

某直升机齿轮传动系统的瞬态热分析*

北京空间飞行器总体设计部 刘志全**
西北工业大学 沈允文 陈国定 苏 华

【摘要】 提出了传动系统瞬态温度场的分析方法,建立了失去润滑条件下传动系统功率损失及对流换热系数的计算模型,该模型考虑了失去润滑后传动系统热状态参数的时变特征。在稳态热分析的基础上,求解了某直升机齿轮传动系统的瞬态温度场,为该传动系统生存能力的预测提供了理论依据。

关键词: 齿轮传动 温度场 热分析

分类号: TH132 V275.1

1 引言

军用直升机传动系统,在战场上遭敌方火力攻击而中弹漏油失去正常润滑的概率很大。在失去润滑这样严苛的工作条件下,传动系统的生存能力很大程度取决于传动系统的瞬态温度场和传动元件材料的热承载能力。笔者在文献[1]中已对某直升机齿轮传动系统(在正常润滑条件下)进行了稳态热分析,本文将在此基础上对该传动系统进行失去润滑条件下的瞬态热分析从而为传动系统生存能力预测提供理论基础。

2 传动系统瞬态温度场的分析方法

求解系统瞬态温度场所遵循的基本原理是,节点的净热流量等于节点相关体积内能的增加。即:

$$q_j = \rho_j C_{pj} V_j (dT_j/d\tau) \quad (j = 1, 2, \dots, n) \quad (1)$$

这里 q_j , ρ_j , C_{pj} , V_j 和 T_j 分别表示第 j 个节点处的“净热流量”、“材料密度”、“材料比热”、“相关体积”和“温度”。 τ 为时间, $dT_j/d\tau$ 为第 j 个节点处的温升率。求解式(1)给出的一系列一阶非线性微分方程(因含有辐射项和对流换热项)的简便数值计算方法是按时间步长(变步长)离散为一个时间序列, k 为循环次数, 则 $\tau^{(k+1)}$ 时刻的温度场 $T_j^{(k+1)}$ 就可用 $\tau^{(k)}$ 时刻的温度场 $T_j^{(k)}$ 递推出来, 即:

$$\tau^{(k+1)} = \tau^{(k)} + \Delta\tau^{(k)} \quad (2)$$

$$T_j^{(k+1)} = T_j^{(k)} + [dT_j/d\tau]^{(k)} \Delta\tau^{(k)} = T_j^{(k)} + (q_j^{(k)} / \rho_j^{(k)} C_{pj}^{(k)} V_j) \Delta\tau^{(k)} \quad (3)$$

利用递推公式(3)就可求解系统的瞬态温度场。但是若时间步长 $\Delta\tau$ 选取不当, 就会发生计算结果的“振荡”现象, 为此时间步长需满足条件 $dT_j^{(k+1)} / d\tau_j^{(k)} > 0$, 即:

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** 男 35岁 博士后 副教授 北京市9628信箱48分箱 100086

$$\Delta \tau_j^{(k)} \leq - \frac{\rho_i^{(k)} C_{pi}^{(k)} V_i}{\partial q_j^{(k)} / \partial \tau_j^{(k)}} \quad (4)$$

对于有 n 个节点的系统, 满足式(4)的 $\Delta \tau_j^{(k)}$ 就有 n 个。在每一次循环时对不同节点可选用统一的一个时间步长 $\Delta \tau^{(k)}$, 即: $\Delta \tau^{(k)} = M \ln(\tau_j^{(k)})$, ($j = 1, 2, \dots, n$)。将上述选定的 $\Delta \tau^{(k)}$ 代入式(3)

