第 7 卷　第 2 期　　航空动力学报　　Vol. 7　No. 2
1992 年　　4 月　　Journal of Aerospace Power　　Apr.　1992

压气机叶片的损伤容限研究

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【摘要】　本文用断裂力学方法对压气机和风扇转子叶片作损伤容限分析。采用 20 节点立体元对叶片作应力场和位移场计算, 用裂纹表面位移法求解裂尖应力强度因子 K_{I}、K_{II} 及 K_{III} 随裂纹长度 a 变化的关系。根据叶片材料的断裂韧性 K_{IC}、叶片径向伸长量 δ_c 以及自振频率偏移量 f_c 值来确定转子叶片失效的准则及临界裂纹长度 a_c 值。利用 Paris 公式并考虑到高周振动应力对低周疲劳裂纹扩展的影响求得叶片的损伤容限寿命 N_f。文中给出了某压气机叶片的算例。为了研究自振频率随裂纹长度变化的关系, 进行了叶片振动实验

一、裂纹尖端应力强度因子计算

本文采用有限元与裂纹表面位移法相结合求解叶片的应力强度因子。这种方法在工程上应用比较简便, 精确度较好。根据有限元计算结果, 可得裂纹面上各节点在 x、y 及 z 轴方向的位移分量 u、v 及 w (图 1)。在裂纹尖端附近, 当取裂纹表面上的节点作分析时 ($\theta = \pi$), K_{I}、K_{II} 及 K_{III} 对 u、v 及 w 的关系式为:

$$\left.\begin{aligned} u &= (2K_{\mathrm{II}}/G)\sqrt{r/2\pi}(1-\mu) \\ w &= (2K_{\mathrm{I}}/G)\sqrt{r/2\pi}(1-\mu) \\ v &= (2K_{\mathrm{III}}/G)\sqrt{r/2\pi} \end{aligned}\right\} \tag{1}$$

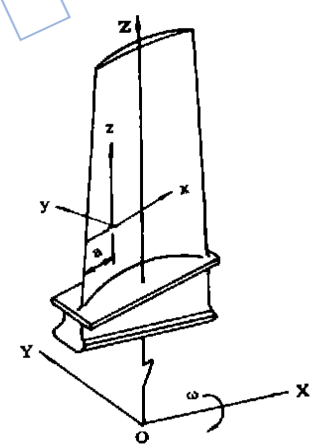

图 1　压气机转子叶片

式中 G 为材料的剪切弹性模量, μ 为泊桑比。将裂纹表面上座标为 r 处节点的位移分量 u、v 及 w 值代入 (1) 式, 可求得该节点的 $K_{\mathrm{I}}(r)$、$K_{\mathrm{II}}(r)$ 及 $K_{\mathrm{III}}(r)$ 值, 取裂纹表面上不同 r 处各节点的应力强度因子值拟合成 $K_{\mathrm{I}} \sim r$、$K_{\mathrm{II}} \sim r$ 及 $K_{\mathrm{III}} \sim r$ 三条曲线, 并用外推法求得 $r=0$ 处的 K_{I}、K_{II} 及 K_{III} 值, 即为该裂纹长度 a 的应力强度因子值。实际经验表明, 除了叶尖由于共振而断裂以外, 叶身上的裂纹大都沿着与径向应力 σ_z 的垂直方向扩展, 这主要是由于 σ_z 值远远大于 τ_{zx}、τ_{zy} 的缘故。因此叶身上水平方向的裂纹 I 型的作用最大, I、II 型的作用很小。取不同的裂纹长度 a, 用上述方法重复计算, 可得 $K_{\mathrm{I}} \sim a$、$K_{\mathrm{II}} \sim a$、$K_{\mathrm{III}} \sim a$ 三曲线。考虑到裂尖塑性区的影响, 应对应力强度因子 K_{I} 进行修正。取等效裂纹长度 $\bar{a}$ 为

$$\bar{a} = a + r_y \tag{2}$$

式中 $r_y = (1/6\pi)(K_{\mathrm{I}}^2/\sigma_s^2)$。利用 $\bar{a}$ 值及 $K_{\mathrm{I}} \sim a$ 曲线可得修正后的 $K_{\mathrm{I}} \sim a$ 曲线。

