

某发动机涡轮故障叶片共振相干分析与可靠性评估

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【摘要】 分析了某发动机二级涡轮叶片的振动特性、振型应力,共振特性;并结合内外场大量的频率统计数据进行了共振相干分析,分析了叶片故障原因,并提出采用限频、调频等排故措施。

主题词: 发动机 叶片 共振 可靠性估计
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某发动机二级涡轮叶片在使用中叶身疲劳断裂故障模式以叶根偏上横向折断,故障次数较多,而叶尖后缘掉块,故障次数较少。断裂叶片经断口金相检查与分析,确认为典型的高周疲劳断裂,属振动疲劳所致,对叶片进行了固有振动特性、共振转速特性分析;同时,对 30 余台发动机,近 2000 片叶片一弯静频测试数据应用威布尔分析方法进行了统计处理,并结合共振转速分析结果进行共振相干分析与可靠性评估。提出采用限频、调频等排故措施。

1 叶片振动特性计算^[1]

采用三维 20 结点等参元,计算了叶片前五阶模态的静、动频率与相应的振型应力分布等。静频与发动机常用工况下的动频,见表 1,叶片前五阶振型见图 1。

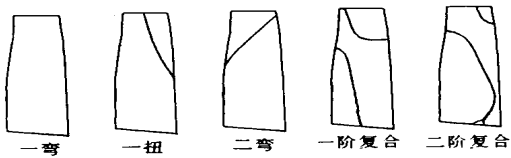


图 1 叶片前五阶振型

叶片一弯模态振型最大振型应力截面位于距叶根 10~70 毫米区间的排气边缘处,在叶盆点 A 部位。在这区间内,静强度有一定的裕度,但振型应力较大,且分布均匀。因此,只要该段内某一位置上含有原始或使用缺陷,便可构成裂纹的疲劳源,这是叶片一弯断裂分布

表 1 叶片静、动频率值(单位: Hz)

转速(r/min)	0	4100	4300	6000	8000	9700	10400	11150
一 阶	763	731	732	743	761	773	766	776
二 阶	1850	1748	1749	1756	1769	1764	1720	1728
三 阶	2757	2605	2606	2614	2628	2615	2549	2557
四 阶	3221	3202	3203	3030	3042	3024	2958	2965
五 阶	4118	3887	3888	3899	3916	3893	3795	3805

在一个区间内的原因所在。

叶片一扭模态最大振型应力截面位于叶身两个部位,一是在叶盆靠排气边缘距叶根 2/3 处,面积较大,另一处在叶背尖部靠近排气边缘处(弦长的 3/4 处),构成叶尖纵向裂纹与掉角的疲劳断裂故障,其断口走向自叶片纵向向叶根发展然后横向断裂。

2 叶片共振特性^[2]与叶片共振相干

经计算,叶片在发动机慢车到最大工况转速范围内,共有 10 个共振点,其中有 3 个危险转速;即: $n=9700\text{ r/min}$ 时, $k=5$ (后支板),叶片产生一弯共振,频率为 777 Hz; $n=10400\text{ r/min}$ 时, $k=10$ (火焰筒),叶片产生一扭共振,频率为 1733 Hz; $n=11650\text{ r/min}$ 时, (超过额定 $n=11150\text{ r/min}$), $k=4$ 与叶片一弯共振,略大于最大转速。

发动机叶片分为三齿旧叶、三齿长寿、三齿故障、三齿生产 4 种类型来分析。应用威布尔分析法,对叶片频率数据进行了分布规律的计算,其相应的参数见表 2,表中也同时给出按正态分布计算时的相应参数值。

故障机平均频率为最高 $f_c=777\text{ Hz}$, 频率分散度也最大 $\sigma=12\text{ Hz}$ 。构成共振相干条件,产生共振。长寿命机、旧叶,其平均频率为 $f_c=765\sim761\text{ Hz}$, 频率分散度还较高, $\sigma=9\sim11\text{ Hz}$ 。

表 2 叶片一弯振动频率特性(单位: Hz)

序号	类别	叶片类型	台数	叶片数	Δf	威 布 尔				正 态		
						η	β	r^2	f_c	μ	σ	r^2
1	2- B	三齿旧叶	5	317	56	761	90	0.971	756	756	11	0.986
2	2- D	三齿故障	7	220	48	782	90	1.00	777	777	12	0.980
3	2- E	三齿生产	8	498	51	779	105	0.538	775	775	10	0.982
4	3- T3	三齿长寿	4	256	42	764	114	0.81	760	761	9	0.991

注: η, β, f_c 分别为威布尔特征参数, 形状参数和均值;
 μ 和 σ 分别为正态均值和标准差, r^2 为拟合系数, Δf 为最大频率与最小频率差。

动态相干分析,就是在叶片共振转速下,将叶片动频用频率分散度形成的分布区和共振转速带分布区间两者相干,凡是有相干区,也就是说叶片的动频值落入转速带中,就有发生共振的可能,相干面积的大小表征共振发生的大小的程度。

对于 $n=9700\text{ r/min}$ 时,动态频率折合系 $k=0.706$,对于 $n=11150\text{ r/min}$ 时,动态频率折合系数 $k=0.58$,三种叶片的典型动态相干图,见如图 2(a) 和(b),相干值见表 3。

表 3 共振相干值

序号	类别	叶片类型	n= 9700 r/min k= 5				n= 11150 r/min k= 4			
			f_c	f_{De}	AI	部位	f_c	f_{De}	AI	部位
1	2- D	三齿故障	777	792	8	高端	777	784	0	—
2	3- T3	三齿长寿	761	776	0	—	761	777	0.7	低端
3	2- B	三齿旧叶	756	771	0	—	756	774	2	低端

