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内啮合斜齿轮的齿面闪温计算

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【摘要】 本文计算了内啮合斜齿轮齿面各点的载荷、曲率半径和切向速度，在此基础上，分别用线接触弹流理论和 Block 基本公式计算了内啮合斜齿轮在工作条件下的齿面接触闪温分布，并对其胶合强度作了基本分析，为此类齿轮的胶合强度设计和校核提供了有效的计算方法。

关键词：内齿轮　斜齿轮　闪温

1 前　言

本文用 Block 基本公式[1]，但齿面各点的载荷、几何、运动条件的计算均考虑了三维分布特点，由此得出齿面闪温的分布，大大提高了计算精度。并用线接触弹流理论的计算方法，从理论角度探讨了内啮合斜齿轮的齿面接触温度，使计算更接近于齿面的实际啮合情况。

本文的计算对象为一对内啮合斜齿轮，其主要参数为：齿数 $Z_1=19$，$Z_2=93$；模数 $m_n=2.25$mm；压力角 $\alpha_n=20°$；螺旋角 $\beta=9.92°$；变位系数 $x_1=0.4$，$x_2=0$；齿宽 $B=27$mm；精度等级 HB-5 输入转速为 10000r/min，齿面法向载荷为 6000N，齿轮本体温度为 100℃，齿轮本体温度下的润滑油粘度为 5MPa·s，齿面粗糙度为 0.8μm。

齿面载荷分布与各接触点的接触刚度和啮合误差有关，可用三维有限元计算得到齿面各点的加载变形，组成齿面结点柔度矩阵，结合啮合误差，经三维接触分析可以得到齿面载荷分布[2]。图 1 所示，就是计算柔度矩阵时本齿轮副中小轮轮齿的有限元网格。

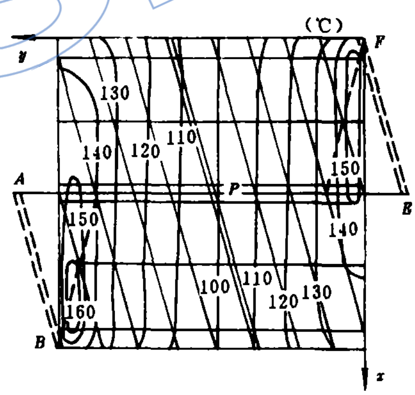

图 1　小轮轮齿的有限元网格

齿面 j 结点的曲率半径可由下式求出：

$$R_j = r_b \cdot \mathrm{tg}\alpha_t / \sin\gamma_b \tag{1}$$

式中：r_b 为基圆半径，α_t 为结点压力角，γ_b 为基圆螺旋升角。

齿面 j 结点沿齿面与接触线垂直的切向速度可由下式求出：

$$u_j = \omega \cdot r_j \cdot \sin\alpha_j \cdot \cos\beta_j \tag{2}$$

式中：ω 为角速度，r_j 为结点回转半径，β_j 为结点螺旋角。

2 Block 基本公式及计算方法

计算齿面闪温的 Block 基本公式可以表示如下[1]：

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$$T_{flu} = 0.62 c_m \mu_{my} p_s^{0.75} (E_r/\rho)^{0.25} |u_1 - u_2| / B \cdot (\sqrt{u_1} + \sqrt{u_2}) \qquad (3)$$

式中：C_m 为加权数（$C_m = 1.5$）；u 为接触结点切向速度；μ_{my} 为局部摩擦系数的平均值，用下式求

$$\mu_{my} = 0.12(p_s \cdot \cos\alpha_o \cdot R_a)^{0.25} / (\eta_o \cdot u_\Sigma \cdot R)^{0.25} \qquad (4)$$

式中：p_s 为结点载荷线密度；R_a 为齿面粗糙度；η_o 为齿轮本体温度下的润滑油动力粘度，u_Σ 为两轮齿接触结点切向速度之和，E_r 为综合弹性模量，当两轮材料相同时，$E_r = E/(1-\nu^2)$，R 为接触结点综合曲率半径，B 为热接触系数。

