

某型发动机转子热弯曲变形 及其影响数值分析

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【摘要】 采用有关文献提出的数值分析方法, 对某型发动机转子的热弯曲变形及其影响进行了定量分析, 得出了一些可供工程实际参考的有益结果。首次在发动机转子轴对称稳态温度场的基础上, 借助热弯曲实验器实验结果, 产生一个非轴对称温度场, 用三维热弹性有限元法计算其热弯曲变形, 采用传递矩阵法计算热弯曲振动响应。上述方法在热弯曲试验器分析中均得到了验证。实践表明这是一种分析航空发动机热弯曲及其影响的简便可行的数值分析方法。

主题词: 温度场 变形 有限元法

分类号: O344.3

航空发动机转子停车后, 在冷却过程中因自然对流换热, 使转子发生热弯曲变形。如果在热弯曲变形过大的情况下再次启动, 会产生很大的振动。我国某型航空发动机曾发生过严重的热弯曲振动故障, 因此有必要研究转子热弯曲及其对振动的影响。这方面的研究以往在国内外开展甚少。文献[1, 2]曾对转子热弯曲及其对振动的影响的数值分析方法进行了研究。本文则着重用该方法具体分析某型发动机转子热弯曲及其对振动的影响。

1 双转子系统热弯曲变形数值分析

某型发动机双转子结构示意图见图 1。由于目前难以得到发动机停车后转子的瞬态温度

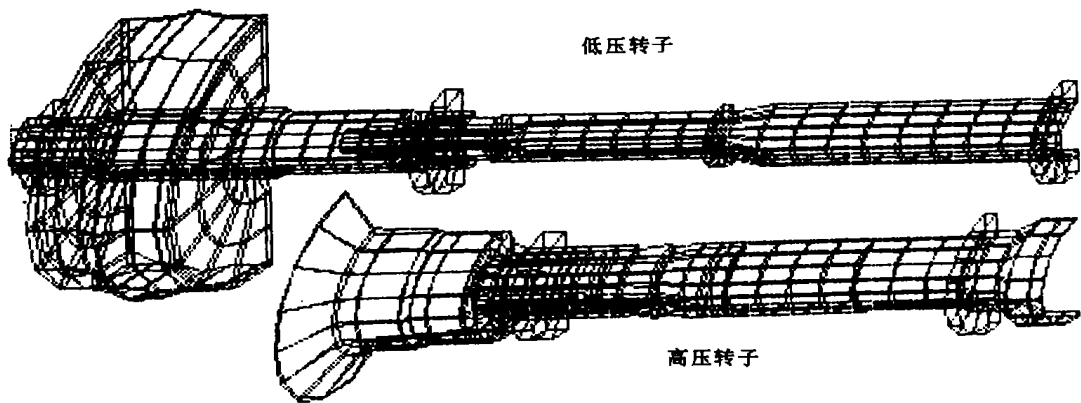


图 1 双转子结构及三维有限元分析模型

场, 本文参考热弯曲试验器在冷却过程中温度与温差的变化情况^[3], 在冷却过程中较长的时间内保持停车瞬时温度的 $\pm 0.5\% \sim \pm 1\%$ 的温度值, 因此本文计算是由给定发动机在工作转速下稳态轴对称温度场基础上, 取轴上、下表面温度 T 的分布见图 2。

