

悬臂式挠性薄片气体动压径向轴承 分析研究

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【摘要】 本文建立了悬臂式挠性薄片气体动压径向轴承的特性分析计算方法, 用差分方法耦合求解径向轴承的雷诺方程和薄片弹性变形方程。给出了径向轴承刚度、阻尼的计算方法和稳定性计算方法。计算分析了设计的悬臂式薄片气体动压径向轴承的静特性和动特性。计算结果表明, 对于所有的偏心率范围和可能的工作运行范围内是恒定稳定的。

主题词: 气体轴承 薄片 分析

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气体动压润滑以摩擦小和工作成本低等优点而获得广泛应用研究。国外已将挠性结构的气体动压润滑轴承成功地应用于航空涡轮冷却器。本文对研制的航空涡轮冷却器用悬臂式挠性薄片气体动压径向轴承进行了理论分析研究。

1 分析方法

1.1 几何关系

研制的悬臂式薄片气体动压径向轴承有由8片轴承薄片组装而成, 轴承薄片一边固定在组成壳体上, 另一边与相邻的薄片之间成自由搭接状态, 轴承几何关系见图1。A点为固定支点, B点为与后一片的搭接点, S点为与前一片的搭接点, C点为薄片的曲率中心。气体润滑轴承薄片工作段SB任意一点的极距为:

$$\rho_i = R_g \left[\cos \beta + \sqrt{R_f^2 / R_g^2 - \sin^2 \beta} \right] \quad (1)$$

式中: $\beta = \theta + \alpha + \gamma - (i-1)(2\pi/N)$

1.2 轴承特性方程

由于气体动压轴承的径向间隙尺寸很小, 一般取润滑气膜处于层流状态和等温过程。当取 $x = R \cdot \varphi$, $z = \bar{z} \cdot R$, $h = \bar{h} \cdot c$, $p = \bar{p} \cdot p_a$ 和轴承数 $\Lambda = (6\mu\omega/p_a)(R/c)^2$ 等无量纲参数, 则无量纲形式的稳态雷诺方程:

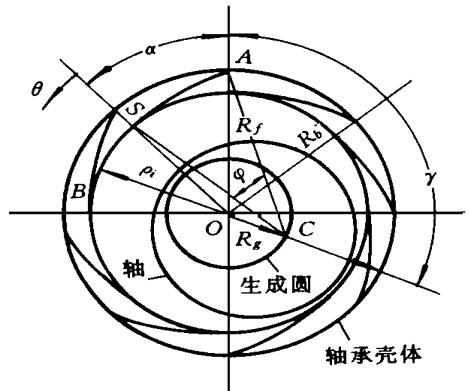


图1 径向轴承几何关系示意图

$$(\partial/\partial z)[\overline{ph}(\partial\overline{\varphi}/\partial z)] + [(\partial/\partial \vartheta)[\overline{ph}^3(\partial\overline{\varphi}/\partial \vartheta)] = \Lambda[\overline{\alpha ph}]/r\partial \vartheta \quad (2)$$

轴承承载分量和轴承的承载能力分别为:

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \int_{B/2}^{R/2} \int_0^{2\pi} p \begin{bmatrix} \sin \varphi \\ \cos \varphi \end{bmatrix} \sin \vartheta d\vartheta dz \quad (3)$$

径向轴承的动特性可由轴承刚度和阻尼系数来描述, 径向轴承刚度和阻尼系数:

$$\begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix} = \int_{B/2}^{R/2} \int_0^{2\pi} \begin{bmatrix} p_x \\ p_y \end{bmatrix} [\sin \varphi \cos \vartheta] r d\vartheta dz \quad (4)$$

$$\begin{bmatrix} D_{xx} & D_{xy} \\ D_{yx} & D_{yy} \end{bmatrix} = \int_{B/2}^{R/2} \int_0^{2\pi} \begin{bmatrix} p_x \\ p_y \end{bmatrix} [\sin \varphi \cos \vartheta] r d\vartheta dz \quad (5)$$

转子和轴承支承系统的稳定性可用相当刚度 K_{eq} 和界限涡动比 Ω_c 判断:

$$K_{eq} = \frac{K_{xx}D_{yy} + K_{yy}D_{xx} - K_{xy}D_{yx} - K_{yx}D_{xy}}{D_{xx} + D_{yy}} \quad (6)$$

$$\Omega_c^2 = \frac{(K_{xx}K_{eq})(K_{yy} - K_{eq}) - K_{xy}K_{yx}}{D_{xx}D_{yy} - D_{xy}D_{yx}} \quad (7)$$

