THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47th St., New York, N.Y. 10017

94-GT-379

DAMAGE TOLERANCE ANALYSIS OF COMPRESSOR BLADE

Jinxin Mao
Beijing Research Centre of Aeronautics Technology
Beijing, China

Qilin Hong, Rongqiao Wang, and Mingda Hua
Jet Propulsion Department
Beijing University of Aeronautics and Astronautics
Beijing, China

ABSTRACT

In this paper, we apply damage tolerance analysis to a certain compressor blade by finite element and fracture mechanics methods. The blade is analysed by using the isoparametric finite element with 20 nodes, its stress and displacement fields are determined, and the critical position where the crack probably initiates is located.Then the value of J–integral with different crack sizes in the critical position are computed using the 3–D J–integral program.On the basis of the fracture toughness of blade material,J_c, the blade extension limit , δ_c, and the deviation of natural frequency, $\triangle f_c$, the failure criterion of the blade is discussed and the critical crack size, a_c, is determined. Then according to the crack growth rate obtained from the testing, the residual life of the blade with different crack sizes is evaluated.The maximum allowable crack size,a_0^* , is determined using the condition that the crack would not grow to critical crack size during double overhaul periods.This value can be used to design the structure of compressor blade or to establish the criterion to judge whether a compressor blade with a crack can be used.In this way the safety and reliability of airplanes is maintained and the costs are reduced.So the damage tolerance analysis of compressor blades is practical and economical.

THE J–INTEGRAL OF CRACKED COMPRESSOR BLADE

The 3–D J–integral in centrifugal force field can be expressed[1]:

$$J=\int_\Gamma [W dy - T_i \frac{\partial u_i}{\partial x} ds) - \iint_A \frac{\partial}{\partial z}(\sigma_{i3}\frac{\partial u_i}{\partial x})dA - \iint_A F_i \frac{\partial u_i}{\partial x} dA \quad i=1,2,3 \qquad (1)$$

The combination of the finite element method (FEM) with the J–integral method is provided to determine the J–integral value of the crack tip.

The FEM form of the 3–D J–integral can be expressed:

$$J=\sum_\Gamma [W\triangle y-(T_x\frac{\partial u}{\partial x}+T_y\frac{\partial v}{\partial x}+T_z\frac{\partial w}{\partial x})\triangle s - \sum_A(\frac{\partial}{\partial z}(\sigma_{xz}\frac{\partial u}{\partial x}+\sigma_{yz}\frac{\partial v}{\partial x}+\sigma_z\frac{\partial w}{\partial x})]\triangle x\triangle y - \sum_A(F_x\frac{\partial u}{\partial x}+F_y\frac{\partial v}{\partial x}+F_z\frac{\partial w}{\partial x})\triangle x\triangle y \qquad (2)$$

Where we set the origin of the coordinates at the crack front edge.and the axes of coordinates are the principle normal,subnormal and tangent of the point,respectively.W is the density of strain energy, T_x,T_y *and* T_z are the stress on the segment $\triangle S$, which is the microelement of the contour Γ, F_x, F_y *and* F_z are the centrifugal forces per unit volume.

Finite element method is used for the calculation of

Presented at the International Gas Turbine and Aeroengine Congress and Exposition
The Hague, Netherlands — June 13–16, 1994

each unknown value versus crack length,a,on the right side of eq. (2), then the values of J are obtained,the curve of J ~ a is obtained as well.

For the influence of plastic zone at the crack tip, the J–integral should be corrected. Using the Bucci method[1], the equivalent crack length a_{eff} is obtained, J_p can be obtained from a_{eff}.

Where

$$a_{eff} = a + r_y \quad (3)$$

$$J_p = J_E(1 + \frac{r_y}{a}) \quad (4)$$

$$r_y = \frac{J_E E'}{\beta \pi \sigma_y^2} \quad (5)$$

$E' = E, \quad \beta = 2$ *for plane stress*

$E' = \frac{E}{(1 - \upsilon^2)}, \quad \beta = 6$ *for plane strain*

Where E is Young's modulus,υ is Poisson's ratio and σ_y is yield stress.

THE FAILURE CRITERION OF COMPRESSOR BLADE

For rotating compressor blade,three theories are disscussed to determine its critical crack size.

