

轴向受载的高速球轴承的拟动力学分析

南京航空航天大学 罗祝三* 吴林丰 孙心德
航空工业总公司第 608 所 高向群

【摘要】提出了对仅受轴向载荷的高速球轴承进行拟动力学分析以掌握滚动元件运动特性的方法。首先确定了钢球和套圈的滚动速度以及套圈相对于钢球的滑动速度,建立了各滚动元件的润滑模型,阐述了建立高速球轴承运动特性分析基本方程的一般原理。通过求解这些基本方程可得到高速球轴承中各滚动元件的运动状态、受力情况、弹流油膜厚度和疲劳寿命,从而可确定高速球轴承不打滑的最小轴向力。

关键词: 滚动轴承 机械传动 动力学分析

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1 前言

Harris^[1]在七十年代就开始对高速球轴承中的滚动元件的运动特性进行了研究。它应用弹性流体动力润滑理论预测了只受轴向力的高速角接触球轴承的打滑情况。此后Boness^[2]修正了油膜切向力的计算模型,提出了防止打滑的最小轴向力。SKF 公司和美国空军推进实验室联合对高速球轴承进行了大量的理论分析计算和性能试验研究,并研制了AT74Y001^[3]等大型计算程序。目前我国对航空高速球轴承的设计计算还主要依据拟静力学方法^[4,5],还不能有效地预测滚动元件的运动规律和不打滑所需的最小轴向力。为此作者提出了仅受轴向载荷作用的高速球轴承运动特性分析方法,以期预测滚动元件的运动状态并作为任意载荷作用下高速球轴承拟动力学分析的基础。

2 套圈与钢球的运动关系

如图 1(a)所示,假定球轴承内圈在轴向载荷 F_x 作用下匀速旋转且外圈固定。 $OXYZ$ 为轴承的总体坐标系,其中 X 轴在外圈的轴线上,指向与轴向载荷方向一致;原点位于受载前滚动体所在平面与 X 轴的交点; Z 轴通过任一钢球中心且指向朝外; Y 轴则由右手坐标系决定。内圈在轴向载荷作用下相应的位移为 δ_0 。图 1(b)中, $oxyz$ 为固连于球心的动坐标系,其 x 轴与 X 轴平行, z 轴为总体坐标原点 O 与球心的连线且指向朝外, y 轴由右手坐标系决定。 ou 为钢球的自转轴线,其方位用 ou 与 xoy 平面的夹角 β 及其投影与 x 轴的夹角 β' 表示。若钢球公转和自转角速度分别为 ω_h 和 ω , 则 ω 在各坐标轴上的分量为 $\omega_x = \omega \cos \beta \cos \beta'$, $\omega_y = \omega \cos \beta \sin \beta'$, $\omega_z = \omega \sin \beta$ 。

钢球与内、外沟道为椭圆接触,其接触角为 α_0 ($p = i$ 为内沟道, $p = e$ 为外沟道)。不妨设钢

球中心固定, 内、外圈分别以角速度 ω 和 ω 旋转, 则内(外)沟道上接触椭圆中任一点 (x_p, y_p) 沿接触区局部坐标系 x_p 和 y_p 方向的速度为

$$v_{xp} = \pm y_p (\omega_b \sin \alpha_p) \quad (1)$$

$$v_{yp} = - (0.5 D_m \mp r_p' \cos \alpha_p) \mp \omega_b \sin \alpha_p \quad (2)$$

钢球上同一点 (x_p, y_p) 沿接触区局部坐标系 x_p 和 y_p 方向的速度为

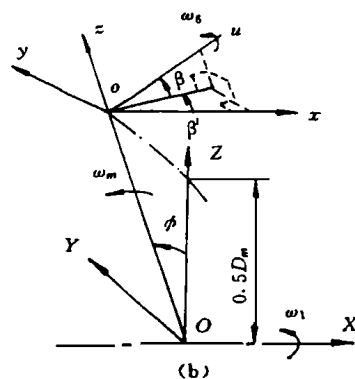
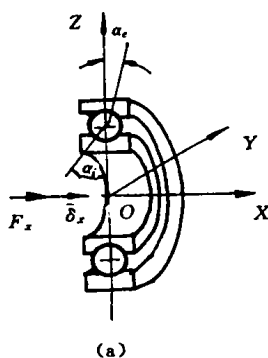