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二、叶片失效准则及裂纹扩展寿命

1. 叶片失效准则　对于压气机转子叶片，当裂纹扩展后判断其失效的准则有三方面：

材料的断裂韧性 K_{IC}　即当 $K_{Ieq} \geq K_{IC}$，这时叶片裂纹失稳扩展。K_{Ieq} 为当量应力强度因子，当 K_{II} 及 K_{III} 比 K_I 小得多时，根据能量原理[1]

$$K_{Ieq} = \{K_I^2 + [(9-8\mu)/(5-8\mu)]K_{II}^2 + [8/(5-8\mu)]K_{III}^2\}^{0.5} \tag{3}$$

叶片径向伸长量 δ　当叶身裂纹扩展后，由于裂纹表面张开位移将使叶尖径向伸长量增大，影响叶尖与机匣之间径向间隙。为了防止转子叶片擦伤机匣，对叶片尖端径向伸长 δ 值有限制，即 $\delta \leq \delta_c$，式中 δ_c 为由于裂纹张开的叶尖伸长量容限值。

叶片自振频率偏移值 Δf_c　叶片的自振频率随着裂纹长度 a 的增长而下降，本文第四节对此作了专门研究。为了防止危险共振，应对叶片的自振频率偏移量给一容限值 Δf_{co} 叶片频率下降相对值 Δf 为：

$$\Delta f = [(f_o - f_a)/f_o] \times 100\% \tag{4}$$

因此 $\Delta f \leq \Delta f_{co}$ f_o 为叶片无裂纹时的自振频率，f_a 是裂纹长度为 a 时的自振频率。当 Δf_c 给定时，通过实验所测得的 f_a 值即可确定临界裂纹长度 a_c。

临界裂纹长度的确定　根据以上三方面分析结果所得的三个临界裂纹长度值是不同的。显然，为了确保安全，应取其中最小的裂纹长度作为临界值 a_c。

2. 低周疲劳裂纹扩展　裂纹扩展速率的 Paris 表达式为 $da/dN = c(\Delta K_I)^n$，c 及 n 为材料常数。对于复合型裂纹，可近似地用 ΔK_{Ieq} 代入上式进行计算[1]，因此疲劳裂纹扩展寿命

$$N = \sum_{a_o}^{a_c} \frac{\Delta a}{c(\Delta K_{Ieq})^n} \tag{5}$$

3. 高周振动应力对裂纹扩展寿命的影响　高周振动应力的影响十分复杂，它与低周的应力强度因子幅值 ΔK 大小、高周与低周的应力幅值比 Q、高周振动的频率值及材料性质等因素有关。由于问题的困难程度，目前主要依靠实验手段来研究。Powell 等人的研究表明，考虑到高周振动应力的影响，裂纹扩展速率将以数十倍甚至于成百倍增大（表 1）[2]。为了精确地对叶片作寿命予估，应对叶片作振动应力实测以及高低周疲劳裂纹扩展的耦合实验，根据实验结果对（5）式中的 c 系数作修正。

表 1　高周振动对裂纹扩展速率的影响（$\Delta K = 35\mathrm{MPa}\sqrt{m}$，$Q = 0.117$）

每一低周循环中的高周循环数	1	10	100	1000	10000	100000	1000000
裂纹扩展速率 (mm/低循环)	1.2×10^{-3}	1.2×10^{-3}	1.3×10^{-3}	2.3×10^{-3}	1.3×10^{-2}	1.2×10^{-1}	1.2

三、某压气机转子叶片计算实例

某压气机转子叶片，工作转速 $n_{max} = 11000\mathrm{rpm}$，材料为 1Cr11Ni2WMoVA，$K_{IC} = 3700\ \mathrm{N/mm^{2/3}}$[3]。取叶身作作应力分析，采用 20 节点三维等参元（图 2）。考虑到叶片的最危险状态，取飞行中最大气体力状态作计算。计算结果表明，进气边的应力水平比排气边的大。进气边的最大应力位于 $R = 304.22\mathrm{mm}$ 处，最大当量应力值为 $\sigma_e = 184.07\mathrm{N/mm^2}$。假定裂纹起始于该点，并沿着与 σ_e 的垂直方扩展。由于裂纹面的局部坐标轴 x、y 与叶片的总体坐标轴 X、

