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重载低速动压润滑推力轴承的理论分析

(哈尔滨锅炉厂有限责任公司, 黑龙江 哈尔滨　150046)　李建平　刘　锐

摘　要: 针对多滑瓦平面推力轴承的弹性变形、承载能力、刚度、油粘度、油膜厚度等参数进行理论分析, 得出这些参数的部分关系, 为此类轴承合理设计提供一些理论依据。

关　键　词: 弹性变形; 动压润滑; 油膜厚度

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符号说明

h, H — 油膜厚度[m] 及无量纲厚度
M, M'_L — 流场节点数及板单元数
N_i, $[N_m]$ — 形函数及其矩阵
r, R — 半径[m] 及无量纲半径
T, T — 轴承摩擦力矩[N·m] 及无量纲摩擦力矩
Y — 弹性板变形[m]
θ_x, θ_y — 弹性板沿 X, Y 方向矢量
μ — 油粘度[Pa·s]
ω — 轴承角速度[r/s]
K — 轴承刚度
N, N' — 流场节点数及板节点数
p, P — 油膜压力[Pa] 及无量纲压力
r_1, r_0 — 轴承内半径及外半径[m]
W, W — 轴承承载量[N] 及无量纲承载量
θ — 极角
λ, λ_i — 轴承数及内半径处轴承数
P_a — 环境压力[Pa]
Ω_i — 单元区域

1　引言

大型多滑瓦平面推力轴承在一些大型转动机械上得到广泛采用, 例如水轮机、立式大型泵、立式回转预热器等常采用平面推力轴承。这类轴承承载能力大, 典型的平均油膜压力可达3.5～7 MPa, 能在高速下形成动压润滑, 也能在非常低的速度下形成动压润滑。如600 MW 机组预热器转速仅1 r/min, 线速度为0.055 m/s。通常要求平均滑动速度大于3 m/s, 才能形成动压润滑, 但试验表明: 这种低速下的轴承也能形成油膜动压润滑, 并能长期正常稳定运行。

2　理论分析

动压轴承的油膜厚度分布情况与轴承的载荷、转速和油特性有关, 还与滑瓦材料及结构有关。因此同时对油膜及滑瓦变形加以考虑, 以求得相互协调的油膜厚度分布, 弹性变形及润滑膜的压力分布, 进而求得轴承的基本特性。本文采用了有限元法对流场及弹性滑瓦间偶合进行了数值计算。

2.1　求解动压润滑压力 P

考虑轴承能长期稳态运转, 假设: (a)润滑介质为牛顿流体, 粘度与压力无关; (b)轴承润滑介质的流动为层流动; (c)流场为等温状态; (d)略去润滑介质的惯性与重力。由此可得雷诺方程[2]。

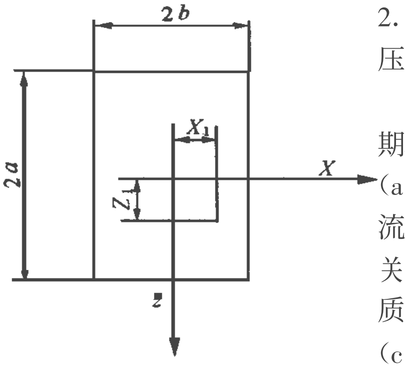

图1

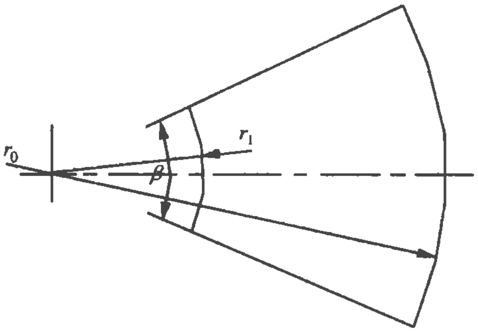

图2

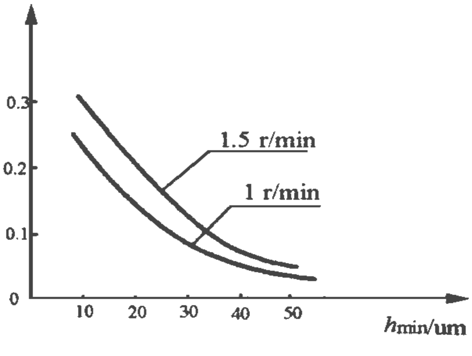

图3　载荷与油膜厚度关系

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rph^3\frac{\partial P}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial\theta}\left(ph^3\frac{\partial P}{\partial\theta}\right)=6\mu\omega\frac{\partial ph}{\partial\theta} \tag{1}$$