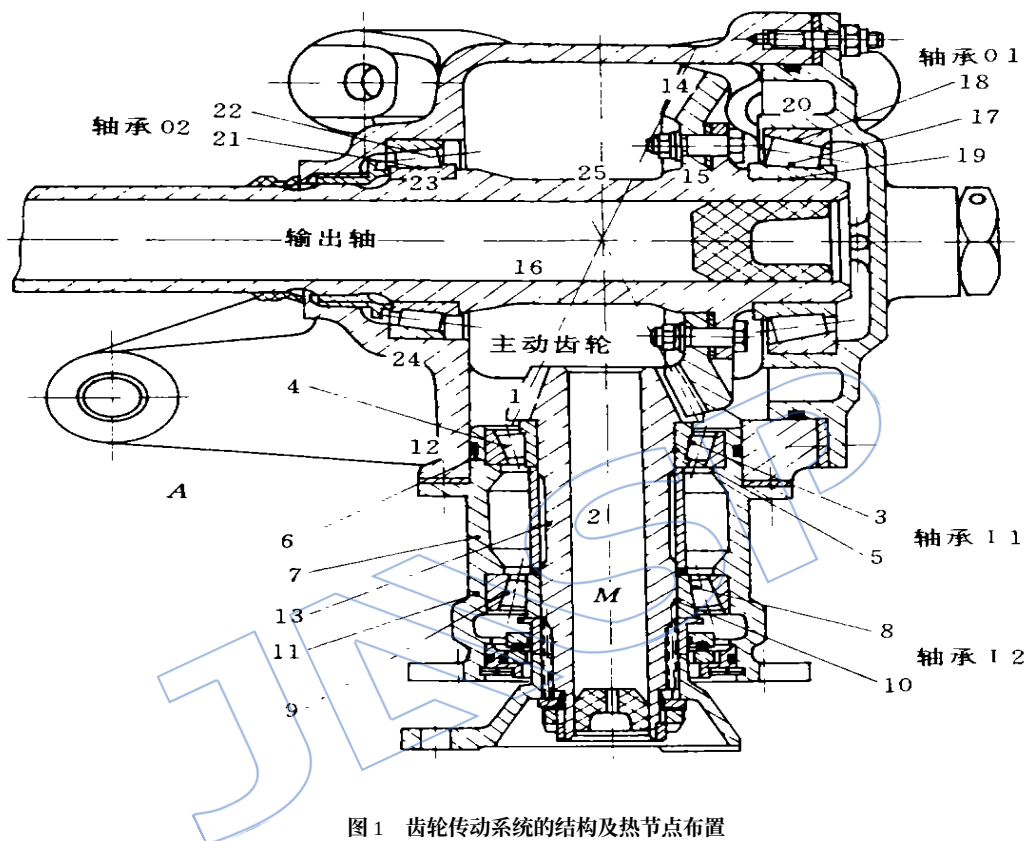


图1 齿轮传动系统的结构及热节点布置

并将有润滑时系统的稳态温度场作为 $\tau = 0$ 时瞬态温度场的初始值, 则可获得系统的瞬态温度场。某直升机齿轮传动系统的结构和热节点布置如图1所示。

3 失去润滑条件下的功率损失及对流换热系数

失去润滑条件下, 弧齿锥齿轮平均功率损失 $N_f^{(G)}$ 取为输入功率 N_i 的 2.5%。 $N_f^{(G)}$ 在主从动齿轮(节点1和节点14)上的分配与文献[1]中对应的分配方法完全一致。

圆锥滚子轴承的平均功率损失 N_f 可按下式计算^[2]:

$$\left. \begin{aligned} N_f &= \pi M_f n_i / 30 \\ M_f &= P \mu d / 2 \\ P &= \begin{cases} F_r & F_a / F_r \leq 1.5 \tan \alpha \\ 0.4(F_r + F_a \cot \alpha) & F_a / F_r > 1.5 \tan \alpha \end{cases} \\ \mu &= 0.0028 \end{aligned} \right\} \quad (5)$$

这里 n_i 为轴承内圈转速(r/min), F_r 和 F_a 分别为圆锥滚子轴承承受的径向力和轴向力(N)。 d 和 α 分别为轴承的内径(m)和接触角。对于传动系统内的4个圆锥滚子轴承 I1, I2, O1 和 O2

可按式(5)分别算出其平均功率损失 $N_f^{(11)}, N_f^{(12)}, N_f^{(01)}$ 和 $N_f^{(02)}$ 。该平均功率损失在轴承内外圈上的分配原则与文献[1]中对应的分配原则一样。