Fracture toughness of J_C

From the theory of fracture mechanics,we know the crack propagates when the value of J–integral is equal to the critical value,J_c,When $J > J_c$,the crack of the blade will propagate unstably.

Radial extension of the cracked blade δ_c

After the crack propagates,because of crack opening displacement by the centrifugal force,the radial extension on blade tip will increase,and influence the clearance between the blade tip and the case.In order to prevent the rotating blade from scratching the case, the blade tip radial extension, δ_c,should be limited,That is $\delta < \delta_c$,where δ_c is the blade tip extension tolerance because of the crack openning.

Deviation of natural frequency of cracked blade $\triangle f_c$ [2].

Based on the experimental data,the natural frequency of cracked blade will drop when the crack length increases.To avoid blade resonance,the tolerance deviation of natural frequency of the blade $\triangle f_c$ should be given,The relative decrease in the frequency is:

$$\triangle f = \frac{f_0 - f_a}{f_0} \times 100\% \quad (6)$$

So $\triangle f < \triangle f_c$,where f_0 is the natural frequency of normal blade and f_a is that of the blade with crack length a.

LIFE OF FATIGUE CRACK PROPAGATION AND MAXIMUM ALLOWABLE CRACK SIZE

The J expression of crack propagation rate is $da / dN = C\ (\triangle J)^r$, C and r are the material constants. $\triangle$J is J–integral range.The crack propagation life can be obtained as follows:

$$N = \int_{a_0}^{a_c} \frac{da}{C(\triangle J)^r} \quad (7)$$

Where a_0 is initial crack length and a_c is critical crack length.From eq. (7) we can get the relationship of a versus N. If we know the overhaul period of the engine.the maximum allowable crack size a_0^* is determined at the condition that the crack would not grow to final crack length during double overhaul periods.

THE DAMAGE TOLERANCE ANALYSIS OF A COMPRESSOR BLADE

The maximum engine speed is $n_{max} = 13028rpm$,the material of rotating blade is TC11 (a kind of titanium alloy) and the fracture toughness $J_C = 42.5KJ/m^2$[3].Finite element method with 20 noded solid element is used for the stress and displacement of the blade under centrifugal and gas forces.The mesh of the blade is shown as fig 1.From the stress calculation,we can know that the stress level of the front edge is larger than that of rear edge. The maximum equivalent stress of front edge $\sigma_e = 21.6Kgf/mm^2$.Assuming that crack initiate at this point,and propagate in the direction of σ_z (mode I), the J–integral is calculated. The curve of the J–integral versus the crack length, a, can be seen in Fig. 2. When $J = J_c$, the critical crack length $a_{1C} = 22.7mm$ is obtained.If $\delta_c = 0.05$mm is given,when $\delta = \delta_c$,the critical crack length $a_{2C} = 15.5mm$ is obtained. Based on the experimental result, the limited deviation of natural frequency $\triangle f_c = 0.5\%$ is *selected*[4], and a / b = 0.06 is determined. Here the string length of blade, b = 49.9mm, now $a_{3C} = 3mm$ is obtained.