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作者简介: 刘　锐(1964－), 女, 黑龙江哈尔滨人, 哈尔滨锅炉厂有限责任公司锅炉设计处工程师.

引入无量纲变量 $P = P/P_a, H = h/h_{\min}, R = r/r_i$，可得

$$\nabla(P H^3 \nabla P - \lambda\theta PH) = 0 \quad (2)$$

$$\lambda = \frac{6\mu\omega r_i^2}{h_{\min}^2 P_a} \cdot \frac{r}{r_i} = \lambda_i R \quad (3)$$

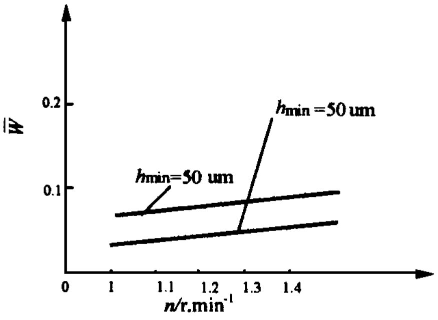

图 4　载荷与转速关系

流场的边界条件为：在润滑区域四周，压力等于环境压力。对于二阶非线性偏微分方程取权函数 δP 则有变分式

$$\delta\phi\{P\} = \sum_{i=1}^{M} \iint_{\Omega_i} \nabla(PH^3 \nabla P - \lambda\theta PH)\,\delta P\,\mathrm{d}A \quad (4)$$

经过化简并注意在边界上有 $\delta P = 0$，有

$$\delta\phi\{P\} = \sum_{i=1}^{M} \iint_{\Omega_i} -(PH^3 \nabla P \nabla \delta P - PH\lambda\theta \cdot \nabla \delta P)\mathrm{d}A \quad (5)$$

令 $R = e^{v}$　(6)

则有 $-\ \delta\phi\{P\} = \sum_{i=1}^{M} \iint_{\Omega_i} [\frac{1}{2}H^3 \frac{\partial P^2}{\partial v} \frac{\partial \delta P}{\partial v} + \frac{1}{2}H^3 \frac{\partial P^2}{\partial\theta} \frac{\partial \delta P}{\partial\theta} - \lambda PH \cdot e^{v} \frac{\partial P}{\partial\theta}]\,\mathrm{d}v\mathrm{d}\theta$　(7)

本文采用八节点四边形二次等参元，节点变量为压力 P，进行插值 $P = [N_m]^T[P_m]$　$\delta P = [N_m]^T[\delta P_m]$

$$H = [N_m]^T\{H_m\} \quad P^2 = [N_m]^T[P_m] \quad (8)$$

将式(8) 代入式(7) 得

$$-\ \delta\phi\{P\} = \sum_{i=1}^{M}\{\delta P_m\}^T \iint_{\Omega_i}[B_m]^T[D_m][B_m]\,\mathrm{d}v\mathrm{d}\theta\{P_m{}^2\} - \sum_{i=1}^{M}\{\delta P_m\}^T \iint_{\Omega_i}[B_m]^T[V_m][N_m]^T\mathrm{d}v\mathrm{d}\theta\{P_m\} \quad (9)$$

式中 $[B_m]$，$[D_m]$，$[V_m]$ 为系数矩阵。将 $\{P_m\}$，$\{\delta P_m\}$，$\{P_m^2\}$ 扩大至整个区域，成为 $\{P\}$、$\{\delta P\}$、$\{P^2\}$。

由于 $\frac{\partial\phi\{P\}}{\partial\{\delta P\}} = 0$　(10)

则有：$\sum_{i=1}^{M}[A_m]\{P\} - \sum_{i=1}^{M}[C_m]\{P\} = \{f(\{P\})\} = \{0\}$　(11)

