

压气机叶片受外物损伤 的剩余振动疲劳寿命

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【摘要】 采用电磁涡流激振的振动疲劳试验,对 TC4 材料制成的平板叶片受外物损伤后的剩余振动疲劳寿命进行了研究。结果表明,叶片的外物损伤程度取决于撞击能量 E 和几何标度 S ,对于一定的叶片,存在不影响疲劳寿命的极限损伤。对叶片损伤处进行修复和适当减小叶片振动应力水平是提高叶片抗外物损伤能力的有效途径。通过钢钛叶片试验分析表明,由于设计叶片稳态应力水平通常以抗拉强度为参考基点,那么钢制叶片的疲劳强度的富裕程度相对要高些。

主题词: 叶片 损伤 剩余 寿命 振动疲劳

分类号: V 216.3

1 平板叶片的设计与试验方法

对于压气机工作叶片受外物损伤后的剩余寿命,我国制定的 GJB 241-87“涡喷、涡扇发动机通用规范”中,有明确的要求。本文采用电磁涡流激振的振动疲劳试验,对 TC4 材料制成的平板叶片受外物损伤后的剩余振动疲劳寿命进行了研究,并与钢叶进行了对比,以期得到一些有益的结果。

根据对外物损伤叶片的寿命评估方法^[1],结合当前的实际条件,本文采用 TC4 制成的平板叶片作为研究对象,并与不锈钢 1Cr11Ni2W2MoV 作对比。TC4 平板叶片是用棒材经与实际制造过程一致的机械加工以及热处理后而制成的。平板叶片设计中主要考虑了:(1)平板叶片的一阶频率与实际叶片一阶频率接近;(2)平板叶片厚度与实际叶片 2/5 叶高以下的可能厚度相近;(3)平板叶片的前缘转接圆弧以及根部过渡圆弧与实际叶片相近;(4)叶片按一定角度装夹,以模拟真实叶片的受力状态。

图 1 示出了厚度为 4 mm、6 mm 和 8 mm 的 TC4 平板叶片和作为对比试验用的厚度为 4 mm 的 1Cr11Ni2W2MoV 平板叶片。

平板叶片的试验方法:由于 TC4 材料属于高电阻率的材料,难以使用电磁涡流激振,故专门设计了两种钢质夹具,以适合不同长度叶片的使用。通过对钢质夹具的激励,带动悬臂支撑的平板 TC4 叶片一起振动。平板叶片是按一定角度成对倾斜对称地通过螺栓而夹持安装的,这一角度是参照实际叶片的弯曲角度选定的(两边各取 6°)。另外,与钢制平板叶片作对比,两者的夹具是相同的。本文采用 PYD-1 型振动疲劳试验系统^[2]进行叶片的振动疲劳试验。

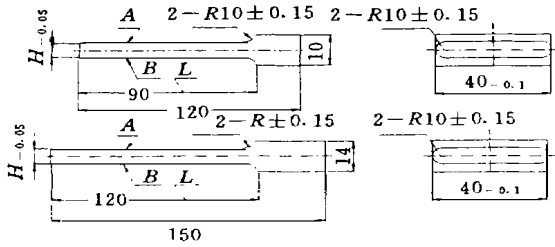


图1 平板叶片示意图

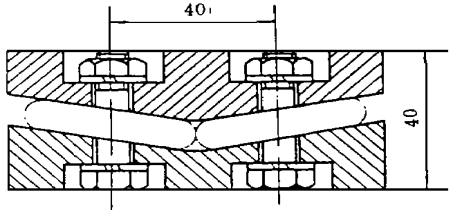


图2 叶片装配示意图

2 TC4 平板叶片的振动疲劳试验

试验前, 首先对试件表面进行打磨, 直至无划痕, 光滑为止; 接着, 在距离根部 10 mm 处利用摆锤用选定的冲头(半径为 3 mm 和 5 mm)撞击叶片, 预制损伤; 随后, 将两片厚度相同叶片成组地固持在支座上, 另一端则装夹在上述夹具上。

经验表明, 试验的疲劳次数控制在 $10^5 \sim 2 \times 10^6$ 较为合适, 文献[3]选定 TC4 锻坯的光滑试件的疲劳强度为 380 MPa。为此, 对于不同厚度叶片的试验振幅, 按“材料力学”中一端固持一端自由的悬臂梁挠度公式进行预估, 经试验证实是可行的。同样, 对于 1Cr11Ni2W2MoV 平板叶片, 选定应力水平为 559 MPa。表 1 给出了 4 种平板叶片的试验应力值和相应振幅值。应力标定是用电阻应变计测量技术实现的。结果表明测试值与理论值相符合。

