Evaluation of stress intensity factor for turbine blade using finite element method

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ABSTRACT

Gas turbines are used in trains, ships, tanks, and alongside steam turbines and in power stations to generate power. During every start-up and shutdown of an aviation gas turbine, the compressor blades are subjected to centrifugal, gas bending and vibratory loads. This repeated loading and unloading can reduce the life of compressor blades. With blading problems accounting for as many as 42 percent of the failures in gas turbines. Previous works on compressor blades have focused mainly on fatigue life estimation in the vicinity of foreign object damage. Geometric modeling of the blade was done using CAD tool CATIA. Static stress analysis was carried out to ascertain the critical region or crack zone of the blade. The maximum Von-Mises stress was found at the fillet region near the root of the blade. The results of Finite element analysis showed that maximum von-Mises stress was found at the 12 o’clock fillet region due to the influence of centrifugal stresses. The maximum Mode I stress intensity factor of 61.4 Mpa√m was found at the surface interception point, for a crack length of 6mm and crack depth of 2.4mm. With the increase in rotational velocity of 5000 rpm, 10000 rpm and 20000 rpm, Fatigue crack length growth rate was estimated to be 1.95 x 10^{-9}, 1.65 x 10^{-7} m/cycle and 4.15 x 10^{-6} m/cycle and the fatigue crack propagation life was estimated to be of 4.3 x 10^{8} cycles, 7.3 x 10^{6} cycles and 5 x 10^{3} cycles respectively.

Keywords: Gas turbines, foreign object damage, Crack zone.

1. INTRODUCTION

The gas turbine is an internal combustion engine that uses air as the working fluid. The engine extracts chemical energy from fuel and converts it to mechanical energy using the gaseous energy of the working fluid (air) to drive the engine and propeller, which, in turn, propel the airplane. A Gas compressor is a mechanical device that increases the pressure of a gas by reducing its volume. Compressors are similar to pumps: both increase the pressure on a fluid and both can transport the fluid through a pipe. As gases are compressible, the compressor also reduces the volume of a gas. As shown in figure 1.1, the compressed gases expand over the turbine blades.

Axial compressors can have high efficiencies; around 90% polytrophic at their design conditions. However, they are relatively expensive, requiring a large number of components.
A conventional gas turbine cycle consists of pressurizing a working fluid (air) by compression, followed by combustion of the fuel; the energy thus released from the fuel is absorbed into the working fluid a heat as shown in figure 1.1. The working fluid with the absorbed energy is then expanded in a turbine to produce mechanical energy, which may, in turn, be used to drive a generator to produce electrical power. Unconverted energy is exhausted in the form of heat which may be recovered for producing additional power.

[1] The efficiency of the engine is at a maximum when the temperature of the working fluid entering the expansion step is also at a maximum. This occurs when the fuel is burned in the presence of the pressurized air under stoichiometric conditions. [2]

1.1 Introduction to Compressor Blade:

Axial-flow compressors are dynamic rotating compressors that use arrays of fan-like airfoils to progressively compress the working fluid. They are used where there is a requirement for a high flow rate or a compact design. Compressor blade is variously made by forging, extrusion or machining. All production blades, until recently, have been made from Type 403 or 403 Cb (both 12 Cr) stainless. During the 1980s, a new compressor blade material, GTD–450, a precipitation hardened, martensitic stainless steel, was introduced. Compressor blades made of titanium alloy are most widely used.

1.2 Fatigue crack propagation:

Stage I: Once initiated, a fatigue crack propagates along high shear stress planes (45 degrees), as schematically represented in Fig.1.2. This is known as stage I or the short crack growth propagation stage.

The crack propagates until it is decelerated by a microstructural barrier such as a grain boundary, inclusions, or pearlitic zones, which cannot accommodate the initial crack growth direction.

Stage II: When the stress intensity factor $K$ increases as a consequence of crack growth or higher applied loads, slips start to develop in different planes close to the crack tip, initiating stage II

Stage III: Finally, stage III is related to unstable crack growth as $K_{\text{max}}$ approaches $K_{\text{IC}}$. At this stage, crack growth is controlled by static modes of failure and is very sensitive to the microstructure, load ratio, and stress state (plane stress or plane strain loading).