由式(3)和式(4)可知，T_{flu} 与 p_s 成线性关系，即：

$$T_{flu} = C_T \cdot p_s \qquad (5)$$

系数 C_T 包括了除载荷外所有其它参数的影响。因此，齿面闪温分布计算可以表示为：

$$\{T\}_{flu} = [C_T]\{p_s\} \qquad (6)$$

式中：$[C_T]$ 为 n 维对角矩阵，对角元素 C_{Tj} 表示 j 结点的系数 C_T；$\{T\}_{flu}$ 为 n 维结点闪温向量，$\{p_s\}$ 为 n 维结点载荷密度向量，n 为齿面结点数。

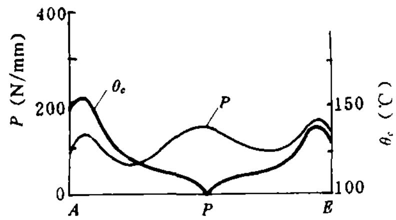

图 2 内啮合斜齿轮的齿面闪温分布

用上式计算得到的齿轮副在工作状态下的齿面闪温如图 2 所示。图中方框表示啮合面，坐标 x 为齿宽方向，y 为齿廓方向，在端面啮合线上度量，图中网格为有限元网格的齿面部份在啮合面上的投影。图框中的平行斜直线，是齿面接触线。由图可见，最高温度区分别位于进入啮合和退出啮合的一角，而在进入啮合角上温度达到最高，这与 Kubo 的斜齿轮胶合试验所测得的胶合区域的分布[3]是相当一致的。

为了使闪温分布的表示更加方便和明确起见，作者用二维坐标来代替三维分布。在图 2 中，啮合路径坐标 s 经过齿宽中点，平行于 y 轴，全长包括端面重合度和轴向重合度。s 坐标上的点 · 代表一条接触线的中点×。由图 2 可见，各接触线中点联线穿过最高闪温区，且与温度梯度方向相同，因此，可以满足闪温分布表示的要求。这一表示方法与 ISO 标准是一致的，尤其当螺旋角为零时，与 ISO 标准的直齿轮表示方法完全相同。图 3 所示，就是用上述方法表示的图 2 的三维闪温分布。图中实线为闪温分布，虚线为载荷密度分布。由上述可知，本文的计算结果，同样可以使用 ISO 标准的闪温准则和温度极限。因此，该方法可以直接应用到工程设计中去。

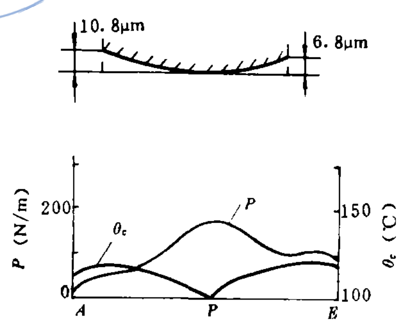

图 3 齿面闪温分布的二维表示

3 线接触弹流理论[4]

线接触弹流运动由下述基本方程予以描述：

运动方程
$$\partial p/\partial x = \partial(\partial u/\partial Z)/\partial Z \qquad (7)$$

Reynolds 方程
$$dp/dx = 12\eta \cdot [(u_1 + u_2)/2][(\rho h - \rho_c h_{cc})/\rho h^3] \qquad (8)$$

油膜厚度方程
$$h = h_{oo} + \frac{x^2}{2R} - \frac{2}{\pi E_r}\int_{x_{in}}^{x_b} p(s)\ln(x-s)^2 ds \qquad (9)$$

润滑油粘度方程

$$\eta = \exp\left\{[\ln(\eta_o \times 10^9) + 2.763]\left(1 + \frac{p}{196.2}\right)^{Z_p}\left(\frac{T_o + 135}{T + 135}\right)^{1.14} - 2.763\right\}\Big/10^9 \quad (10)$$