图 1 球轴承的坐标系

$$v_{bxp} = r_p' (\omega_b \pm y_p (\omega \sin \alpha_p + \omega \cos \alpha_p)) \quad (3)$$

$$v_{byp} = \pm r_p' (\omega \cos \alpha_p - \omega \sin \alpha_p) \mp x_p (\omega \sin \alpha_p + \omega \cos \alpha_p) \quad (4)$$

式中, $p = i$ (上面一组符号), e (下面一组符号); D_m 为轴承平均直径(m); r_p' 为点 (x_p, y_p) 在接触线方向与球心的距离。

由式(1) - (4) 可得套圈与钢球的滚动速度 $U_{qp} = (v_{qp} + v_{bqp})/2$, ($q = x, y$; $p = i, e$) 和套圈相对于钢球的滑动速度 $V_{qp} = v_{qp} - v_{bqp}$

3 润滑模型

钢球与套圈的接触区中心膜厚 h_{ac} 可应用 Arcard- Cowking 的点接触中心膜厚公式^[3] 计算。钢球高速滚动时, 接触入口处因油膜中出现大的速度梯度导致产生粘性剪切热, 使油膜温度升高, 粘度降低, 从而使油膜厚度减小, 故用热降因子 Φ_1 对油膜厚度进行修正。 $\Phi_1 = \min \{e^X, 1\}$, 其中 X 是与润滑油物理参数、环境温度、赫兹应力和滚动速度有关的参数^[6]。同时, 当滚动体滚过沟道上某一位置时, 可能在润滑剂未及供应前, 相邻滚动体已滚至刚才位置, 这就出现了润滑剂不足即缺油润滑状态, 使油膜厚度减薄, 用缺油因子 Φ_2 来修正溢油时的油膜厚度。缺油因子 Φ_2 定义为缺油时的油膜厚度与溢油时的油膜厚度之比, 其值和入口区油膜初始形成点至接触区中心间的距离(月牙距离)有关。这可通过求解数个非线性方程得到^[6]。因此考虑入口区热效应和缺油影响下接触区中心油膜厚度为 $h_c = \Phi_1 \Phi_2 h_{ac0}$

在钢球与套圈接触区中弹流牵曳力是指油膜作用于固体表面沿运动方向的切向摩擦力, 该力对从动件是驱动力, 对主动件是阻力, 对钢球的运动状态影响很大。按部分弹流理论, 其牵曳力为 $T_s = \mu_a Q_a + \mu (Q - Q_a)$ 。式中: μ_a 为凸峰接触的滑动摩擦系数, $\mu_a = 0.05 \sim 0.10$; Q_a 为凸峰接触承受的载荷, $Q_a = EA \sigma_0 I (h/\theta \alpha) / (4\pi^2)$; E 为综合弹性模量; A 为接触面积; σ_0 为凸峰斜率分布均方根; $I (h/\theta \alpha)$ 为膜厚比和表面形貌参数的函数; Q 为钢球与沟道的接触载荷; μ 为弹性流体动力润滑的摩擦系数。在实际计算时, 接触区被分为若干等厚的薄片, 对每一薄片应用上述公式求出牵曳力, 然后再迭加起来。

钢球与保持架兜孔接触入口区和钢球与套圈沟道接触入口区的润滑模型呈流体动力润滑模型。钢球与套圈和保持架兜孔之间为点接触, 当两表面运动时, 在接触点处产生油膜把两表面分离, 并在其周围建立起流体动压力 F , 其切向分量为 $F_{\tau 0}$ 。同时在滚动方向上把润滑油从低