在失去润滑条件下,机匣内的对流换热介质为空气,机匣内空气与弧齿锥齿轮齿面的对流换热系数仍近似地按正常润滑情况下对应的换热系数公式(文献[1])计算,所不同的是公式中的普朗特数、导热系数、运动粘度需要代入机匣内空气对应的热物性参数而不是润滑油的热物性参数^[3]。同理,机匣内空气与圆锥滚子轴承之间的对流换热系数也可近似地按有润滑情况下对应的换热系数公式(文献[1])计算。但需将公式中的导热系数、普朗特数、运动粘度替换为机匣内空气对应的热物性参数^[4]。除此之外,其它节点处(节点号为 $j=2, 7, 11, 12, 20, 24, 25$)的对流换热系数可用下式计算^[5]:

$$\alpha_j = 0.3 Re_j^{0.57} x_j K_j / L_j \quad (6)$$

式中: Re, K, x 和 L 分别为雷诺数、导热系数、修正系数和定型尺寸。需要指出的是,在失去润滑条件下,由于传动系统温度场的时变特性,所以有关材料的热物性参数也将随温度场的变化而变化。机匣内空气的热物性参数随机匣内空气温度的变化关系为:

$$\left. \begin{aligned} \text{普朗特数: } Pr(T) &= 0.707 - 2 \times 10^{-4} & 10^\circ\text{C} \leq T \leq 100^\circ\text{C} \\ \text{导热系数: } K(T) &= 2.43 \times 10^{-2} + 8 \times 10^{-5} T & 10^\circ\text{C} \leq T \leq 100^\circ\text{C} \\ \text{运动粘度: } \nu(T) &= \begin{cases} [14.16 + 0.93(0.1T - 1)] \times 10^{-6} & 10^\circ\text{C} \leq T \leq 100^\circ\text{C} \\ [17.95 + 1.036(0.1T - 5)] \times 10^{-6} & T > 50^\circ\text{C} \end{cases} \end{aligned} \right\} \quad (7)$$

金属材料的密度 $\rho(\text{kg}/\text{m}^3)$ 和比热 $C_p[\text{J}/(\text{kg} \cdot ^\circ\text{C})]$ 随温度的变化不是很大,可近似将其视为定值,即: $\rho_j = 7850$ 和 $C_{pj} = 641$ ($j=1, 2, 5, 10, 13, 14$); $\rho_j = 7810$ 和 $C_{pj} = 670$ ($j=3, 4, 8, 9, 17, 18, 21, 22$); $\rho_j = 2680$ 和 $C_{pj} = 963$ ($j=6, 7, 11, 12, 20, 24$); $\rho_j = 7830$ 和 $C_{pj} = 550$ ($j=15, 19, 23, 25$)。这里 j 为节点号。文献[1]中提及的导热系数 K_b 和 K_s 随温度 T 的变化规律为:

$$K_b(T) = -3.36 \times 10^{-5} T^2 + 2.3 \times 10^{-2} T + 37.836 \quad (100^\circ\text{C} \leq T \leq 900^\circ\text{C}) \quad (8)$$

$$K_s(T) = -2.5 \times 10^{-5} T^2 - 2.55 \times 10^{-2} T + 43.8 \quad (100^\circ\text{C} \leq T \leq 400^\circ\text{C}) \quad (9)$$

4 节点净热流量及节点相关体积

某节点 j 的净热流量 q_j 等于功率损失(发热量)在该节点上的分配 Q_j 加上流入该节点的热流量 Q_{Nj} 减去流出该节点的热流量 Q_{OUTj} 即:

$$q_j = Q_j + Q_{Nj} - Q_{OUTj} \quad (10)$$

对于本文研究的在失去润滑条件下的直升机齿轮传动系统

$$Q_{Nj} = \sum \frac{T_w - T_i}{R_{wcj}} \quad (11)$$

$$Q_{OUTj} = \sum \frac{T_i - T_x}{R_{jcj}} + \sum \frac{T_i - T_y}{R_{jvy}} + \sum [(T_j + 273)^4 - (T_z + 273)^4] \sigma \epsilon A_z \quad (12)$$