表 1 试验应力水平和相应振幅

试件材料	厚度 (mm)	应力水平 (MPa)	叶尖振幅 (mm)
TC4	4	380	2.40
TC4	4	253	1660
TC4	6	380	1.93
TC4	8	380	3.17
1Cr11Ni2W2MoV	4	559	1.88

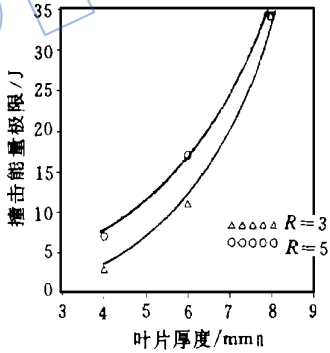


图3 极限损伤的确定

失效标准: 对于钢和铝制的压气机叶片, 常以其固有频率下降 2% 作为叶片振动疲劳破坏的标准^[4]。但钛合金的试验结果表明^[5], 在 0.1% 频率降低的情况下已出现可见裂纹, 到 1% 时裂纹长度已很可观, 故此处暂以 1% 频率降低作为钛合金的破坏标准。事实上, 本文的试验证实了从 0.1%~1% 频率下降过程是相当快的, 一般只有几十秒钟。

极限损伤的确定: 极限损伤是极限撞击能量的一种直观表达形式。实验表明, 对于厚度(δ)一定的平板叶片和一定的损伤半径(R), 存在着一个极限能量 E , 在此能量下, 损伤叶片具有与完好叶片相当的寿命, 即损伤对叶片的振动疲劳寿命没有影响。图 3 中给出了相应的极限损伤试验结果。

缺口性质与应力水平的影响: 为弄清 TC4 损伤叶片的疲劳寿命下降的真正原因和解决办法, 对厚度为 4 mm 的 TC4 叶片进行了人工缺口和应力水平降低后的两组对比试验。

在厚度为 4 mm 的 TC4 叶片上, 采用锉刀制成一个人工缺口, 其部位和几何形状尺寸与

撞击损伤的完全一致, 当在相同应力水平下试验时, 结果其疲劳寿命达到 1.76×10^6 次循环, 与光滑叶片的疲劳寿命 2.44×10^6 次循环相当。

对于 $E = 34 \text{ J}$, $S = R/\delta = 5/4$ 的 TC4 叶片还进行了另一组试验。将此次试验的应力水平由原来的 0.66 σ_b 降到 0.25 σ_b , 其余条件不变。结果损伤叶片的疲劳寿命由 0.306×10^6 次循环增加到 2.78×10^6 次循环, 比原先增加了 8 倍。

结果表明对叶片损伤处的修复和适当减小振动应力水平是提高叶片抗外物损伤能力的有效途径。

钢与钛叶片的对比: 为了对比 1Cr11Ni2W2MoV 与 TC4 两种现行常用的压气机工作叶片材料, 分别对它们进行了同等条件(光滑与损伤试件形状 $S = 3/4, 5/4$ 与撞击能量 $E = 34 \text{ J}$ 等)下的疲劳试验。然而, 在选定它们的试验应力水平时, 发现抗拉强度与疲劳强度间相对关系的差异甚大, 显然, 疲劳带来明显影响。如果仅从疲劳强度角度出发, 选定钢制和钛制平板叶片的试验应力水平分别为 559 MPa 和 380 MPa, 钢制与钛制的寿命相差不大(对于 $S = 3/4, E = 34 \text{ J}$ 均在 2.0×10^5 次循环左右, 而对于 $S = 5/4, E = 34 \text{ J}$, 均在 3.0×10^5 次循环左右。), 但是它们的应力水平, 钢制的是其抗拉强度的 0.56 倍, 而钛制的为 0.38 倍。如以抗拉强度作为叶片设计应力水平(离心与弯曲应力)的参考基点时, 那么, 钢制叶片疲劳强度的富裕程度显然要比钛制的高。

3 结 论

(1) 采用本文的电磁涡流疲劳试验系统和相应的钢质夹具一起使用, 可满意地对 TC4 材料的平板叶片进行疲劳试验; (2) 叶片的外物损伤程度取决于撞击能量 E 和几何标度 $S (R/\delta)$, 对于一定的叶片, 存在不影响疲劳寿命的极限损伤; (3) 对叶片损伤处进行修复和适当减小叶片振动应力水平是提高叶片抗外物损伤能力的有效途径。(4) 通过试验分析表明, 由于设计叶片稳态应力水平通常以抗拉强度为参考基点, 那么钢叶片疲劳强度的富裕程度比钛叶片要高些。

