上海大学出版社

2005年上海大学博士学位论文 102

凸度滚子的稳态热弹流设计和动态等温特性研究

● 作者：孙浩洋

● 专业：机械设计及理论

● 导师：陈晓阳

上海大学出版社

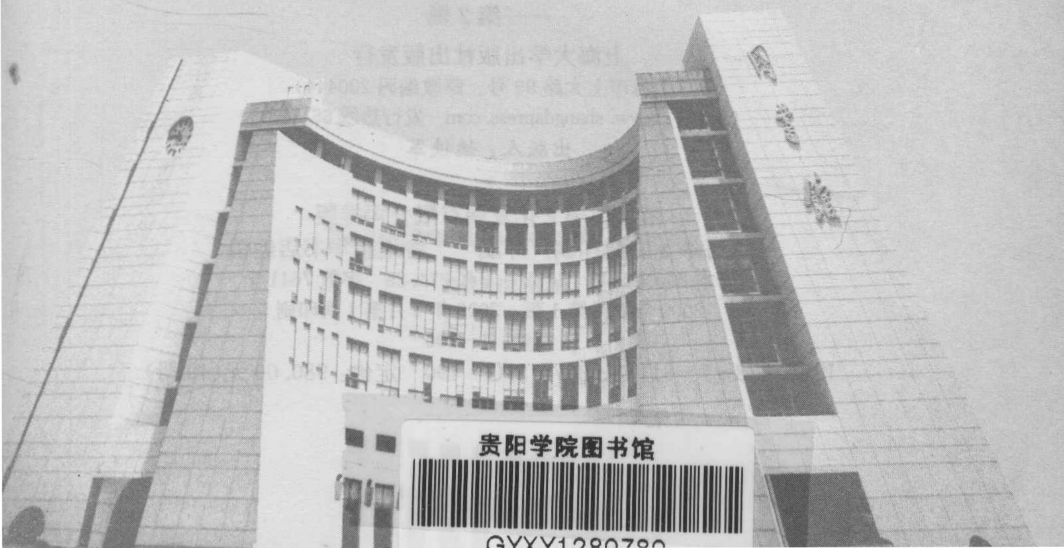
2005年上海大学博士学位论文 102

凸度滚子的稳态热弹流设计和动态等温特性研究

● 作者：孙浩洋

● 专业：机械设计及理论

● 导师：陈晓阳



图书在版编目(CIP)数据

2005 年上海大学博士学位论文.第 2 辑/博士论文编辑部编.—上海：上海大学出版社，2009.6

ISBN 978-7-81118-367-2

Ⅰ.2…　Ⅱ.博…　Ⅲ.博士—学位论文—汇编—上海市—2005　Ⅳ.G643.8

中国版本图书馆 CIP 数据核字(2008)第 180878 号

2005 年上海大学博士学位论文

——第 2 辑

上海大学出版社出版发行

(上海市上大路 99 号　邮政编码 200444)

(http://www.shangdapress.com　发行热线 66135110)

出版人：姚铁军

*

南京展望文化发展有限公司排版

上海华业装潢印刷厂印刷　　各地新华书店经销

开本 890×1240　1/32　印张 274.25　字数 7641 千

2009 年 6 月第 1 版　2009 年 6 月第 1 次印刷

印数：1～400

ISBN 978-7-81118-367-2/G·490　定价：980.00 元(49 册)

Shanghai University Doctoral Dissertation (2005)

A Study on the Steady Thermal EHL Design and Transient Iso-thermal EHL Characteristics of Profiled Rollers

Candidate: Sun Hao-Yang
Major: Mechanical Design and Theory
Supervisor: Chen Xiao-Yang

Shanghai University Press
· Shanghai ·

上海大学

本论文经答辩委员会全体委员审查，确认符合上海大学博士学位论文质量要求.

答辩委员会名单：

主任：**马家驹**　教授，浙江大学机械与能源工程学院　310027

委员：**李柱国**　教授，上海交通大学机械动力学院　200030

张直明　教授，上海大学机电工程与自动化学院　200072

安　琦　教授，华东理工大学机械与动力工程学院　200237

刘　谨　教授，上海大学机电工程与自动化学院　200072

导师：**陈晓阳**　教授，上海大学轴承研究室　200072

评阅人名单：

孙大成	教授，美国纽约州立大学宾汉顿分校机械工程系 (DC Sun, Professor, Department of Mechanical Engineering, State University of New York at Binghamton)	
胡元中	教授，清华大学精仪系摩擦学实验室	100084
张直明	教授，上海大学轴承研究室	200072

评议人名单：

张立明	教授，美国宾夕法尼亚州立大学机械与核工程系 (L Chang, Professor, Department of Mechanical and Nuclear Engineering, the Pennsylvania State University)	
王成焘	教授，上海交通大学机械动力学院	200030
马家驹	教授，浙江大学机械与能源工程学院	310027
杨沛然	教授，青岛理工大学机械工程学院	266033

答辩委员会对论文的评语

论文以滚子摩擦副为研究对象，展开滚子弹流成膜机理与凸度设计研究.论文有学术价值和应用背景.