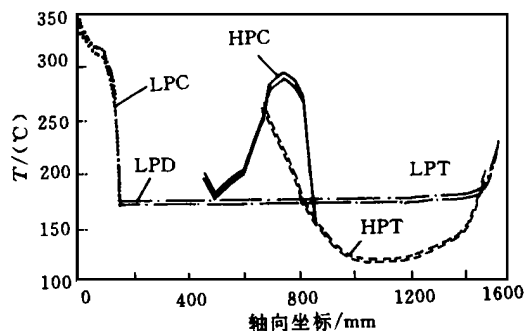


图 2 轴上下表面的温度分布

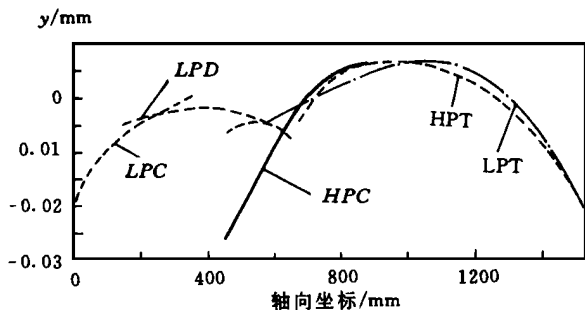


图 3 轴的挠度分布

进行热弯曲变形计算时, 采用 ADINA 程序中三维 8 结点单元等参单元^[4]。因结构及温度前后对称, 因此取各部件一半进行计算。各轴沿周向分为 8 层单元, 沿径向分为一层单元, 共 920 个等参元, 2034 个节点(见图 1)。为了准确地模拟弹性支承对热弯曲的影响, 本文不仅用三维体元模拟 3 个中介支承和 3 个外支承, 同时利用单位载荷法确定在给定支承柔度条件下三维体元等效弹性模量。经计算得到各部件轴心线热弯曲变形挠度 y 的曲线如图 3 所示。

2 双转子系统热弯曲振动数值分析

由热弯曲变形计算结果, 采用多转子系统热弯曲振动响应分析方法^[1,2]计算了该机双转子的热弯曲振动响应。双转子结构振动分析计算简图如图 4 所示。本文计算了各种工作转速下, 各级盘处的挠度、轴承受力及弯转角和各转子间的位能分配。

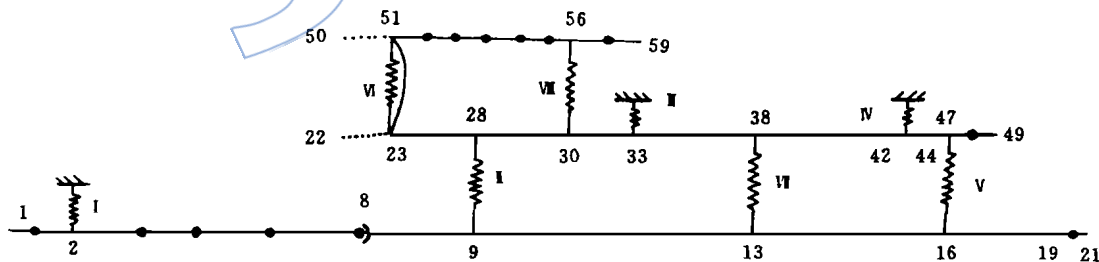


图 4 双转子结构振动分析模型

计算所得地面慢车及最大转速时低压协调进动和高压协调进动的热弯曲响应和位能分配列于表 1。表 1 中 $y_{rs}(19)$ 及 $y_{rs}(44)$ 分别表示低压涡轮盘及高压涡轮盘处的热弯曲响应挠度。 Π 为系统能量, Π_1 , Π_2 , Π_3 分别为低压轴、高压轴和高压压气机盘鼓子结构的能量占系统能量的比例。计算结果表明地面慢车时热弯曲响应明显大于其它转速。高压协调进动时地面慢车转速的热弯曲响应与位能最大。

表 1 低、高压协调进动时轴的热弯曲响应

转速(1/s)		低 压 协 调		高 压 协 调	
		391. 66	1168. 25	764. 35	1352. 88
挠 度 (mm)	$y_{rs}(19)$	0.12×10^{-1}	0.813×10^{-3}	0.91×10^{-1}	0.33×10^{-2}
	$y_{rs}(44)$	0.12×10^{-1}	0.269×10^{-3}	0.105×10^{-1}	0.31×10^{-2}
能 量	$\Pi(\text{N} \cdot \text{m})$	0.0275	0.0215	0.12×10^3	0.0616
百分数	Π_1	46.9%	90.5%	19.4%	10.2%
	Π_2	46.7%	6.64%	56.7%	66%
	Π_3	6.4%	2.83%	23.9%	23.8%