1.3 薄片弹性变形方程组

用薄壳理论的有矩理论计算分析径向轴承薄片系变形, 各点位移所表示的微分方程组:

$$\left(\frac{\partial}{\partial \alpha^2} + \frac{1-\mu}{2} \frac{\partial}{R^2 \partial \vartheta} \right) u + \left(\frac{1+\mu}{2} \frac{\partial}{R \partial \alpha} \right) v + \left(\frac{\mu}{R} \frac{\partial}{\partial \alpha} \right) w + \frac{1-\mu^2}{Et} q_x = 0 \quad (8a)$$

$$\left(\frac{1+\mu}{2} \frac{\partial}{R^2 \partial \vartheta} \right) u + \left(\frac{1-\mu}{2} \frac{\partial}{\partial \alpha^2} \frac{\partial}{R \partial \alpha} \right) v + \left(\frac{\partial}{R^2 \partial \vartheta} \right) w + \frac{1-\mu^2}{Et} q_\theta = 0 \quad (8b)$$

$$\left(\frac{\mu}{R} \frac{\partial}{\partial \alpha} \right) u + \left(\frac{\partial}{R^2 \partial \vartheta} \right) v + \left(\frac{r^2}{12} + \nabla^2 \nabla^2 + \frac{1}{R^2} \right) w - \frac{1-\mu^2}{Et} q_n = 0 \quad (8c)$$

式中: $\nabla^2 = (\partial/\partial \alpha^2) + (1/R^2)(\partial/\partial \vartheta)$; μ 为泊松系数; E 为弹性模量; t 为薄片厚度; q_x , q_θ 和 q_n 为三个方向载荷分量。

1.4 基本方程组求解过程

用差分法求解非线性椭圆型偏微分雷诺方程和径向轴承弹性薄片系弹性变形方程组。气膜厚度表达式将雷诺方程和弹性变形方程联系在一起, 由几何关系计算出初始的气膜厚度 $h_e(z, \vartheta)$, 由气膜压力得轴承薄片的变形 $h_e(z, \vartheta)$, 最后得轴承的气膜厚度:

$$h(z, \vartheta) = h_0(z, \vartheta) + h_e(z, \vartheta) \quad (9)$$

对于一个薄片, 已知进出口边气膜厚度 h_0 , S 和 B 两点从静平衡位置到满足以上要求的气膜厚度所需移动的距离分别为 d_s 和 d_B , 下标 S 和 B 分别代表在 S 和 B 点。薄片的受力示意图见图 2。 P_d 为上一片薄片对本片薄片的作用力, P_u 为下一片薄片对本片薄片的作用力。由卡氏定理可得 S 和 B 点位移为:

$$W_{S1} = \frac{P_u R^2}{2EI} \left[\vartheta_0 \sin(\theta - \vartheta) + \frac{1}{2} \sin(\theta - \vartheta) - \frac{1}{2} \sin(\theta - \vartheta) \right] \quad (10a)$$

$$W_{B1} = \frac{P_u R^3}{2EI} (\theta - \sin \theta \cos \theta), \quad W_{S2} = \frac{P_d R^3}{2EI} (\vartheta - \sin \vartheta \cos \vartheta) \quad (10b)$$

$$W_{B2} = \frac{P_d R^3}{2EI} \left[\vartheta_0 \sin(\theta - \vartheta) + \frac{1}{2} \sin(\theta - \vartheta) - \frac{1}{2} \sin(\theta - \vartheta) \right] \quad (10c)$$

$$\text{由线性叠加原理得: } W_{S1} + W_{S2} = d_s, \quad W_{B1} + W_{B2} = d_B \quad (11)$$

联立上面各式即可迭代求得接触力 P_u 和 P_d , 另外, 还考虑到薄片的变形是二维的, 因此其接触力 P_u 和 P_d , 在宽度方向上分布形式近似为抛物线。

2 计算结果及分析

用本文的方法对设计的悬臂式薄片气体动压径向轴承进行计算分析。轴承结构参数 轴颈半径 $R = 15 \text{ mm}$, 轴承半径 $R_b = 16 \text{ mm}$, 轴承长度 $L = 30 \text{ mm}$, 薄片数 $N_f = 8$, 薄片厚度 $t = 0.1 \text{ mm}$, 薄片半径 $R_f = 21 \text{ mm}$, 薄片重叠角 $\varphi = 47^\circ$ 。图 2 为径向轴承各薄片的接触力以及最小气膜厚度的分布情况。轴承各薄片间的接触力即为各薄片搭接之间的相互作用力, 该力为径向轴承提供了支承刚度, 是随径向轴承的工作状态不同而变化的。从图中计算结果可见第五片轴承薄片的接触力最大, 其气膜最小厚度为最小。气膜最小厚度为最小则气膜压力最大。