注: f_{Dk} 和 AI(%) 分别表示动态中心频率和相关面积

相干图表明: 对于 $n=9700\text{ r/min}$, $k=5$, 一弯共振情况: 三齿故障机, 在频率分布的高端有

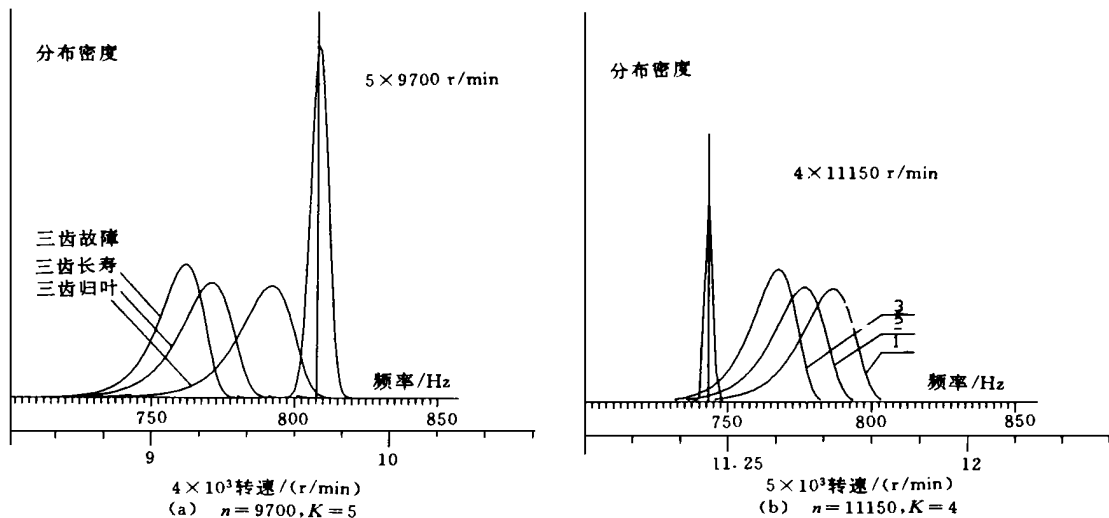


图 2 典型一弯共振相干

相干,故障机叶片面积约占 8%,三齿旧叶、长寿命机叶片无相干,因无共振。对于 $n = 11150 \text{ r/min}$, $k = 4$,一弯共振情况:原来中心频率低者,都可能落入此转速下发生共振,而原来中心频率高者,则避开此转速下的共振,也说明故障机叶片不发生在此转速下的共振。

3 结论与提高可靠性措施

(1) 叶片疲劳断裂是一弯共振所致,且发生在发动机转速为 $n = 9700 \text{ r/min}$,为 5 次谐波激励,断裂部位在叶身进排气边处,且相干面积占 8%。由于叶片频率有一定的分散度,发动机转速也有一定的转速带,有相干是叶片断裂的原因所在。(2) 长寿命叶片无相干区,说明不会产生共振。(3) 避开共振可采用限频与调频的方法。限频:仅就 $n = 9700 \text{ r/min}$,按长寿命机的频率范围来控制叶片的频率分布值就可。该叶片的高端限频值不大于 780 Hz ,对于目前大量生产的叶片,采用限频最为简便可行。调频:调频的原则是降低叶片的固有频率,使叶片中心频率下调,其调幅值为在 $2\% \sim 4\%$ 就可。

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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

out and some measures have been proposed for elimination of the failure modes.

Key Words Engines Blades Resonance Reliability estimation

FLOW VISUALIZATIONS OF FLOW FIELD IN ENDWALL REGION OF A COMPRESSOR CASCADE

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ABSTRACT

This paper describes flow visualizations of the flow field in the end-wall region of a compressor cascade. Within the cascade passage without radial clearance, it was found that many low-energy fluids exit in the corner between the suction surface and the endwall, and some vorticities of the corner vortex come from the leading edge horse shoe vortex. Tangential migration of the pressure-side horse-shoe vortex leads to flow mixing among the endwall boundary layer, suction surface boundary layer and the horse-shoe vortex. Small radial clearance leads to a weak leakage vortex that is far away from the suction surface, while large radial clearance leads to a strong one closer to the suction surface. The corner vortex is not obvious due to blowing of the leakage flow. In the endwall region, reaction among the vortices and the boundary layers result in much more flow mixing and unsteadiness.

Key Words Cascades End effects Vortex Flow visualization

EFFECTS OF BLADE CURVING ON CLEARANCE FLOW LOSSES

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ABSTRACT

Detailed experimental investigations of the flows in the cascades of conventional straight blades and positively curved ones, both with 2.3% tip clearance, were carried out in a low speed wind tunnel. The measuring planes were arranged as 4 before, 11 in 4 after the cascades and 1 in the middle of the tip clearance. Flows inside the clearance were searched in great detail with a micro five-hole pitot tube of 1mm head size and another of 5mm head size in the passage. The quite detailed information about the tip leakage flows and the flows in the cascades has been obtained, such as flow vectors, pressure and loss distributions throughout the clearance and in the passage. In comparison with the conventional straight blades, positive blade curving decreases the flow vectors within the tip clearance and also reduces the strength of the leakage vortex. As a result, the mass flux crossing the tip clearance decreased, the interaction between leakage vortex and passage vortex in the curved cascade also decreased. Thereby, the total flow losses downstream of the curved blade have been cut down by 8%.

Key Words Cascades Bending End effects Leakage Losses