Y 之间的夹角为 $\alpha=52.58°$。按总体坐标系计算所得的裂纹面位移分量 U、V 应转换为对应于局部坐标系的位移分量 $u=U\cos\alpha+V\sin\alpha$，$v=-U\sin\alpha+V\cos\alpha$。将 u、v 及 w 值代入 (1) 式求得 K_{I}、K_{II} 及 K_{III}，并用 (2) 式对 K_{I} 作修正。图 3 为裂尖应力强度因子随裂纹长度 a 变化的曲线。图上还给出按 (3) 式计算的 K_{Ieq} 曲线及 K_{IC} 值。可见，当 $a=39.5$mm 时，$K_{\mathrm{Ieq}}=K_{\mathrm{IC}}$，这时裂纹失稳迅速扩展（弦宽为 $b=86.17$mm），将使叶片彻底破坏。图 3 上还给出了由于裂纹面张开位移所造成的叶尖附加径向伸长量 δ 的曲线。通常叶片尖端的径向间隙值控制得十分严格，现取容限值 $\delta_c=0.05$mm，可得临界裂纹长度为 19.4mm。

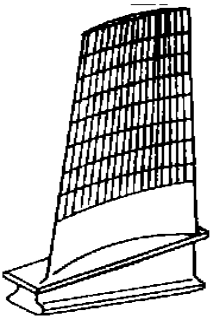

图 2　叶片有限元网格

根据第四节的实验结果，限制自振频率的偏移量 $\Delta f_c=0.5\%$，即 $a/b=0.06$。因 $b=86.17$mm，得临界裂纹长度为 5.17mm。

比较以上三种不同的失效方式的临界裂纹长度值，可知应取自振频率的偏移量作为叶片失效判据。即临界裂纹长度 $a_c=5.17$mm。

1Cr11Ni2WMoVA 是一种不锈钢，Weber 等人的实验结果表明[4]，各不锈钢的裂纹扩展速率基本相同，可以用下式估算不锈钢在室温、空气环境中的疲劳裂纹扩展速率：

$$da/dN=3.0\times10^{-10}(\Delta K)^{3.25} \qquad (6)$$

式中 a 的单位为 in，K 的单位为 Ksi $\sqrt{\text{in}}$ ($1\text{Ksi}\sqrt{\text{in}}=34.76\text{N}/\text{mm}^{2/3}$)。将 (6) 式的系数 $c=3.0\times10^{-10}$ 及 $n=3.25$ 代入 (5) 式，并取 $a_o=0.5$mm，经单位换算后得裂纹长度 a 随循环次数变化的曲线 (图 4)。当取 $a_c=5.17$mm 时，可得循环寿命 $N_f=2.95\times10^5$ 次。

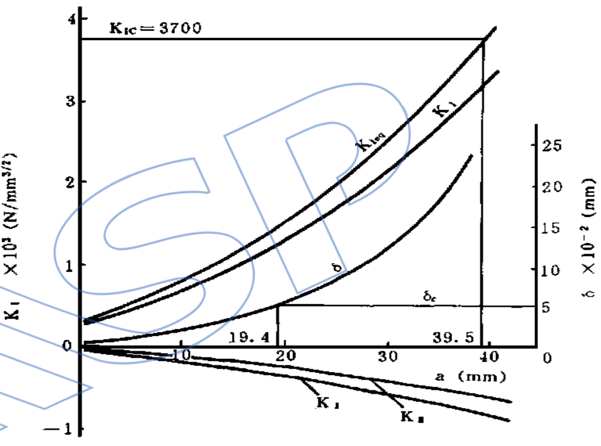

图 3　应力强度应子随裂纹长度的变化

关于高周振动对叶片寿命的影响，由于缺乏实测叶片振动载荷谱数据，无法作较精确估算。现参照表 1 的经验数据取高低周应力比为 $Q=0.117$ 作初步估计：假定每一低循环中包含有 10^5 次高周振动，则循环寿命降为 $N_f=2950$ 次，而当假定每一低循环中包含有 10^6 高周振动时，循环寿命仅为 $N_f=300$ 次。可见高周振动对叶片裂纹扩展寿命的影响是重要的。