式中 $[A_m]$，$[C_m]$ 为单元系数矩阵，其元素分别为

$$a_{ij} = \iint_{\Omega_k} \frac{1}{2}H^3\left(\frac{\partial N_i}{\partial v} \cdot \frac{\partial N_j}{\partial v} + \frac{\partial N_i}{\partial\theta} \cdot \frac{\partial N_j}{\partial\theta}\right)\mathrm{d}v\mathrm{d}\theta \quad (12)$$

$$C_{ij} = \iint_{\Omega_k} H\lambda e^{2v} \frac{\partial N_i}{\partial\theta} N_j \mathrm{d}v\mathrm{d}\theta \quad (13)$$

($k = 1, 2\cdots\cdots M$; $i, j = 1, 2\cdots\cdots 8$)

解非线性方程组(11) 用牛顿—拉普逊法求

$[P]_{i+1}\{\Delta P\}_i + \{P_i\}$　(14)

$[E]_i\{\Delta P\}_i + \{f(P_i)\} = \{0\}$　(15)

要求 $\|\{\Delta P\}\| \leqslant \varepsilon$

式中 $\{E\}_i = 2[\sum_{i=1}^{M}[A_m]]\,\mathrm{diag}\{P_1, P_2\cdots\cdots P_N\}_i - [\sum_{i=1}^{M}[C_m]]$　(16)

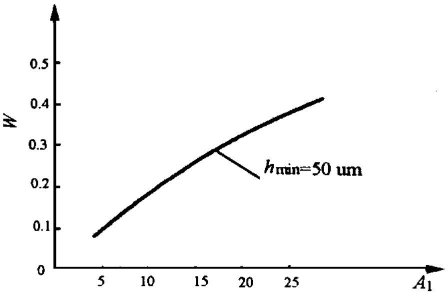

图 5　载荷与轴承数关系

解出方程(14) 便可得流场分布

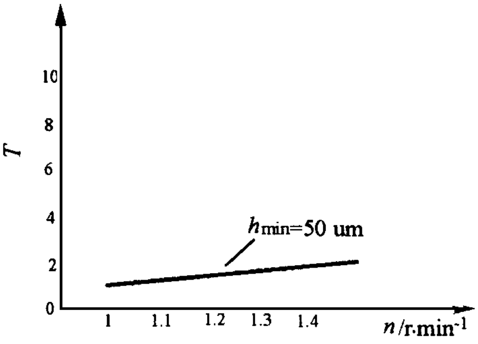

图 6　摩擦力矩与转数关系

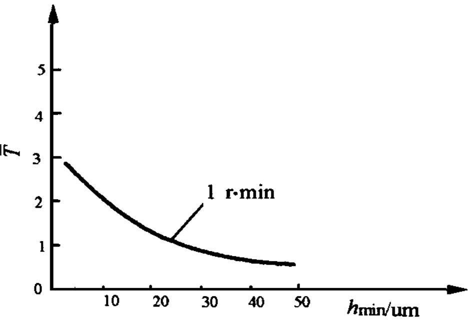

图 7　摩擦力矩与油膜厚度关系

2.2　求解弹性变形

采用与流场相同的网格，共有 M′ 个板单元，N' 个节点。关于弹性变形量的计算在许多有关弹流理论书籍中都作了介绍。本文仅列出矩形面积为 $2\bar{a} \times 2\bar{b}$（见图 1）上承受均布压力而引起的 $(\bar{x}_1, \bar{z}_1)$ 点上弹性变形[3] 为

$$Y = \frac{2P}{\pi}\int_{-\bar{a}}^{\bar{a}}\int_{-\bar{b}}^{\bar{b}} \frac{\mathrm{d}\bar{x}_1\,\mathrm{d}\bar{z}_1}{[(\bar{z}\ \bar{z}_1)^2 + (\bar{x} - \bar{x}_1)^2]^{1/2}} \quad (17)$$

式中参数都是无纲量。

2.3　轴承承载能力、刚度、摩擦力矩计算

$$W = \frac{W}{P_a r_i^2} = \int_1^{r_0/r_i}\int_0^{\beta}(P - 1)R\mathrm{d}R\mathrm{d}\theta \quad (18)$$