创新成果主要有：

(1) 基于多重网格技术的数值分析方法，构建了重载稳态有限长线接触热弹流的算法，经与 Wymer 等的实验结果的对比，验证了算法的正确性.

(2) 对工程中常见的相交圆弧修形滚子与对数滚子的成膜机理和考虑弹流效应的凸度设计方法进行了研究，并分析了热效应、非牛顿效应、滚子表面划痕等因素的影响，揭示了载荷、速度、润滑油性能等工况参数的影响.

(3) 提出了摆动工况下有限长线接触弹流的分析算法，揭示了摆动过程中的基本弹流特性，并通过工程实验定性验证了分析结果的正确性.

论文条理清晰，层次分明，论据充分，数据可信，表明作者已具备扎实的理论基础和系统深入的专业知识，较好地掌握了该领域的国内外发展动态，具有较强的独立从事科研工作的能力.答辩过程中，思路清晰，回答问题正确.

答辩委员会表决结果

经答辩委员会无记名投票表决,5 票(全票)同意通过孙浩洋的博士学位论文答辩,5 票(全票)通过建议授予孙浩洋工学博士学位.

答辩委员会主席：**马家驹**

2005 年 9 月 15 日

摘　要

工程中应用十分广泛的滚子类摩擦副通常在润滑条件下工作，其压力分布、膜厚膜形及温度分布对机器零部件的性能和寿命有很大影响，需进行凸度设计以改善此类摩擦副的承载能力和润滑状况. 本文以滚子类摩擦副为应用对象，研究了有限长线接触弹性流体动力润滑问题，探讨了凸度滚子的稳态热弹流设计和动态等温特性，考察了润滑剂、载荷、速度等工况参数和凸度修形参数对压力分布、膜厚膜形、温度分布的影响，讨论了加减速、起停、急停以及摆动等特殊变速运动下的压力分布和成膜特性. 完成的主要工作如下：

一、基于多重网格技术，通过引入附加项强制构造温度分析矩阵主对角优势，限制压力温度的合理范围以及对于苛刻工况由工况参数接近的相对温和工况的计算结果提供良好初值等数值技巧，构建了适用于有限长线接触热弹流分析的高效稳定的计算方法，可在接触长宽比达到 100、接触压力达到 2.0 GPa的苛刻工况下得到收敛解. 以此为工具，系统完整的定量模拟了 Wymer 等在此领域完成的经典光干涉试验，分析结果与试验结果吻合很好，从而验证了分析程序的正确性.

二、系统深入分析了工程中常用的相交圆弧修形滚子的重载稳态热弹流特性，包括此种滚子的两个修形参数：修形长度和修形半径的影响；速度、载荷和滑滚比等工况参数的影响；Eyring 非牛顿效应的影响；并探讨了弹流温度场与压力场分布规律的相

似性以说明凸度设计对弹流温度分布的影响. 研究表明：只要修形参数合适,相交圆弧修形滚子将分别在修形起始位置以及靠近轴向出口位置出现两次轴向颈缩,轴向颈缩与径向颈缩共同阻碍了润滑油流出接触区从而增加膜厚,即"封油效应". 合理修形的此类滚子可对工况有较好的自适应性,从成膜的角度讲,润滑失效与"封油效应"的无法建立是对应的;端部的压力集中程度主要由修形半径和载荷决定. 使用 Eyring 非牛顿流体有利于改善此类接触副的承载能力和润滑状况,但 Eyring 非牛顿效应对这种滚子的凸度设计没有明显影响. 压缩功是导致弹流温度梯度与压力梯度相似性的主要原因. 凸度设计在改善压力分布的同时也将改善温度分布,进而改善由热效应导致的各种疲劳现象.

三、系统全面研究了对数滚子的重载稳态热弹流特性. 指出干接触状态下的理想轮廓——Lundberg 对数轮廓在弹流状态下凸度量不足,定义了膜厚分布系数和压力分布系数,据此综合考虑压力和膜厚分布的条件下提出了修正 Lundberg 对数轮廓,定义了凸度量修正系数并提出了该系数的合理取值区间的概念. 研究了凸度量修正系数随载荷、速度、润滑油参数的变化规律：发现凸度量修正系数 δ 的下限 δ_1 随载荷的增加、速度的降低以及润滑油粘度的降低而增加,凸度量修正系数 δ 的上限 δ_2 随速度的降低以及润滑油粘度的降低而增加,δ_2 随载荷的增加有微幅增加但受载荷的影响不显著. 研究指出：使用大粘压系数的润滑油时,线性修正 Lundberg 轮廓无法得到理想的压力分布,并讨论了表面划痕对接触副承载能力和润滑状况的影响.