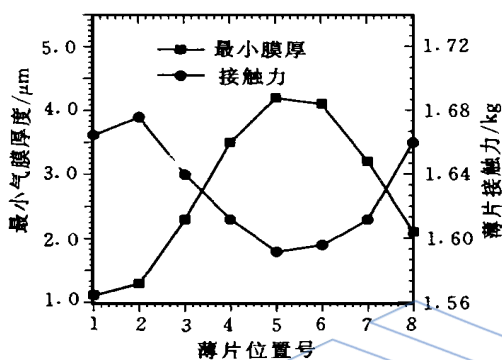


图2 薄片的参数特性

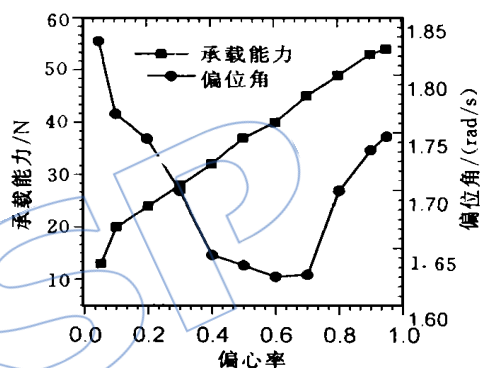


图3 轴承静特性

图 3 为转速 $n = 8 \times 10^4 \text{ r/min}$ 时, 轴承承载能力和偏位角随偏心率变化的情况。在该转速下, 随偏心率的增大, 轴承的承载能力提高。

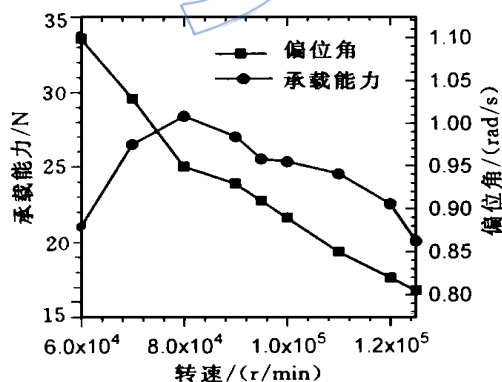


图4 轴承运转特性

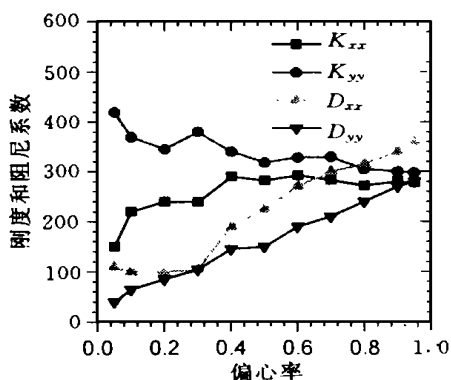


图5 轴承刚度和阻尼系数

图 4 中偏位角均随转速的升高而单调地下降。承载能力 $n = 80000 \text{ r/min}$ 在附近最大。而轴承中的最小气膜厚度随转速升高而增大。轴承承载能力与转速成正比例关系, 与最小气膜厚度成反比例关系。当转速升高时承载能力一方面要随转速而升高, 另一方面却要随最小气膜厚度增大而减小。两者综合的结果使得必然存在一个转速极值点。对于本文径向轴承结构,

计算结果表明最大承载能力的速度极值点为 $n = 8 \times 10^4 \text{ r/min}$ 处。

图 5 是直接刚度系数和阻尼系数等八个轴承动特性系数的变化。随偏心率的增大, 直接刚度系数趋于定值, 而直接阻尼系数则有明显的提高, 并且均明显地大于交叉刚度和阻尼。