压区泵入高压区会产生滚动摩擦力 F_{R0} 。两物体表面存在相对滑动时, 润滑油对表面有滑动摩擦力 F_{∞} 。保持架与引导挡边间的润滑模型按向心滑动轴承的情况处理。

4 基本方程

对仅受轴向载荷作用的高速球轴承进行拟动力学分析时假设: (1) 钢球相对外圈具有 6 自由度运动, 保持架相对内圈或外圈作平面运动; (2) 内圈匀速运动, 保持架角速度是各球公转角速度之平均值; (3) 忽略球心在 x 和 z 方向的加速度及哥氏加速度, 忽略由此产生的惯性力。

任一角位置 ψ_j 的钢球与沟道的接触变形量满足变形协调方程^[41] $\Delta_{ij} \cos \alpha_{ij} - A_{rj} + \Delta_{ej} \cos \alpha_{ej} = 0$, $\Delta_{ij} \sin \alpha_{ij} - A_{aj} + \Delta_{ej} \sin \alpha_{ej} = 0$ 。式中: Δ_{ij} 、 Δ_{ej} 为钢球中心至内、外沟道曲率中心的距离; A_{aj} 、 A_{rj} 为内、外沟道曲率中心的轴向距离和径向距离。钢球所受力为一空间力系。根据达朗伯原理, 在动坐标系 $oxyz$ 上钢球处于平衡状态时有 6 个平衡方程^[6]。这样对每个滚动体有 8 个独立方程, 对应有同样多的未知量, 即 α_{ij} 、 α_{ej} 、 δ_{ij} 、 δ_{ej} 、 ω_{hj} 、 ω_{ij} 、 ω_{ej} 、 ω_{ej} ($j = 1, 2, \cdots, Z$)。

按基本假定, 保持架作平面运动。在 OYZ 平面上保持架的受力可由 3 个平衡方程式^[6]表示, 未知量为保持架兜孔中心相对于 $\psi = 0$ 的钢球中心的位移 y_c 、保持架中心位移 δ_y 、 δ_z 。

因此只考虑仅受轴向载荷的情况, 各滚动体的运动规律和受力状态相同, 所以除内圈沿 X 轴的平衡方程^[6]外, 其它 5 个平衡方程将自动满足。这样内圈仅有一未知量 δ_x 。

5 计算结果与分析

为说明本文所述的高速球轴承拟动力学分析模型的合理性和计算程序 BAQDAN 计算结果的可靠性, 现应用 SKF 公司和 NA SA 共同开发研制仅受轴向载荷的高速球轴承拟动力学分析程序 AT74Y001 的计算实例^[31]进行计算和分析, 其结果见表 1。

表 1 计算结果比较

计算项目	符号	AT74Y001 计算结果	BAQDAN 计算结果	BAQSAN 计算结果
内圈轴向位移(mm)	δ_x	0.104	0.0901	0.0812
接触角/(°)	α_i	28.77	29.632	29.704
	α_e	6.94	6.574	6.588
球与套圈接触力(N)	Q_i	1418	1366	1411
	Q_e	5524	5445	5495
球与保持架法向力(N)	Q_{CB}	0.051	0.045	
钢球公转角速度(1/s)	ω_h	1217.4	1212.9	1214.9
	ω_b	10734	10675	10598
钢球自转角速度(1/s)	ω_l	10730	10659	
	ω_j	67.53	42.18	
	ω	281.3	575.8	
保持架转速(r/min)	n_c	11625	11582	
弹流油膜厚度(μm)	h_i	0.0733	0.0760	0.1202
	h_e	0.1078	0.1102	0.1203
疲劳寿命(h)	L_{10}	142	141	138