四、构建了适用于动态等温有限长线接触弹流分析的算法,突破了摆动问题的研究. 分析了加减速、起停、急停几种特

殊的运动形式，并用点接触弹流试验结果进行了定性验证，分析结果与试验结果的规律一致. 研究表明：在速度为零的瞬间膜厚可以存在，这是动态效应的作用. 对于复杂的摆动问题，用建立两套坐标系统的方法解决了润滑区入口和出口周期变换造成分析的困难，并用网格镜像和延拓的方法，建立了任意摆动运动的求解方法. 分析了正弦运动的弹流特性，并研究了摆动频率、不同凸型以及凸度量对其压力分布、膜厚膜形的影响. 研究指出：在摆动过程中，中部膜厚的变化显著滞后于速度的变化，端部膜厚的变化对速度变化的滞后性不明显. 速度的变化导致总承载面积的变化并在载荷平衡条件的约束下引起压力大小的变化，而压力大小的变化反过来又改变了滚子轴向压力分布，影响了边缘效应的出现. 总承载面积的变化与卷吸速度方向承载宽度的变化一致而与滚子轴向承载长度的变化相反. 低速时滚子端部的载荷分布和润滑状况较高速时恶劣.

五、通过对对数轮廓和相交圆弧修形轮廓两种凸型，以及不同凸度量的对数凸型滚针轴承的摆动疲劳寿命试验证实：对数轮廓优于相交圆弧修形轮廓，滚针凸度量对接触副摆动疲劳寿命影响显著. 修形量合适的滚针轴承摆动寿命远高于修形量不合适的滚针轴承.

本文研究有助于认识滚子类摩擦副的稳态热弹流润滑机理和动态等温特性，可为进行接触副的优化设计及性能分析提供良好的基础.

关键词 摩擦学，弹流润滑，有限长线接触，凸度设计，摆动，动态特性

Abstract

The widely used line contact friction pairs work mostly under lubrication conditions. The pressure, film thickness, and temperature distributions play important role in the performance and service life of such friction pairs. Therefore, crowning design is necessary to increase their load capacity and improve lubrication condition. In this dissertation, the line contact EHL of finite length is studied. Crowning designs based on steady thermal and transient isothermal EHL of profiled rollers are discussed. The effects of lubricants, applied load, velocity as well as crowning parameters on pressure, film thickness and temperature distributions are investigated. The pressure distribution and oil film structure of several types of non-steady state motion, including acceleration/deceleration, stop/start, rapid deceleration and oscillation are obtained. The main work is as follows:

1. An effective, robust and stable algorithm is established based on the multi-level multi-integration technique and several numerical skills: introducing additive items to construct the temperature matrix, constricting the pressure and temperature in a reasonable range during the calculation process, and using the solutions of some similar operating conditions as the initial values for more severe operating conditions. Numerical trials

show that convergent solutions could be obtained under severe working conditions (the contact pressures exceed 2.0 GPa and the length-width ratio of contact area is over 100). Using this algorithm, systematic and complete numerical simulations of the classical interferometry experiments by Wymer's group are carried out. The numerical and experimental results agree quite well with each other. Therefore, the reliability of the calculation program is verified.

2. The steady thermal EHL behavior for cylindrical rollers with crown-profiled ends at heavy load is systematically analyzed, including the following aspects: the effects of crowning length and crowning radius; the effects of velocity, applied load and slip-slide ratio; and the effects of the Eyring non-Newtonian fluids. Moreover, the similarity of the pressure and temperature distribution is investigated to discover the influence of the crowning design on the temperature distribution. It has been concluded that, if the crowning parameters are suitable, such rollers could establish two times of constriction in the cylindrical direction, the first is at the location of the crowning place, while the second is at the exit region on roller edge. The two cylindrical constrictions as well as the axial constriction embarrass the outlet flow of the lubricants, thicken the oil film consequently and constitute the "oil close effect". The results show that the lubrication properties could be optimized that let the contacts adapt to the operating conditions if the rollers are suitably crowned. From the point of oil constitution, lubrication failure is corresponding to the

demolishment of the "oil close effect". The height of the edge pressure is mainly decided by the applied load and the crown radius. The results also show that The Eyring effects have little influence on the crowning design although it could increase the load capacity and lubrication conditions of the finite line contacts, and the similarity of the temperature and pressure distribution is mainly caused by the compress work, therefore, by the crowning design, not only the pressure but also the temperature distribution could be optimized, as a result, some fatigue phenomenon relevant to the thermal effect could be amended at the same time.

