bar{K}_{ij}$、$\bar{d}_{jj}(i,j = x, y)$ 分别见图2和图3。

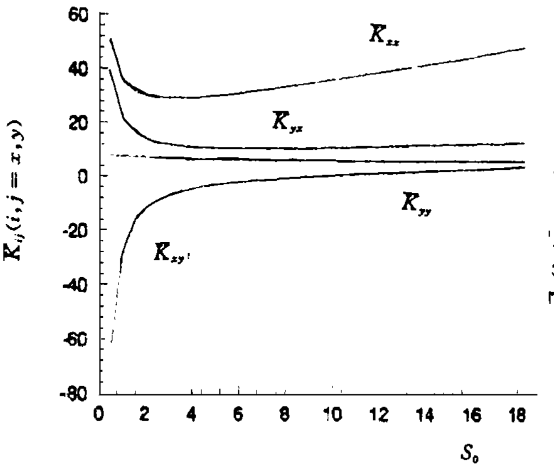

Fig.2 Relationship of s_0 and $\bar{K}_{ij}$

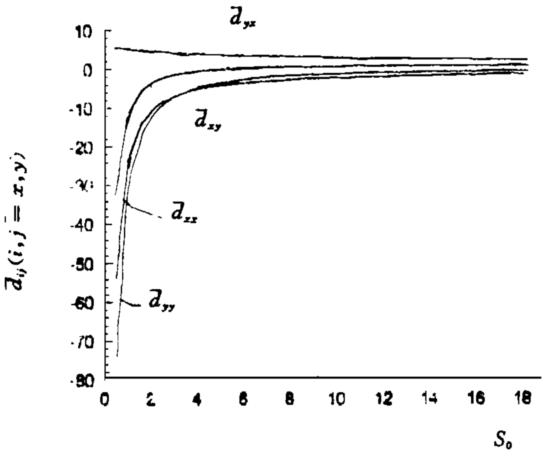

Fig.3 Relationship of s_0 and $\bar{d}_{ij}$

3 结 束 语

对于多油叶轴承结构形式及坐标系, 这里给出的求解动力特性系数的方程和具体算式适用于同类轴承的计算问题, 是对轴承进行稳定性分析的基础。

符 号 表

C ——半径间隙, μm;
d —— 轴颈直径, m;
R_j —— 轴颈半径, m;
R ——圆弧半径, m;
e_p —— 弧轮廓的预偏心距, μm;
l ——轴承长度, m;
$d_{ij}(i,j=x,y)$ ——阻尼系数, $N/\mu m \cdot s^{-1}$;
$\bar{d}_{ij}(i,j=x,y)$ ——无量纲阻尼系数;
F_x, F_y ——x, y 方向 承载力分量, N;
h ——间隙(膜厚) 函数, μm;
$K_{ij}(i,j=x,y)$ —— 刚度系数, N/m;
$\bar{K}_{ij}(i,j=x,y)$ ——无量纲刚度系数;
p —— 油膜压力, N/m^2;
p_x, P_y —— 由微扰动 Δx, Δy 引起的压力偏导数, $N \cdot m^{-1}/\mu m$;
$p_{\dot{x}}, P_{\dot{y}}$ ——由微扰动 $\Delta\dot{x}$, $\Delta\dot{y}$ 引起的压力偏导数, $N \cdot s \cdot m^2/\mu m$;
O_b —— 轴承中心;
O_j —— 轴颈中心;
$O_i(i=1,2,\cdots,n)$ —— 圆弧 i 的中心;
n—— 油叶数;

β—— 弧包角;
x, y, z —— 固定直角坐标;
S_0—— 索默菲尔德数, $S_0 = \dfrac{W\Psi^2}{ld\eta\omega}$;
W —— 外载荷;
η ——动力粘度系数, Pa•s;
ω_j —— 轴角速度, rad/s;
ω_b —— 轴套角速度, rad/s, ($\omega_b = 0$); ;
θ_1^i, θ_2^i —— 分别为第 i 个弧轮廓的起始角和终止角;
$\omega = \omega_j + \omega_b$
ρ ——润滑油密度, kg/m^3;
Ψ—— 相对半径间隙, $\Psi = \dfrac{C}{R_j}$;
e_i ——O_j 对于 O_i 的偏心距;
φ_i——O_j 对于 O_i 的偏位角;
θ'—— 由 O_bx 线为起始线沿轴转动方向计量的角度;
θ_i—— 由 O_jO_i 线为起始线沿轴转动方向计量的角度;
下标“O”—— 平衡态值;
$\Delta(\quad)$ ——微扰值;

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Calculation Method on Film Dynamic Coefficients of Multi-lobe Journal Bearings

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Abstract

Stiffness and damping coefficients are important characteristic. Coefficients that reflect the dynamic respond characteristics of journal bearings. The calculation method on these coefficients for liquid lubricated bearings is described in this paper, and calculation of actual example problem is carried out by means of numerical method.

Key words: Multi-lobe journal bearings, Dynamic coefficients, Calculating method

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