The failure of cracked components is governed by the stresses in the vicinity of the Crack tip. The singular stress contribution is characterized by the stress intensity factor $K$. Stress intensity factors depend on the geometry of the component and on the special loading conditions (tension, bending, thermal stresses...). A procedure for their determination is the weight function technique where the weight functions are only dependent on the crack geometry.
1.3 Literature Review:

The purpose of this literature review is to provide background information on the issues to be considered in this project and to emphasize the relevance of the present project work.

1.3.1 Review of Selection of Critical Region for Crack Initiation:

The area of the maximum stress was located on the convex blade surface. The crack was initiated from the convex surface of the blade profile, about 6mm above the blade locking piece. The crack front shape just after the initiation was close to circular. In order to predict crack growth stress intensity factor was evaluated at each crack front. [3]

The critical stress value is selected based on the maximum principal stress criterion proposed by Erdogan and Sih. The maximum principal stress value at each step is calculated and the position of the stress is determined on the boundary. [4, 5]

Many theories like maximum strain energy criteria, maximum strain energy release criteria and maximum stress energy are used for determination of critical region. But for crack initiation Maximum circumferential stress criterion was considered. [6, 7]

1.3.2 Review of Crack Geometry:

The crack growth simulations in FRANC3D an initial flaw on the surface or within the body of blade attachments was introduced into the model. In that investigation, two different types of cracks are simulated: A corner crack (90° with a constant crack radius) and a side flaw with an elliptical profile. [8]

![Illustration of a semi-elliptical surface crack in a plate under bending](image)

**Fig 1.3 Illustration of a semi-elliptical surface crack in a plate under bending**

1.4 Problem Definition:

Cracks appear in axial flow gas turbine compressor blade due to varying loading condition, foreign object damage and high-stress concentration. Hence the behaviors of these crack need to be studied in order to determine the growth of the crack and to predict the fatigue life of the blade. This problem was solved using finite element analysis as other techniques such as analytical, experimental which needs the new mathematical model and appropriate equipment to solve this kind of problem thus increasing the cost and time to solve these kinds of problems. This project work aimed to find a critical region or crack zone and predict fatigue crack growth and crack propagation life.

1.5 Motivation for the Study:

Aerodynamics and structural mechanics have had a significant impact on the development of airplanes and flight vehicles. Among the many components of a modern jet engine, (or turbo machine), its blades (fan blades, turbine blades, compressor blades etc.) are especially important. Compressor blades experience vibrations during rotation, leading to stresses and strains that can cause significant and expensive damage to the engine. Both centrifugal and aerodynamic forces and their attendant vibrations, also have significant effects on the blade. If a problem arises in the compressor section it will significantly affect the whole engine function and, of course, the safety of the aircraft. The broken blade could cause the puncture of the engine casing. Failures of any high speed

1.5 Main Objective:

The main objective of the project is to determine fatigue crack growth rates and crack propagation life for various three-dimensional crack depths in axial flow compressor blade. For achieving the objective, three-dimensional modeling of the geometry of the compressor blade was done using CAD tool CATIA. ANSYS mesh tool was used for generating the mesh of the analysis model. ANSYS commercial code was used for static stress analysis.

2. GEOMETRIC MODELLING

Three-dimensional geometry of the compressor blade is modeled using CATIA tool. CAD model of the first stage of axial flow compressor blade is shown in figure 2.1.
3. FINITE ELEMENT MODELING

This step consists of generating a mesh for the given continuum and then defining loads and boundary conditions. Symmetry conditions cannot be used and the whole 3D model of the compressor blade is to be modeled.

3.1 Mesh details

The meshing of the shaft was performed by Ansys mesh tool. Meshed Model of the blade is as shown in figure 3.1. The meshing of the blade is done using tetrahedral elements. Because of the non-axis symmetric loading conditions on the blade, three-dimensional meshing was done. Fracture module method for crack generation required that elements be of higher order. Therefore out of choice of tetrahedral and hexahedral elements, tetrahedral elements of type SOLID 186 were chosen for accurate results. Also fracture module used for crack generation requires that all of the elements be either hexahedral or tetrahedral. SOLID186 is a higher order 3-D 20-node solid element that exhibits quadratic displacement behavior. The element is defined by 20 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions. The element supports plasticity, hyperelasticity, creep, stress stiffening, large deflection, and large strain capabilities. Therefore it was ensured that all of the elements are of the type tetrahedral or SOLID 186 type.