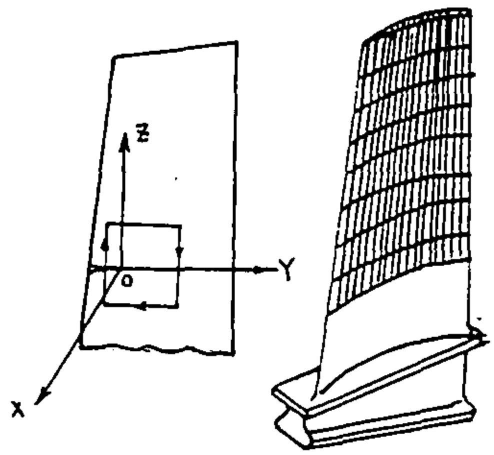

Fig. 1 The mesh of the blade

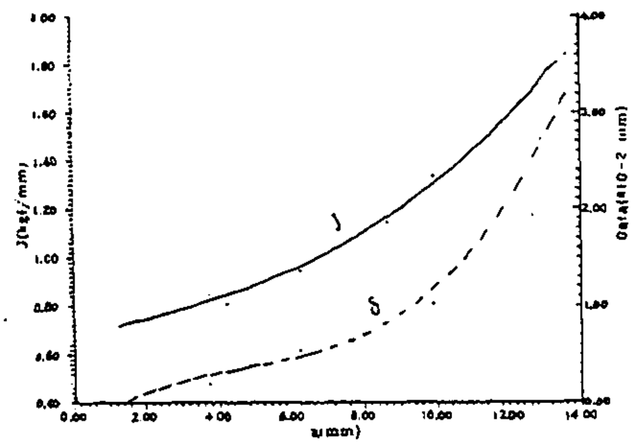

Fig. 2 The curve of J–Integral and δ versus a

Comparing three different critical crack lengths, a_{1C}, a_{2C} and a_{3C}, the deviation of natural frequency of the blade should be taken as the failure criterion of the blade. Then the real critical crack length is determined as $a_c = 3mm$.

After the J–value of different cracks size are computed, it is converted to value of K.As suming $a_0 = 0.25mm$, experimental result shows that the propagation rate of the material of TC11 can be expressed as $da / dN = 1.0790 \times 10^{-1} (\triangle K)^{3.0605}$ [3]. Applying eq. (7),we can get the relationship of crack length,a,versus the number of cycle, N[5] (see Fig. 3).

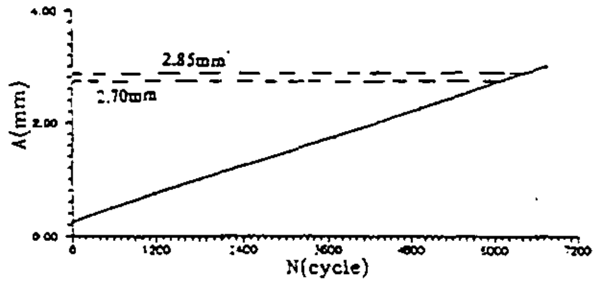

Fig. 3 Crack propagation life

Because 100 hours of the engine use results in 167 "Zero–Max–Zero" cycles, we now get the relationship of a versus t, see Fig. 4.

Assuming that the overhaul period of engine is 100 hours, The maximum allowable crack length is obtained as 2.85mm at the condition that the crack would not grow to final crack length during double overhaul period. If the overhaul period is 200 hours, so $a_0^* = 2.7mm$.

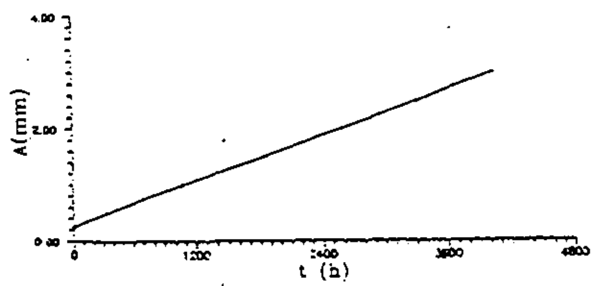

Fig. 4 The curve of a versus t

CONCLUSION

(1) Due to the complex geometries and loading conditions in compressor blade, the combination of 3–D FEM with J–integral method can be used to obtain the J–integral

of the compressor blade in the critical location.

(2) When the crack in the blade propagates, material fracture toughness,additional extension or the deviation of natural frequency of the cracked blade can be used to determined critical crack size.

(3) The maximum allowable crack size a_0^* can be used to establish the criterion to judge whether the safety and reliability of engine was assured and cost was reduced.

REFERENCES

[1] Jinxu Nie, Qilin Hong, "Fracture MechanicsTheory and Application. in Aeroengines", 1985.

[2] Xue Shifeng, "On the Closure of I−II Mixed Mode Crack", Proceedings of the IV Conference of ASIAN–PACIFIC Congress on Strength Evaluation, pp. 1036–1041, 1991.

[3] Aeronautics Material Institute, "Material data handbook", Aeroengine general corporation, 1979.

[4] He Yong, "Vibration Test Research of Compressor Blade", Master's Dissertation, 1986.

[5] Weber J. H. and Hertzberg R. W., "Effect of Thermomechanical Processing on Fatigue Crack Propagation",Metallurgical Transactions, 4, Feb,1973.