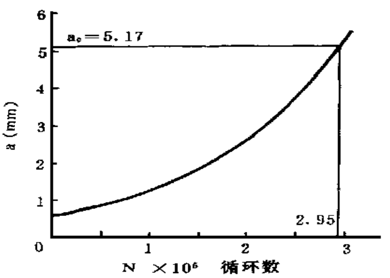

图 4　叶片裂纹扩展寿命曲线

四、叶身裂纹扩展的自然振动频率实验

为了研究裂纹扩展之后叶片自然振动频率的变化，取某压气机第 1 级（不锈钢）叶片及第 4、5 级（铝合金）叶片共五件作振动实验。由于叶片根部截面的削弱对低阶自振频率的影

响最明显，在各叶片的进气边或排气边距叶根 10mm 处用薄锯片分别予制出不同长度的裂纹。用专门的燕尾形槽夹具将叶片榫头紧固，按共振原理测出各叶片试件的一弯、二弯、一扭的静频 f_{1B}、f_{2B}、f_{1T} 值（表 2）。实验表明，当叶片上的裂纹长度 a 与弦宽 b 之比值 $a/b \leq$

表 2　叶片在不同裂纹长度 a 时的自振频率 f_{1B}、f_{2B}、f_{1T} 的实验值

试件	材料	裂纹位置	裂纹长度 a (mm)	相对裂纹长度 a/b	f_{1B} (Hz)	f_{2B} (Hz)	f_{1T} (Hz)
1	不锈钢	进气边	0	0	175	545	1092
			1.268	.019	175	544	1092
			3.557	0.054	174	544	1092
			5.029	0.077	174	544	1091
2	铝合金	进气边	0	0	536	2214	1720
			1.355	0.034	535	2214	1720
			3.743	0.094	531	2205	1705
			5.060	0.128	524	2198	1698
3	铝合金	排气边	0	0	526	2204	1741
			1.077	0.027	526	2204	1741
			3.828	0.095	523	2192	1730
			5.196	0.130	520	2188	1724
4	铝合金	排气边	0	0	574	2522	1692
			1.056	0.029	573	2516	1690
			3.580	0.099	567	2501	1680
			5.510	0.153	560	2490	1675
5	铝合金	排气边	0	0	593	2600	1710
			1.055	0.029	593	2598	1709
			3.560	0.097	590	2597	1697
			5.388	0.148	587	2590	1680

0.06 时，不锈钢叶片的静频 f_{1B}、f_{2B}、f_{1T} 均基本上保持不变。对于铝合金叶片，不论裂纹位于进气边或排气边，其 f_{1B}、f_{2B}、f_{1T} 下降的相对值 $\Delta f \leq 0.5\%$。

结论　(1) 压气机转子叶片的形状及载荷比较复杂，采用三维等参元和裂纹面位移法相结合，求解应力强度因子 K_{I}、K_{II}、K_{III} 十分有效。(2) 根据压气机的具体工作条件，当叶身上的裂纹扩展时，应采用材料的断裂韧性、叶尖附加径向伸长量容限值及叶片自振频率偏移容限值三种方法作为叶片失效的判据。(3) 叶片的低周（指发动机转速自零到最大转速再回零的循环）疲劳对裂纹的扩展寿命影响不大。由于叶身的应力水平往往设计得比较低，低周疲劳裂纹扩展得比较慢。然而，在迭加上高周振动应力的影响后，叶片裂纹将迅速扩展，使寿命明显下降。因此高周振动是决定叶片裂纹扩展寿命的重要因素。从损伤容限设计考虑，必须改善叶片的振动特性。在自振频率一定的条件下，应减小强迫振动的激振力、增加叶片抗振阻尼的性能，尽可能使振动应力减小，以提高叶片寿命。

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fringe pattern, it is possible to subtract two time average pattern at any given frequancy. In result, the fringe pattern is obtained with high visibility but only valid at the given frequency. A phase shifting technique is adopted to overcome this shortcoming. A time average image is put into processor and frame store (renewed and put into processor per 40ms), then a subsequent image with a phase shift of ΔΦ resulted from sinusoidal modulation in object beam is recorded and subtracted from the first image. This method is similar to modulation of light intensity function of speckle pattern. The advantage of this method is the capabilities of obtaining real time fringe pattern of vibration with high resolution and of performing frequency scanning at a wide range. Its application to the vibration pattern measurement of disk-blade coupling in an aeroengine is a great success