3. The steady thermal EHL characteristics of the logarithmic profile rollers at heavy load are systematically investigated. It is concluded that the ideal profile in elasto-static state, Lundberg logarithmic profile, is insufficient in crowning value in EHL state. The pressure and film thickness distributions must be combinablenably considered in designing suitable crowning, therefore, the film thickness distribution index and the pressure distributions index is defined respectively. A linearly modification coefficient of the Lundberg profile, δ, is defined and the relationships of δ with applied load, velocity, lubricant parameters are investigated. It has discovered that there is an optimum range of the crowning value expressed by δ as [δ_1, δ_2] for a particular operating condition. δ_1 significantly increases with the increase of applied load and with the decrease of velocity and lubricant viscosity; while δ_2 significantly increases with the decrease of velocity and

lubricant viscosity. δ_2 slightly increases with the increase of applied load, however, the influence of the applied load on δ_2 is not pronounced, and for a high viscosity-pressure index oil, satisfactory pressure distribution can not be realized by linearly modifying the Lundberg profile. The effects of the surface scratch on the load capacity and lubrication conditions are also discussed.

4. An algorithm for transient iso-thermal finite line contact EHL problems is developed. Several types of non-steady state motion, including acceleration/deceleration, stop/start, rapid deceleration and oscillation are analyzed with this algorithm. A qualitative comparison with the point contact experimental results of EHL is made. The consistency is good. It is shown that, when the velocity decreases to zero, the oil film can remain for a short time because of the transient effects. For the complicated oscillation motion, two coordination systems are employed during the calculation process to overcome the difficulties of periodic reversal of the inlet and outlet domains. A mirror extension technique of the calculation grid is used to develop the algorithm for the arbitrary oscillation motions. The EHL behavior of sinusoidal velocity motion, its pressure and film thickness characteristics, and the effects of oscillating frequency as well as the roller profile and crowning value are investigated. It is concluded that, in the middle of the roller, the film variation lags considerably behind the velocity variation, whereas at the roller edge such phenomenon is not significant. With the

change of velocity, the contact area varies, consequently the pressure varies under the load balance restriction As a result, the pressure distribution in the cylindrical direction also changes and influences the edge effect. The total contact area varies with the contact width in the entrainment direction, while inversely varies with the contact length in the cylindrical direction. The edge pressure and lubrication states at lower speeds are less satisfactory than that at higher speeds.

5. Experiments of rollers with a crown-profile end and logarithmic profile show that the latter is better than the former, and experiments of logarithmic rollers with different crowning values show that the crowning values influence the oscillation fatigue life considerably, and that rollers with suitable crowning values have much longer oscillation fatigue life.

The research is useful for understanding the steady thermal and the transient iso-thermal EHL characteristics of roller friction pairs. The study provides a good foundation for the optimum design and performance analysis of such friction pairs.

Key words tribology, EHL, finite line contact, crowning design, oscillation, transient characteristics

主要符号表

b　载荷 w 作用下的 Hertz 接触区半宽，$\sqrt{8wR/\pi E'L}$，m

b_0　与无量纲参考载荷 w_0 对应的 Hertz 接触区半宽，$\sqrt{8w_0R/\pi E'L}$，m

c　润滑油的比热，J/(kg・K)

c_a, c_b　固体 a 和固体 b 的比热，J/(kg・K)

C_3　润滑油的热膨胀系数，K^{-1}

$C_{ua}(t), C_{ub}(t)$　固体 a 和固体 b 的速度动态系数，$C_{ua}(t)=u_a(t)/u_{e0}$，$C_{ub}(t)=u_b(t)/u_{e0}$

$C_w(t)$　载荷的动态系数，$w(t)/w_0$

d　固体 a 和固体 b 的温度计算域的厚度，3.15 b，m

d_s　滚子表面划痕深度，m

E_a, E_b　固体 a 和固体 b 的杨氏弹性模量，Pa

E'　综合弹性模量，$[(1-\mu_a^2)/(2E_a)+(1-\mu_b^2)/(2E_b)]^{-1}$，Pa

E^*　文献[37]定义的综合弹性模量，$(1/E_a+1/E_b)^{-1}$，Pa

f　对稳态问题为摩擦系数；对动态问题为频率，s^{-1}

G　无量纲材料参数，$\alpha E'$

h　油膜厚度，m

$h_1=x=0$　截面的端部最小膜厚，m

h_c　中心膜厚，即 $x=0, y=0$ 位置的膜厚，m

$\bar{h}$　数值分析中使用的无量纲油膜厚度，h/h_0