计算所得各轴承弯转角列于表 2。表 2 中轴承号为图 4 中的结点号, 由表 2 可见, 高压协调进动时, 地面慢车转速下, 低压压气机前滚棒轴承(2 号结点) 偏转角达到 0.0018 r/min, 即该轴承有可能超过轴承偏转角的允许值。航空发动机中热弯曲故障往往是因为热弯曲振动造成滚棒轴承受力和偏转角过大, 造成轴承抱死。

表 2 低、高压协调进动时轴承转角(r/min)

轴承号	转速(r/min)	低压协调转速(1/s)		高压协调转速(1/s)	
		391. 66	1168. 25	764. 35	1352. 88
2	转角 $\times 10^4$	0.56	0.48	18.0	0.12
9	转角 $\times 10^4$	0.13	0.021	6.3	0.052
13	转角 $\times 10^4$	0.44	0.14	8.8	0.068
16	转角 $\times 10^4$	0.28	0.25	4.8	0.20
33	转角 $\times 10^4$	0.27	0.044	24	0.035
42	转角 $\times 10^4$	0.12	0.041	1.4	0.28

计算所得涡轮盘处的热弯曲响应挠度 y_{rs} 及系统位能与角速度平方的比值见图 5 和图 6。

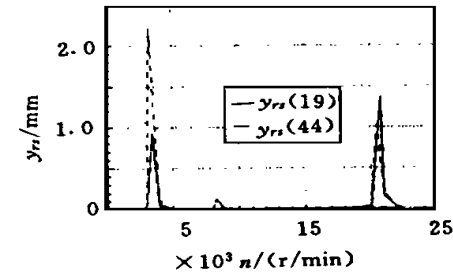


图 5 涡轮盘处与热弯曲响应

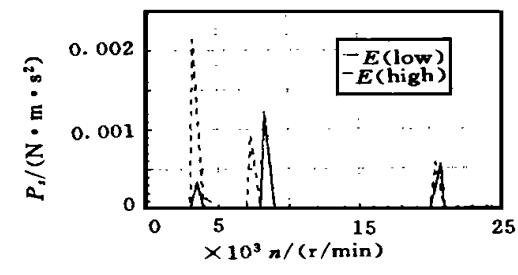


图 6 转子系统的能量与角速度平方的比值

图 6 中 $E(\text{high})$ 和 $E(\text{low})$ 分别代表高、低压轴协调进动时系统的能量与角速度平方的比值 P_s 。由图 5, 6 可见, 无论是低压还是高压协调进动, 一阶临界转速是对热弯曲变形最敏感的转速。

3 结 论

(1) 转子热弯曲变形与轴上、下表面温度差相对于轴的平均温度的百分比值成正比; 在单个转子热弯曲变形时, 热弯曲振动响应与初始挠度成正比。

(2) 对外支承多于两个的转子系统, 应考虑支承刚度对转子热弯曲变形的影响。对本文转子系统, 若不考虑支承刚度对转子热弯曲变形的影响所得的在涡轮盘处热变形结果(0. 00937 mm) 与本文结果(0. 0188 mm) 相差一半以上。

(3) 本文采用的分析方法经过实验与考题的考核, 使用方便, 计算速度快。如果能够提供准确的轴表面温度分布, 用本文方法可以得到轴的温度场与热弯曲变形, 进而可求得具有较高精度的热弯曲振动响应。

(4) 发动机设计阶段如果已算得工作转速下稳态温度场, 便可以采用本文方法预估发动机对热弯曲变形敏感转速及敏感程度, 并可以通过修改转子结构设计, 使慢车转速避开一阶临界转速, 并有足够的裕度, 而且在地面慢车转速热弯曲响应(包括挠度、轴承受力和弯转角) 不大, 同时系统位能不大。

(5) 由表 1 可见, 哪个转子存在热弯曲而引起该转子协调进动时, 则对应转子能量占总能量的百分比最大。

(6) 热弯曲响应在低转速区大于不平衡响应^[2], 叶尖尖隙对于热弯曲特别敏感, 因此评定热弯曲振动水平首要的是盘处的挠度, 其次是滚棒轴承的弯转角和轴承力, 再次便是系统位能。综合以上各种热弯曲造成的影响因素, 可用以分析、预防及排除热弯曲故障。