表 1 中所给出的高速球轴承拟动力学分析程序 BAQDAN 的计算结果与 SKF 公司的 AT74Y001 程序的结果基本一致。可见文中拟动力学分析模型和润滑模型是合理的, 计算结果是可信的。再将拟动力学分析与拟静力学分析(BAQ SAN)结果相比, 其轴承的接触负荷分布和疲劳寿命是相近的。然而拟静力学分析不能求出钢球自转转速的分量, 也不能分析钢球与保持架的作用力, 计算弹流油膜厚度时也不能考虑缺油和热效应等影响因素。

表 2 表示了轴向载荷对保持架转速的影响。当轴向载荷较大或打滑度较小时, 对钢球的公转转速和自转转速影响不大。但当轴向载荷很小(如 $F_x \leq 1000 \text{ N}$) 时, 钢球与外圈的接触角 α

表 2 轴向载荷对保持架转速的影响

轴向力 $F_x (\text{N})$	接触角		公转转速 $n_m (\text{r/min})$	转速比 n_m/n_i	旋滚比	
	$\alpha_i / (^\circ)$	$\alpha_e / (^\circ)$			W_{ri}	W_{re}
700	26.184	0.0738	11437	0.4575	—	—
1000	26.372	0.2506	11460	0.4584	0.471	0.014
5000	27.848	2.401	11562	0.4625	0.495	0.013
14679	29.632	6.574	11582	0.4633	0.498	0.054

接近于零, 保持架转速下降很多。由表 2 可知, 虽然该轴承的工作载荷为 14679 N, 但其不发生过度打滑的最小轴向载荷不应小于 $1000 \text{ N}^{[6]}$ 。

6 结 论

通过上述分析和计算, 可以看出: (1) 若只需计算高速球轴承的负荷分布或疲劳寿命则可用拟静力学方法来计算; (2) 若需预测滚动体和保持架的运动情况, 或计算保持架的受力情况, 或要精确计算接触区弹流油膜厚度, 则需用拟动力学分析方法; (3) 高速球轴承所需的最小预负荷可通过分析钢球公转角速度、接触角和疲劳寿命等参数随轴向力变化的关系来确定。

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- 12°. Moreover, the swirls at the duct exit have different senses of rotation when the blade is held at these two angles. The study lays the foundation for suppression of the duct swirl and its simulation.

Key Words Air inlets Flow distortion Flow characteristics Control problems

DETERMINATION OF REVOLUTION DIFFERENCE LINE FOR TWIN-SPOOL TURBOJET ENGINE

Shang Yi and Guo Yufei

(2nd Dept. Nanjing University of Aeronautics and Astronautics, Nanjing 210016)

ABSTRACT The revolution difference of the low and high pressure rotors is a parameter for acceptance tests of a twin-spool turbojet engine. It indicates the relation between the reduced revolution of the high pressure rotor and the reduced turbine inlet temperature and also shows the matching between the low and high pressure rotors. In order to determine the revolution difference for a twin-spool turbojet engine it is necessary to define a standard revolution difference line for this type of engine. This paper analysis considers various possible approaches for the revolution difference line computation and suggests how to define the standard revolution difference line in practice.

Key Words Twin-spool jet engines Rotation speed Differences Computation

STUDY ON AIRCRAFT ENGINES USED IN COAL-FIRED DIFFERENT-VELOCITY BED COMBINED CYCLE SYSTEM

Zhao Li, Xu Xiangdong, Zhu Weimin

(Dept. of Thermal Power Engineering, Tsinghua University, Beijing 100080)

ABSTRACT A new combined cycle system for generating electrical power from coal-carried heat Partial Gasification Coal-fired Combined Cycle (CGCC) is introduced by Tsinghua University, Which adopts a gas turbine modified from FT-8 aeroengine. Through analyzing the function of the gas turbine, using modeling technique, the design and off-design regimes of the gas turbine are considered comprehensively. It is proved that application of the FT-8 to CGCC system has a great advantage.