ANALYSIS OF TENON AND MORTISE CONTACT PROBLEMS BY BOUNDARY ELEMENT METHODS

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ABSTRACT The boundary element equations of 2-D elastic contact problems are established by the incremental principle and some concrete approaches to solution of the contact procedure are considered. The contact stresses of the dove tail and the pine tree joints of the disk/blade assembly are numerically analyzed. From the comparsion of the numerical results of boundary element methods (BEM) with those of FEM and photoelasticity experiments it is concluded that the results of BEM are satisfactory in contrast with FEM, the BEM not only simplifies data preparation but also gives the results of the same accuracy level with fewer discrete elements and saves the computer time tremendously.

A COMPOUND FATIGUE INVESTIGATION OF PLATE SPECIMEN UNDER LOW-CYCLE LOAD SUPERPOSED ON HIGH CYCLE LOAD

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ABSTRACT According to real operating conditions of turbine-engine blades in service, a series of combination tests of various load matching and frequency matching for plate specimens was carried out on the compound fatigue testing rig which can simulate operating loads on the blades. From the test results and theoretical analyses, some characteristics and the regularities of this compound fatigue are obtained. A new method of life prediction for this compound fatigue is presented in this paper. The calculated results of this method are in good agreement with the experiments

RESEARCH ON DAMAGE TOLERANCE OF COMPRESSOR BLADE

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ABSTRACT This paper discribes the damage tolerance analysis of compressor blade by fracture mechanics. Finite element method with 20-nodes solid elements is used for the stress calculation. A displacement method is provided to determine the stress intensity factors K_{I}, K_{II} and K_{III} versus crack length a of the blade. Based on the material toughness

K_{IC}, additional extension δ_c and deviation of natural frequency f_c of the cracked blade, the failure criterion of the compressor blade is discussed and the critical crack length is determined. By the use of Pris formula and in consideration of the influence of high cycles on low cycle fatigue crack propagation, the damage tolerance life of the blade is obtained. As an example, a calculation of a certain compressor blade is given. In order to investigate the relation of natural frequency versus crack length, the vibration of compressor blades has been tested. The presented method can be used for the strength evaluation of turbo-jet engine.

FINITE ELEMENT ANALYSIS OF COMPLEX DISK BODY WITH ECCENTRIC HOLE

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ABSTRACT A strategy of discretization process for the 3-D disk body of complex cross-section has been developed on the basis of available functions of I-DEAS system. The cutting and mending techniques are employed to realize the mesh formation at the local regions of eccentric holes. In result, it is possible to solve effectively the contradiction between element distortion and over-large scale of solution, and thus the 3-D analysis of the disk with eccentric hole can be completed at one time. Also in this paper an engineering optimum method is provided by adjusting the thickness of the disk so as to control the stress level at the edge of holes.

HOLOGRAPHIC VIBRATION MEASUREMENT OF DISC-BLADE COUPLING IN HIGH-SPEED ROTATION

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ABSTRACT A new measuring technique is presented which combines holographic interferometry and image derotation to determine the behaviour of disc-blade coupling vibration during high-speed rotation. The measuring technique and its optical system have been verified by the test of a model circular disc. The primary test results of a real disc-blade coupling are given which show the obtained holograms of rotating members to correspond to the results of vibration theory analysis and frequency spectrograms. Therefore, it is possible to expect this technique to be an effective testing measure for aeroengine designing and troubleshooting.

RESEARCH ON HIGH-LOW CYCLE COMPLEX FATIGUE AND ACCUMULATIVE DAMAGE FOR Ti-ALLOY TC11

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ABSTRACT The high-low cycle complex fatigue behaviours of Ti-alloy TC11 were researched systematically at room and elevated temperatures. At the same time, the effects of complex stress ratio m, test temperature and prestress overload for SEN specimen on complex fatigue life N_{fL} were taken into consideration. The work comes to the conclusion that: The complex fatigue life decreases obviously with m increased, especially when m = 35%, the N_{fl} decreases more than 10 times, and there occurs a knee on the m —logN_{fL} curve near m = 10%. The complex fatigue of the alloy TC11 is very sensitive to test temperature