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VIBRATION CHARACTERISTICS ANALYSIS FOR A SHROUDED TURBINE BLADE WITH AIR- COOLING HOLES

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ABSTRACT

A finite element model has been established for analyzing vibration characteristics of a shrouded turbine blade with air- cooling holes. The effects of uniform and nonuniform temperature distribution, holes and constraint conditons of the shrouds on the vibration characteristics are considered. According to the resonant fatigue- damage life theory, the optimum clearance between neighboring shrouds is determined to increase the service life. The results of the analysis show that the air- cooling holes have less, but the constraint conditions and temperature distributions have significant effect on natural frequencies of the blades.

Key Words Engines Blade vibration Finite elements

A SIMPLE METHOD FOR CALCULATION OF RESIDUAL STRESS IN THERMAL BARRIER COATING

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ABSTRACT

The residual stresses are always emerged in plasma sprayed coatings due to their spray method. The accurate calculation of the residual stresses is important for strength evaluation and thermal fatigue prediction of the coatings, as well as for controlling and evaluating the spraying process. First of all, a main process causing residual stress is identified by analyzing plasma spray process and simplified into a model. The residual stresses in the coated part is resulted from the difference in thermal expansivities of the various materials involved. According to the above mentioned, authors bring forward a simple method for calculating residual stresses, which can be easily used with finite element method. Finally, as a demonstration, cylinder- type specimens are chosen to calculate residual stresses with FEM under various calculating conditions.

Key Words Thermal barrier coatings Residual stress Finite element methods

A NUMERICAL ANALYSIS OF THERMAL BENDING DEFORMATION AND ITS INFLUENCE ON ROTOR

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ABSTRACT

Thermal bending deformation and its influence on an aeroengine's rotor are analyzed numerically, and some useful results for engineering are obtained. On the basis of axial symmetrical static temperture field of engine's rotor, its axial non- symmetrical temperture field is formed by the aid of thermal bending test data, three- dimension thermal elastic FEM is used to calculate the thermal bending deformation, and transfer matrix method

is employed to calculate thermal bending vibration response. These methods are verified by thermal bending tests. In general, this numerical method is simple and applicable to the thermal bending analyses and investigation of its influence on aircraft engine.

Key Words Temperature field Deformation Finite element methods

TOOTH CONTACT ANALYSIS OF MODIFIED HELICAL GEARS

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ABSTRACT

An approach for calculating tooth working-surface contact and tooth edge contact of modified helical gears is proposed. The generation of tooth surface and Tooth Contact Analysis(TCA) of the modified helical gears under various errors can be simulated on computer by the aid of this approach. Then, the tooth modification by changing tooth profile of rack-cutter and by CNC machine is considered. As an example, TCA on pair of modified helical gears is completed by using above mentioned approach, and the improvement for contact under errors is shown. This method can be used for modification of helical gears.

Key Words Helical gears Contact problems Simulation

LOADED TOOTH CONTACT ANALYSIS OF MODIFIED HELICAL GEARS

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ABSTRACT

A simulation approach for loaded tooth contact analysis is presented. Deformation of the tooth, deflection of the supporting system, backlash between the teeth, gaps on points except temporary contact point, manufacturing and assembling errors are considered. In this procedure, the accurate geometry resulted from TCA is foundation of whole calculation, and the flexibility factor matrix by using finite element method is adopted. Besides, the non-linear contact analysis between multi-pairs of teeth can be done only through the mechanical and geometrical analyses of single-pair of teeth.

Key Words Helical gears Bearing capacity Contact problems

RESONANCE INTERFERENCE ANALYSIS AND RELIABILITY ASSESSMENT FOR A FAILED TURBINE BLADE

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ABSTRACT

A series of analyses for blades of second turbine in a given aero-engine have been accomplished such as vibration analysis, resonance analysis, modal stress analysis, and statistical analysis for the blade nature frequencies obtained in field and mass-production. The failures of the blades have been investigated by the synthesis of the obtained results and a resonance interference analysis. In result, the failure sources have been found