其中 $Z_p = 0.72 - 0.26\ln(1 + T/135)$

润滑油密度方程　$\rho = \rho_o[1 + C_A p/(1 + C_B p)] + D_t(T - T_o)]$　(11)

式中：$C_A = 0.326 \times 10^{-3}(1/MPa)$，$C_B = 0.283 \times 10^{-3}(1/MPa)$，$D_t = -0.875 \times 10^{-3}(1/℃)$

能量方程　$\rho c_p(u\partial T/\partial x) = K(\partial^2 T/\partial Z^2) - (T/\rho)(\partial\rho/\partial T)(u\partial p/\partial x) + \eta(\partial u/\partial Z)^2$　(12)

界面温度方程

$$\left.\begin{aligned} T(x,o) &= \frac{K}{\sqrt{\pi K_1 \rho_1 c_{p1} u_1}} \int_{x_{in}}^{x} \left.\frac{\partial T}{\partial Z}\right|_{Z=o} \frac{ds}{\sqrt{x - s}} + T_o \\ T(x,h) &= \frac{K}{\sqrt{\pi K_2 \rho_2 c_{p2} u_2}} \int_{x_{in}}^{x} -\left.\frac{\partial T}{\partial Z}\right|_{Z=h} \frac{ds}{\sqrt{x - s}} + T_o \end{aligned}\right\} \quad (13)$$

压力边界条件　在入口处 $x = x_{in}$，$p = 0$

在出口油膜破裂处　$x = x_b$，$p = dp/dx = 0$　(14)

温度和速度边界条件　在 $Z = o$ 处　$u = u_1$，$T = T(x,o)$

在 $Z = h$ 处　$u = u_2$，$T = T(x,h)$　(15)

在入口处　$T = T_o$

以上式中：b 为 Hertz 接触区半宽；p 为油膜压力；η、ρ 为润滑油的粘度与密度；η_o、ρ_o 为温度为 T_o 时的 η、ρ；T_o 为齿轮本体温度；x 为垂直于接触线的切线方向的无量纲坐标；h 为油膜厚度；Z 为膜厚方向；s 为滑滚比；h_{oo}、ρ_c 为 $dp/dx = 0$ 处的膜厚和密度；h_{oo} 为膜厚方程中的常数；c_p、c_{p1}、C_{p2} 为润滑油和固体的比热；K、K_1、K_2 为润滑油和固体的导热系数。

上述方程组用差分法求解，差分网格在膜厚方向分 10 层，在 x 方向不等距划分 60 份，计算得到的油膜中最高温度作为闪温，示于图 4 中。由图 4 可见，闪温值大于 Block 公式的计算值，与其它研究结果是一致的[5]。该值较大的原因是取了油膜中的最高温度，与 Block 公式的中闪温概念略有不同。

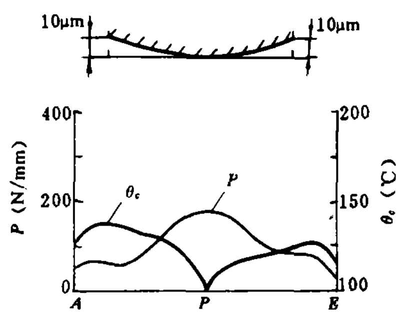

图 4　线接触弹流理论计算的齿面闪温分布

弹流理论与 Block 公式相比较，使用了较少的假设和人为给定的参数补偿，因此有较高的仿真度，但计算量大，尤其是目前尚缺少大量的相应实验以提供工程实用的数据。但无疑随科学技术的发展，这一方法将会显示出明显的优越性。