轴承刚度

$$K = \mathrm{d}W/\mathrm{d}h_{\min} \qquad (19)$$

无量纲摩擦力矩

$$T = \frac{T}{P_a h_{\min} r_i^2} = \int_1^{r_0/r_i}\int_0^{\beta}\left(\frac{\lambda R^3}{6H} + \frac{RH}{2} \circ \frac{\partial P}{\partial \theta}\right)\mathrm{d}R\,\mathrm{d}\theta \qquad (20)$$

3　算例

以 600 MW 机组回转式空气预热器轴承（见图 2）为例 $\beta = 51^{\circ}$，$r_i = 292$ mm，$r_0 = 762$ mm，转速为 1 r/min，润滑油牌号为 N680。正常运转温度为 40 ℃，滑瓦为 6 个，总载荷为 450 吨。经计算得到最小油膜厚度为 50 μm，改变参数可计算得到各参数间的关系如图 3 ～ 图 8 所示。

4　结论

（1）轴承承载量随 $h_{\min}$ 减小和转速上升而增加，轴承数 λ 综合反映 $h_{\min}$ 及转速的影响。

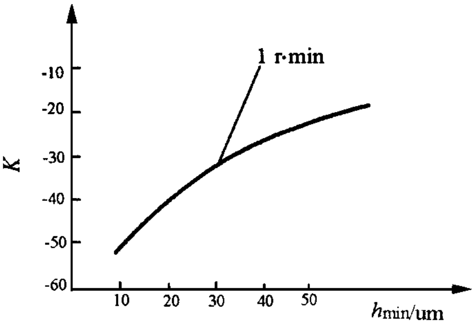

图 8　刚度与油膜厚度关系

（2）轴承刚度随 $h_{\min}$ 减小而增加。

（3）轴承摩擦力矩随 $h_{\min}$ 减小和随转速增加而增加，近似线性关系。

（4）滑瓦产生弹性变形，峰值点同压力峰接近。

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（何静芳　编辑）

简　讯

火电站化学管理的改进

据“火力原子力发电”1999 年 11 月号报道，日本东北电力公司东新浮火力发电厂开发出化学管理的新技术。

1. 开发具有改进耐氧化性的透平油。分析了作为氧化抑制剂的 DBEP 剂量对耐氧化性能的影响。结果，新开发的透平油比普通透平油耐氧化性约提高 30％。

2. 完成了使用 JIS 保障剂（磷酸钠）代替普通药剂的实际装置试验。因为 JIS 保障剂具有很少的腐蚀成份，水冷壁管的腐蚀速度减小，从而延长了循环锅炉化学清洗的时间间隔。

3. 供联合循环装置余热锅炉用的磷酸钠自动喷注法。

该电厂把喷注磷酸钠的方法从半自动改为受锅炉水导电率控制的自动喷注法。在联合循环装置的 6 台余热锅炉中，自动控制磷酸浓度到目标值范围内。

（思　娟　供稿）

Trent 将驱动高速集装箱船

据“Diesel &Gas Turbine Worldwide”1999 年 10 月号报道，英国罗尔斯－罗伊斯公司已获得一份合同，这将是针对船舶发动机最大的一次订货，使用航改型燃气轮机驱动革新的超级高速船队，将变革横渡大西洋的海上贸易。

美国宾夕法尼亚州费城的 FastShip（高速船）航运公司将为 25 台船用 Trent 型燃气轮机订立合同，每船 5 台和共计 5 台备品。合同还包括在每台发动机整个寿命期间对其成套设备提供 20 年的供给和维修保障。

在拓展其业务中，高速船航运公司将订购 4 艘高速集装箱船－FastShip。FastShip 将装用每台额定功率为 50 MW 的 4 台 Trent 发动机，航速将高达 40 节。该集装箱船总长为 265 m，船宽为 40 m，满载排水量为 36 300 t。这些船舶计划在 2000 年进行海上试验，并于 2003 年投入营运。此项目也包括在费城和法国的瑟堡开发新的终端设施。该公司预期对于时间敏感的高值货物将产生优质需时仅 7 天的门对门北大西洋航线。