这里, R_{wcj} 和 R_{jcj} 为传导热阻, R_{jvy} 为对流换热热阻, $\sigma = 5.67 \times 10^{-8} \text{W}/(\text{m}^2 \cdot \text{K}^4)$ 为玻尔兹曼黑体辐射常数, ϵ 为表面黑度, A_z 为辐射换热面积。下标中的 w, x, y, z 均指与节点 j 有直接换热关系的节点号。 q_j 及 V_j ($j=1 \sim 15, 17 \sim 25$)的算式所占篇幅较大(详见文献[6]),此处不一一罗列。失去润滑情况下的传导和对流热阻仍按文献[1]中的热阻公式来计算,但需考虑失去润滑后热物性参数随温度变化的因素。

5 瞬态热分析结果及讨论

根据上述瞬态热分析思想和数学模型,笔者编程计算了某直升机齿轮传动系统的瞬态温

度场。需要输入的结构参数和工况参数与该传动系统稳态温度场计算时的一样。这里的边界条件是: (1) 机匣外空气温度 $T_a = 25^\circ\text{C}$; (2) 机匣内空气温度 $T_H^{(k+1)} = T_H^{(k)} + 0.02\Delta\tau^{(k)}$, T_H 初值为 70°C ; (3) 16 节点的温度 $T_{16}^{(k+1)} = T_{16}^{(k)} + 0.05\Delta\tau^{(k)}$, T_{16} 的初值为 70°C 。取循环次数 $k = 800$ 次。计算结果: (1) 传动系统输入轴有关节点温度随时间的变化关系如图 2 和图 3 所示。

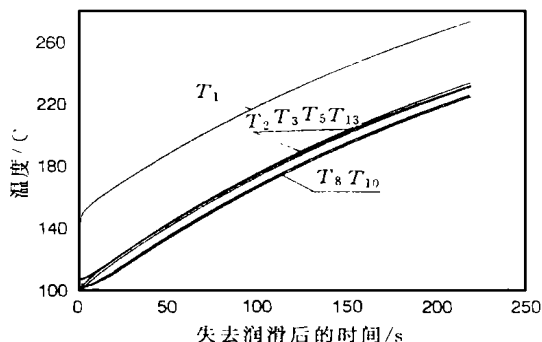


图 2 输入轴部件瞬态温度场

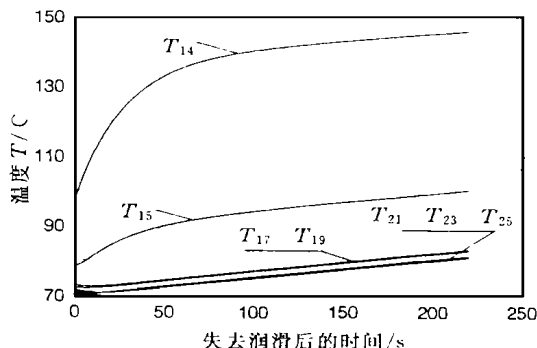


图 3 输出轴部件瞬态温度场

由图 2 和图 3 可见: (1) 输入轴有关节点 (1, 2, 3, 5, 8, 10, 13) 的温升率最大, 当时间经历 $\tau = 220$ 秒时, 主动齿轮齿面温度上升了 151°C , 已达到 272°C , 其余各节点温度在原有基础上上升了 $120^\circ\text{C} \sim 130^\circ\text{C}$ 。主动齿轮齿面是整个传动系统中温度最高的部位。(2) 输出轴有关节点的温升率较之于输入轴有关节点的温升率小得多, 在 $\tau = 220$ 秒的时间经历内, 大多数节点温度仅升高 $10^\circ\text{C} \sim 20^\circ\text{C}$, 从动齿轮齿面温度上升 48°C 。(3) 从 T_3, T_8, T_{17}, T_{21} 随时间变化的曲线来看, 在 4 个轴承中, 轴承 I1 和 I2 在失去润滑后发生失效的可能性大于轴承 O1 和 O2。(4) 与文献[7]所揭示的温度时变规律比较, 本文的瞬态温度场计算结果基本反映了传动系统的热时变规律。

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RELIABILITY OF ENGINE BLADE NONDESTRUCTIVE TESTING

Li Dengdi and Fu Huimin

(5th Dept Beijing University of Aeronautics and Astronautics, Beijing 100083)

ABSTRACT The attention has focused on quantifying the capability of nondestructive testing (NDT) system for guaranteeing structural safety through damage tolerance analysis. A method of reliability assessment for engine blades NDT is presented, which can determine exactly the probability of flaw detection (POD) and assess the probability of flaws missed (POM) in the engine blades, as well as control the largest size of the flaw missed at inspections with high probability of flaw detection and confidence level. This method also raises the flaw detection probability and prevents the flight accidents caused by the missed flaws in engine blades.