4　内啮合斜齿轮齿面闪温的计算分析

内啮合斜齿轮的齿面闪温研究至今较少，原因是精确的计算比较困难，此外也通常认为内啮合的几何条件优于外啮合，胶合的可能性较小。

作者用 Block 公式计算本齿轮副在改变齿轮参数时的齿面闪温，以考察参数设计与齿轮胶合强度的关系，计算结果绘于图 5 中。图 5(a)是压力角对齿面闪温的影响。由图可见，当压

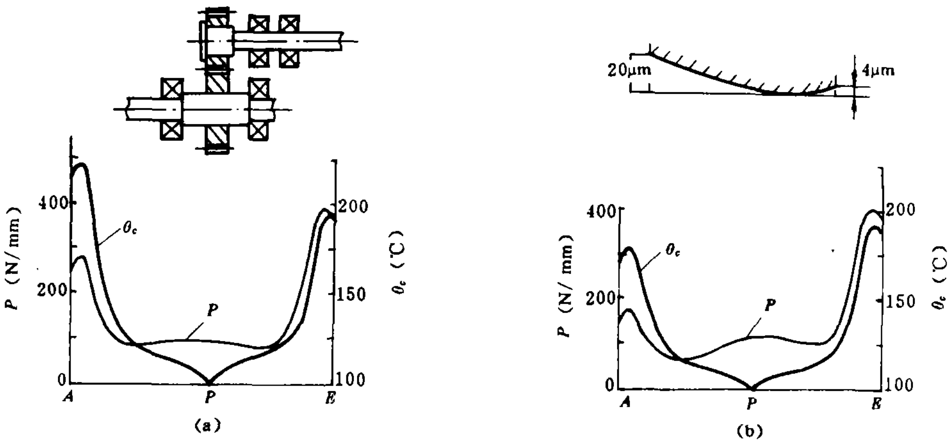

图5 齿轮参数与齿面闪温的关系(a. 压力角的影响;b. 变位系数的影响)

力角增大时,啮入端最小综合曲率半径 R_{min} 很快增加,而齿面最大速度滑差 Δu_{max} 则减小,使最高闪温 T_{max} 有很大的下降。图5(b)是小轮变位系数的影响,当 x_1 增加时,Δu_{max} 开始下降,后又很快上升,最大速度滑差的位置由啮入端转移到啮出端,但由于 R_{min} 增大,总的效果仍使闪温下降。由图5(a)、(b)中看到,对于 $\alpha=20°$,$x_1=0$ 的标准齿轮副,在啮入端的最小综合曲率半径还不到0.5mm,因而使齿面接触温度高达250℃,超过了胶合极限。这样,内啮合斜齿轮的啮入角(小轮根部和大轮顶部)仍有胶合危险,须通过校核、设计加以避免。

5 结 论

本文用 Block 公式和线接触弹流理论计算了内啮合斜齿轮在工作状态下的齿面闪温三维分布,得出以下结论:

(1)Block 公式计算简便实用,尤其是长期应用中大量实验和实践数据的积累,为这一方法的工程应用准备了条件。本文中提出的内啮合斜齿轮闪温计算的 Block 方法,充分考虑了载荷、几何、运动诸条件的三维分布特点,计算精度大大高于 ISO 标准,可用于重要传动的设计。

(2)线接触弹流理论计算具有较高的仿真度,但计算复杂,它的应用也需要积累实验和实践的经验。

(3)内啮合斜齿轮中小轮根部和大轮顶部进入啮合的一角是胶合危险点,设计中应注意。

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the area ratio. Other parameters have little effect on it. The results provide the basis for testing and transonic calculation of the axsiymmetric convergent-divergent nozzle.

ELIMINATION OF OVERTEMPERATURE IN TURBOJET

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ABSTRACT This paper analyzes the reasons of the overtemperature in a turbojet and provides the available measures to eliminate it, such as the strict requirements for the engine overhaul at the repair factory and the reasonable engine adjustment in the field maintenance. It is essential for the field maintenance to adjust properly the relationship between the turbine pressure ratio and the exhaust nozzle area, so that the turbine gas temperature comes down without afterburning temperature drop. In this way, the influence of the above problem on the operational performance of the engine can be minimized on condition that the engine reliability is guaranteed.