（思　娟　供稿）

Shaanxi，China，Post Code：710049）// Journal of Engineering for Thermal Enegy &Power. — 2000，15(4). —364 ~366

An analysis was perfomed of the flow process of a heat exchange tube bank in an ice storage tank，and a physical model featuring the actual flow process has been set up. An analytical solution was obtained through a theoretical deduction. On the basis of the above the authors have provided a theoretical method for the accurate calculation of the flow distribution and system pressure drop of the heat exchange tube bank as well as the design of the latter. **Key words**：ice storage tank，heat exchanger，flow characteristics，flow distribution，pressure drop

非线性刚性转子一轴承系统的混沌研究＝**A Study on the Chaotic Motions Existing in a Nonlinear and Rigid Rotor-bearing System** [刊，汉] /ZHANG Xin-jiang，WU Xin-hua，HAN Wan-jin（College of Energy Science and Engineering under the Harbin Institute of Technology），LI Jian-zhao（Harbin No. 703 Research Institute，Harbin，China，Post Code：150036）// Journal of Engineering for Thermal Energy &Power. — 2000，15(4). —367 ~369

In connection with the specific features of a nonlinear rotor-bearing system and under a relatively wide range of parameters a study has been conducted of the stability of a rigid Jeffcott rotor-bearing system using a short bearing model. The study was perfomed on the basis of the rotor dynamics and nonlinear dynamics theory and with the use of a numerical integration and Poincaré mapping method. The results of calculation show that there exist chaotic motions in the above-mentioned system. With the help of a numerical method obtained in some parameter domains of the system were the following：bifurcation diagrams，response curves，time histories，frequency spectrum and phase diagrams，shaft centerline locus and Poincaré mapping diagram. All the above gives a visual display of the operating condition of the system in some parameter domains. Meanwhile，an analysis was conducted of the effect of the bearing geometric dimensions on the stability of the system. The results of the numerical analysis can provide a theoretical basis for the design and safe operation of this type of rotor-bearing system. **Key words**：rotor dynamics，nonlinearity，rotor-bearing system，chaotic motion，stability

重载低速动压润滑推力轴承的理论分析＝**Theoretical Analysis of a Dynamic-pressure Lubricated Heavy-duty and Low-speed Thrust Bearing** [刊，汉] / LI Jian-ping，LIU Rui（Harbin Boiler Co. Ltd.，Harbin，China，Post Code：150046）// Journal of Engineering for Themal Enegy &Power. — 2000，15(4). —370 ~372

A theoretical analysis was conducted of a multiple-slide pad and plane thrust bearing with respect to such a variety of parameters as elastic defomation，load-bearing capacity，rigidity，oil viscosity and oil film thickness，etc. Some of the relationships governing these parameters，thus obtained，can serve as a theoretical basis for the rational design of the above-cited bearing. **Key words**：elastic defomation，dynamic pressure lubrication，oil film thickness

三压再热汽水系统 IGCC 的设计工况和变工况性能＝**Design and Off-design Performance of the Integrated Gasification Gas-steam Combined Cycle（IGCC）of a Triple-pressure Reheat Steam-water System** [刊，汉] / LU Ze-hua，ZHAO Shi-hang，SHANG Xue-wei，CAO Ren-feng（Qinghua University，Beijing，China，Post Code：100084）//Journal of Engineering for Thermal Energy &Power. — 2000，15(4). —373 ~375

With the integrated gasification gas-steam combined cycle（IGCC）of a triple-pressure reheat steam-water system serving as an object of study proposed in the present paper is the design scheme of an integrated air separation IGCC system. Set up was a mathematical model involving the following units：a gasification furnace，a purification system，a gas turbine，an air separation unit，a heat recovery boiler and a steam turbine. A series of calculations were performed of both the design and off-design performance of the IGCC system. Analyzed was the effect on the system off-design performance in the case of the gas turbine adopting different control and regulation laws as well as in the case of the steam turbine assuming different operational modes. In addition，a rational operational mode has also been proposed. **Key words**：integrated gasification gas-steam combined cycle，integrated air separation unit，off-design operating conditions，regulation law and