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参 考 文 献

- 1 康继东 钛制压气机叶片外物损伤的维修性研究 博士后科研工作报告, 南京航空航天大学, 1996
- 2 徐志怀 电(磁)涡流技术在振动疲劳试验中的应用 航空学报, 1987, 8(2): B55- 61
- 3 国际航空编辑部 斯贝 MK202 发动机应力标准 1979
- 4 压气机叶片疲劳试验的自动化 石川岛播磨技报, 1975, 15(3): 523
- 5 侯静泳, 杨景成 叶片及其材料振动疲劳测试中几个问题的研究 材料工程, 1985, (4): 24- 29

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engine gas path component faults is investigated. By organizing the fault samples quantitatively, the construction of BPN is built and applied to the fault diagnosis of a low bypass ratio turbofan engine. The diagnostic results show that BPN can not only isolate the gas path component faults, but also identify the severity of component performance deterioration. It is proved that the BPN is adaptive to random errors in measure system and different engine operation regimes for a control plan. But the construction of BPN must be rebuilt under the condition of different engine control plans. Because it has a little ability of self-organization, it is difficult for BPN to isolate the engine faults quantitatively when several faults occur at the same time.

Key Words Aircraft engine Network Fault diagnosis

DYNAMIC SIMULATION OF AVIATION HIGH- SPEED ROLLER BEARINGS WITH SURFACE ROUGHNESS EFFECT

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ABSTRACT A new dynamic analysis method for high-speed roller bearings is put forward by coupling dynamic theory of high-speed roller bearing with Partial Elastohydrodynamic Lubrication (PEHL) theory. With taking the surface roughness effects of bearing components into consideration, the dynamic characteristics of high-speed roller bearings are analysed in detail. The results indicate that the surface roughness and surface roughness texture of bearing component exert a considerable influence on the dynamic characteristics of the high-speed roller bearings. The improvement of the surface manufacturing quality of the bearing components can suppress the dynamic instability of bearing components in operation. Our experimental work verifies not only our analysis, but also the conclusion made by Averbach^[1] that high-speed roller bearings operate in mixture lubrication state.

Key Words High-speed bearing Roughness effect Dynamic analysis

RESIDUAL VIBRATION FATIGUE LIFE OF COMPRESSOR BLADE DAMAGED BY FOREIGN OBJECT

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ABSTRACT The residual vibration fatigue life of TC4 plate blade subjected to Foreign Object Damaged (FOD) is investigated by means of eddy current excited vibration fatigue tests. The results show that the extent of FOD depends on both impact energy E and geometric scale S . There exists a critical damage for a given blades. Repairing of the damaged parts and lowering of the vibration stress in the blade are effective measures to improve the resistance of the blade to FOD. Moreover, the comparison of the titanium and steel blades indicates that the excessive fatigue strength of the steel blade is more than that of the titanium

one, because the designed stress is usually based on the tension strength of the blades

Key Words Blade Damage Residual Life Vibration Fatigue

SIMILARITY TRANSFORMATION OF FIGHTER ENGINE DESIGN LOADING SECTIONS

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ABSTRACT This paper deals with a similarity- transformation method for obtaining engine design loading section. The principal method of flight dynamics is used and the thrust of the engine serves as the key of the transformation. The loading sections of other similar engines can be obtained from transforming the measured section of a prototype engine with success. This method has been applied in engineering practice.

Key Words Aircraft engine Loading spectrum Similarity

NUMERICAL SIMULATION OF COMBUSTION PROCESS IN A LIQUID H_2/O_2 ROCKET ENGINE

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ABSTRACT Numerical simulation is employed in calculation of the combustion processes in the rocket engine which uses liquid hydrogen and oxygen as propellants. A random spray model is used to describe the initial conditions of oxygen droplets. The evaporation rate of the oxygen droplets at high pressure is calculated by ZKS model. The Arrhenius model is adopted to compute the chemical reaction rates. PISO algorithm extended by the authors is used to calculate the spray combustion flow. The convection terms of the governing equations are discretized by a second- order upwind scheme.

Key Words Spray combustion Algorithms Hydrogen/oxygen engines

AN EQUIVALENT MECHANIC MODEL OF DOUBLE EXTENDIBLE NOZZLE

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ABSTRACT In order to simplify the kinematics of double extendible nozzle and make it easy to calculate, its equivalent mechanic model is established with equivalent forces and masses by means of loading and kinematic analyses of its actuators and extendible cone. Then the kinematics of the complex mechanism is turned into that of equivalent components and its mechanic characteristics can be simulated and calculated.

Key Words Rocket engines Jet nozzles Physical models