Key Words Aircraft engine; Blades; Nondestructive tests; Flaw; Reliability

ROBUST H_∞ OUTPUT FEEDBACK CONTROL OF STRUCTURED AND UNSTRUCTURED PARAMETER UNCERTAIN SYSTEM FOR AEROENGINE

Wang Xi

(14th Dept Beijing University of Aeronautics and Astronautics, Beijing 100083)

Zeng Qingfu

(Northwestern Polytechnical University, Xi'an 710072)

ABSTRACT The robust stability and robust performance of aeroengine mixed uncertain system are analyzed. By introducing structured singular value μ synthesis method, the robust H_∞ output feedback control is investigated under mixed structured and unstructured parameter perturbations. Disturbance rejection and servo tracking performance with the designed controllers for aeroengine uncertainty systems are simulated on a nonlinear model of twin-spool turbojet engine.

Key Words Uncertainty system; Synthesis method; Aeroengine; Control

TECHNICAL NOTES

TRANSIENT THERMAL ANALYSIS OF A HELICOPTER GEAR TRANSMISSION SYSTEM

Li Zhiquan

(Mechanism Division, Beijing Institute of Spacecraft System Engineering, Beijing 100086)

Shen Yunwen, Chen Guoding, Su Hua

(Mechanical Engineering Department, Northwestern Polytechnical University, Xi'an 710072)

ABSTRACT Survivability of a gear transmission system in attack helicopter after Loss-Of-Lubrication (LOL) is greatly dependent on the transient temperature fields of the systems. A helicopter gear transmission system was researched. A method is put forward

to calculate the transient temperature fields of this system after LOL and the models for power losses and heat transfer (convection) coefficients are established. In these models, the time-variance characteristics of the thermal physical parameters, such as viscosity, thermal conductivity are considered. A computer program is worked out for calculating the transient temperature fields of the system on the basis of these models. In the computation, the calculational results of the steady state temperature field in the transmission system are used as initial values of the transient temperature fields and the time steps are properly controlled so as to prevent "data oscillation". The transient temperature fields of the gear transmission system are obtained from the computation and can serve for predicting the survivability of the gear transmission system.

Key Words Gear transmission Temperature field Thermal analysis

APPLICATION OF SQP TO ACCELERATION CONTROL OF TURBOFAN ENGINE

Chen Guangning

(China National Aero-Technology Import and Export Corporation)

Fan Ding

(Northwestern Polytechnical University)

ABSTRACT The optimal control for turbofan engine acceleration control has been investigated. The optimal method used in this paper is Sequential Quadratic Programming (SQP), one of the most successful methods for solving nonlinear constrained problem. Many limits in the process of engine acceleration have been studied such as compressor surge margin, overtemperature limit, overspeed limit, rich extinction in combustor, the maximum fuel flow and limit of the actuator property. The results of simulation show that SQP method is suitable and feasible in solving the problem of aero-engine acceleration control; the engine potentialities are brought into full play and the engine acceleration performance is improved greatly.

Key Words Nonlinear programming Optimization Control

MODELLING AND SIMULATION OF MAIN FUEL CONTROL SYSTEM FOR A TURBOFAN ENGINE

Cheng Tao, Qiying, Meng Qingning

(4th Dept. Beijing University of Aeronautics and Astronautics, Beijing 100083)

ABSTRACT A turbofan engine and its main fuel control system with hydromechanical regulator are studied. The rotational speed control system and the acceleration control system are modelled according to the analysis of the engine control program. The temperature sensor, temperature amplifier and blade control system are also modeled. According to these mathematical models, all systems are simulated with the SIMULINK in toolbox of MATLAB. This work has important value for further research and improvement in the engine main fuel control system.

Key Words Turbofan engine Fuel regulator Model Simulation