DYNAMIC CHARACTERISTICS OF TWO NEW VIBRATION MODES OF THE DISK-SHELL SHAPED GEAR

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(Beijing University of Aeronautics and Astronautics)

Gao Xiangqung

(Nanhua Power Plant Research Institute)

ABSTRACT Two new vibration modes of the disk-shell shaped big medium gears placed on the three separate medium shafts of a turboprop engine have been found. They have the same nodal diameters as the conventional ones but their frequencies are higher. The tooth ring vibrates both radially and axially and has greater deflection than the gear hub. The resonance of these two new nodal diameter modes is much more dangerous than that of the conventional nodal diameter modes. Moreover they occur just nearly at the upper and lower bounds of the gear operating speed range. A special detuning method is developed for removing the resonance of these two new modes out of the upper and lower bounds respectively and the effectiveness of the damping rings in this case has been researched. The vibration responses measured on the reductor casing have been then reduced to a quite low level after the damping rings were applied to the three big medium gears.

CALCULATION OF FLASH TEMPERATURE ON TOOTH SURFACE OF INTERNAL HELICAL GEARS

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(Northwestern Polytechnical University)

ABSTRACT An accurate calculating approach for flash temperature of internal helical gears is presented. Firstly, the load distribution on tooth surface is obtained by using 3-D finite element method and loaded tooth contact analysis technique. Then, the relative velocities and curvature radii

of every node on the tooth surfaces for a pair of internal helical gears are determined. Under these conditions, the flash temperature on tooth is calculated by using Block's basic equation. Further, the thermal elastohydrodynamic analysis of line contact is applied to determination of the temperature distribution in oil film. This analysis is more accurate, though more tedious. The calculated results reveal the relationship between the gear parameters and flash temperature, which will help engineers in designing internal helical gears with high scuffing load capacity.

TRACTION CHARACTERISTICS OF SYNTHETIC LUBRICANTS AT HIGH SLIDING SPEED CONTACTS

Chen Guoding, Wang Buyin, Wu Liyan, Li Jianhua

(Northwestern Polytechnical University)

ABSTRACT The traction characteristics of synthetic lubricants at high sliding speed contacts are studied according to the thermal partial elastohydrodynamic lubrication theory for consideration of surface roughness effect and the Ree-Eyring rheological model for mirroring the non-Nowtonian behavior of the lubricant. The analysis program developed incorporates a computational algorithm which can efficiently and accurately find out the pressure and temperature distributions and determine the traction coefficient of synthetic lubricants. The variations of the traction coefficient of synthetic lubricants with the load, rolling and sliding speed, lubricant viscosity and ambiance temperature are obtained and the comparison between the calculated results presented in current work and the experimental results of ref. [2] is also shown. The method adopted in present investigation is instructive for dynamic study of aviation high-speed rolling bearings.

THERMAL ANALYSIS OF AEROENGINE MAIN SHAFT BALL BEARING

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(Beijing University of Aeronautics and Astronautics)

ABSTRACT An analysis of the heat generation in a high speed ball bearing system of an aeroengine is considered in detail on the basis of dynamical analysis. First, the heat generation rate is calculated according to the elastohydrodynamic lubrication theory. Then, considering complex relationship of heat transfer, the temperature contribution in the ball bearing system is calculated by using the combination of the finite element method, finite difference method, system heat equilibrium method and empirical formulas. Contribution of inner heat sources and treatment of boundary conditions in the calculation are analyzed thoroughly. Finally, thermal analysis of the ball bearing for a specified Aeroengine is made. Calculation results are shown in a good agreement with the experimental data offered by Shenyang Aeroengine Research Institute.