图 6 表明相当刚度随 K_{eq} 增大而增大, 临界涡动比的平方始终为负值, 不存在失稳转速, 即轴承在任何偏心下均是恒定稳定的。

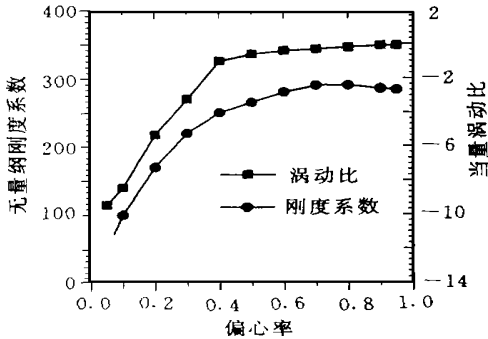
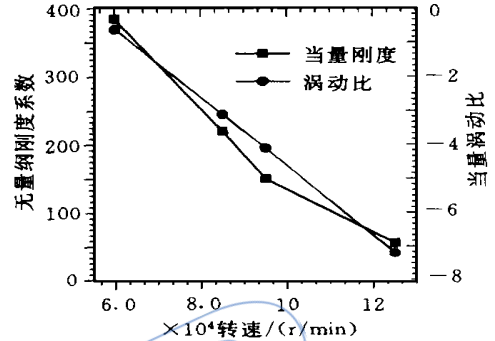


图 6 相当刚度与涡动比



7 相当刚度与涡动比和转速

图 7 中轴承相当刚度 K_{eq} 随转速升高而下降。但均为正值, 界限涡动比 Ω^2 均为负值。所以至少在 $n = 6 \times 10^4 \text{ r/min}$ 到 $n = 12.5 \times 10^4 \text{ r/min}$ 的可能工作运行范围内是绝对稳定的。且随转速升高, 稳定性储备逐渐增加。

3 结 论

本文对悬臂式薄片气体动压径向轴承的静动特性计算分析有如下结论: (1) 悬臂式薄片气体动压径向轴承的最大气膜压力出现在第五片薄片上。随偏心率和转速的增大, 轴承承载能力均提高。(2) 在不同的运行过程中, 径向轴承的承载能力在 $n = 8 \times 10^4 \text{ r/min}$ 附近最大; (3) 悬臂式薄片气体动压径向轴承的轴承刚度和阻尼系数均较大, 有好的动态稳定性。对于所有的偏心率范围和可能的运行转速范围内, 轴承均是恒定稳定的, 其高速特性好。(4) 用本文建立的计算分析方法可为悬臂式薄片气体动压轴承提供静动特性分析。

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FINITE ELEMENT ANALYSIS AND EXPERIMENTAL MEASUREMENT OF STIFFNESS OF HOOP

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ABSTRACT It is important to determine the stiffness coefficients of the hoops precisely for the vibration analysis of a pipeline system. For this purpose the finite element models for calculating the stiffness coefficients of the hoops are established in accordance with the structural features of the various hoops used in aeroengine pipeline systems. The stiffness coefficients of a grounded hoop for single pipe and a hung hoop for double pipes are obtained by the finite element analysis. In addition, the stiffness coefficients of a typical hung hoop for double pipes are measured by using the established experimental method. The comparison between the calculational and experimental results of the hoop shows that the provided method is feasible in the engineering practice of vibration analysis for a pipeline system.

Key Words Hoops stiffness Finite element analysis Measurement

AN ANALYSIS OF A GAS LUBRICATED COMPLIANT MULTILEAF JOURNAL BEARING

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ABSTRACT A performance analysis model of the gas lubricated compliant multileaf journal bearing of the high-speed rotor for air cycle machine of aircraft environmental control system has been established. In the analysis, the differential method is used to solve the compressible Reynolds equation, which governs the airflow in the journal bearing. The solution is coupled with the load deflection equations of the leaves to obtain such information as minimum film thickness, the stiffness coefficients, and the equivalent damping coefficients. The graphical solutions are provided for a range of relevant geometric and operational parameters. The journal bearing has good stability in all range of eccentricity ratios and all possible operating speeds.

Key Words Gas lubricated bearings Compliant Multileaf Analysis

EXPERIMENTAL STUDY OF A GAS LUBRICATED COMPLIANT MULTILEAF JOURNAL BEARING

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ABSTRACT The gas lubricated compliant multileaf journal bearing of the high-speed rotor for air cycle machine of aircraft environmental control system was investigated experimentally. In the earlier work, an analysis model was developed to predict the performance of the air lubricated compliant multileaf journal bearing. In the experiments, the load deflection tests revealed the elastohydrodynamics of the compliant leaves; the starting torque tests found out the frictional influence between leaves and journal; the air cycle machine operational tests demonstrate the dynamic characteristics of the journal bearing. All of the experimental results show that the journal bearing can run steadily in wide operating range, and it