Key Words Combination Cycles Gas turbines Performance analysis

QUASIDYNAMIC ANALYSIS OF HIGH-SPEED THRUST BALL BEARINGS

Luo Zhushan, Wu Linfeng, Sun Xinde

(5th Dept. Nanjing University of Aeronautics and Astronautics, Nanjing 210016)

Gao Xiangqun

(Nanhua Powerplant Research Institute, Zhuzhou 412002)

ABSTRACT A quasi-dynamic analysis of high-speed thrust ball bearings is proposed to predict the kinematic characteristics. The rolling velocity and relative sliding velocity of each point in contact zone of balls and rings in a ball bearing are determined at first. According to the elastohydrodynamic and hydrodynamic lubrication theories, the reactions between the rolling pairs and the effects of heat and oil starvation on the thickness of oil film are considered. Then the principles for setting up the basic equations of the balls, the cage and the inner ring are established for the quasi-dynamic analysis of the thrust bearings. The kinematic characteristics, the load distribution, the thickness of the oil film and the fatigue life of the ball bearings can be obtained from solution of those equations. It is shown that the

rotary speeds of the cage and the balls decrease and their skiddings become serious as the thrust goes down, especially to a small value. So the minimum thrust preload for prevention of skidding of the balls on the inner race can be estimated.

Key Words rolling bearings Mechanical drives Kinetic analysis

INTERMITTENT AND CHAOTIC PHENOMENA IN A RUB IMPACT ROTOR SYSTEM

Chu Fulei, Feng Guanping, Zhang Zhengsong

(Dept. of Precision Instruments, Tsinghua University, Beijing 100084)

ABSTRACT Vibration characteristics of a rub impact rotor system supported on oil film bearings were investigated. Elastic impact and the Coulomb type of frictional relationship was assumed. Rotating speed and the system damping were used as control parameters to discover routes to and out of chaos and to study various forms of periodic, quasi-periodic and chaotic vibrations. Very rich types of chaotic vibrations were found for the model discussed. Also the system motion shows two different forms of intermittent phenomena. One is the interchange between periodic and quasi-periodic vibrations. Another is between periodic and chaotic vibrations. Vibration features such as chaotic vibration, intermittent phenomena and broad-band of periodic vibration can be effectively used to diagnose the rub impact fault which often happens in a rotor system.

Key Words Rotors Chaos Vibration Damping

EXPERIMENTAL INVESTIGATION ON ROTOR VIBRATION CONTROL BY ELECTORHEOLOGICAL DAMPER

Meng Guang, Ying Dazhang, Yao Guozhi

(Institute of Vibration Engineering, Northwestern polytechnical University, Xi'an 710072)

ABSTRACT In this paper the Electrorheological (ER) fluid and its characteristics are introduced briefly and the application of an ER damper in rotor vibration control is studied experimentally. It is found that by increasing the applied electrical field strength, the damping and stiffness of ER damper are increased, the vibration amplitude of the rotor system supported on ER damper is decreased in the sub-critical speed range and at the critical speed, and is increased in the super-critical speed range. The critical speed of the rotor system can be changed by means of the applied electrical field strength. The damping provided by the ER damper has the properties of both the Coulomb damping and the viscous damping. Experimental results show that the ER damper has obvious effect on vibration control, and features instantaneous control, little energy consumption and broad frequency range. Besides, its structure is simple.

Key Words Rotors Electric current Rheostats Vibration Control action

AN EXPERIMENTAL STUDY OF HEAT TRANSFER BY JET IMPINGEMENT ON ROUGHENED SURFACE WITH INITIAL CROSSFLOW

Zhang Dalin, Chang Haiping, Han Dong

(2nd Dept. Nanjing University of Aeronautics and Astronautics, Nanjing 210016)

Sheng Rongchang

(Zhuzhou Power Plant Research Institute, Zhuzhou 412002)

ABSTRACT Impingement heat transfer from the rib roughened surface with