The fine mesh was used neat the fillet region as the region is prone to cracks. Figure 3.2 shows that fine elements are used to model fillet region near the root.
Figure 3.2 Fine mesh of elements at the fillet region

Meshing Details of the model is shown in table 3.1 All the elements of solid 186 type are used for modeling the shaft.

3.2 Material Properties of the Compressor Blade:

In this project, a Titanium-Aluminium-vanadium alloy is used. This type of material can be used for blades, discs, rings, airframes, components.

<table>
<thead>
<tr>
<th>Components</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium</td>
<td>90</td>
</tr>
<tr>
<td>Aluminum</td>
<td>6</td>
</tr>
<tr>
<td>Vanadium</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 3.2 Composition of Titanium-64 alloy

<table>
<thead>
<tr>
<th>Physical property</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>4620 kg/m$^3$</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>96 000 MPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>1040 MPa</td>
</tr>
<tr>
<td>Yield strength</td>
<td>930 MPa</td>
</tr>
<tr>
<td>Mode I critical stress intensity factor</td>
<td>55 Mpa/m</td>
</tr>
<tr>
<td>(parameter of Paris equation) C</td>
<td>1.0E-11</td>
</tr>
<tr>
<td>(parameter of Paris equation) m</td>
<td>3.2</td>
</tr>
</tbody>
</table>
3.3 Initial and Boundary Conditions:

3.3.1 At the Root of the blade

All the three degrees of freedom in X, Y and Z direction were constrained at the root of the compressor blade as shown in fig 3.3

![Fig 4.8 Fixed supports at the root of the compressor blade](image)

3.3.2 Initial conditions:

A rotational velocity of 2100 rad/sec (20000 RPM) was applied on the global X axis which simulated the blade to rotate about the X-axis at a distance of 100 mm away from the axis in y-direction. This defines the initial rotational velocity for the whole part which consists of only one blade as shown in figure 3.4

![Fig 3.4 Rotational velocity applied to the blade](image)

3.5 Crack Geometry

A three-dimensional semi-elliptical crack was initiated on the shaft surface. The crack is oriented with respect to blade axis along the maximum Vonmises stress plane. The nomenclature of the crack is as shown in figure 3.5

![Figure 3.5 Crack geometry](image)
In the fracture module, a crack is created by defining the crack domain and crack location using co-ordinate system. The shape of the crack is defined by a major axis and minor axis of the semi-elliptical crack. Contour radius, circumferential radius, and mesh contours are defined. Contact pairs between the fractured surfaces can also be defined.

4 RESULTS AND DISCUSSION

Static stress analysis was done to identify the stresses in the critical region of the compressor blade. The analysis is done to find the stress intensity factors and their modes along the crack front. A benchmark problem whose solution is available in literature has been solved in order to validate the obtained results of stress intensity factor solution.

4.1 Static Stress Analysis Results:

Static Stress analysis was carried out to ascertain the critical region of blade rotating with a rotational velocity of 20000 RPM. The critical region or the crack zone is a region in which maximum Equivalent (von-mises) stress occurs. This maximum stress is 781.5 MPa as shown in figure 4.1.

Similarly, the static analysis was carried out for the blade rotating at 10000 RPM and 5000 RPM, whose results showed the maximum stress of 347.37 MPa and 86.843 MPa respectively at the same critical region as shown in figure 4.1.

4.2 Stress Intensity Factor Solution using Fracture Module

Stress intensity factor solution for a three-dimensional crack has been computed by the numerical method and its solution are presented in the section numerical results. For validation of the results obtained a benchmark problem has been solved by using fracture module in ANSYS and its solution is compared with that available in the literature. Figure 4.2 shows the mode I stress intensity factor at the location of the crack, the maximum SIF is 26.9 MPa√ at the surface interception points b = 0.4 mm and a = 0.16 mm.
Figure 4.2 Stress intensity factor $K_I$ for $b = 0.4$ mm and $a = 0.16$ mm

Figure 4.3 shows the mode I stress intensity factor at the location of the crack, the maximum SIF is 31.8 MPa$\sqrt{\text{m}}$ at the surface interception points for $b = 0.6$ mm and $a = 0.24$ mm.

Figure 4.3 Stress intensity factor $K_I$ for $b = 0.6$ mm and $a = 0.24$ mm

Figure 4.4 shows the mode I stress intensity factor at the location of the crack, the maximum SIF is 31.8 MPa$\sqrt{\text{m}}$ at the surface interception points for $b = 0.32$ mm and $a = 0.8$ mm.

Figure 4.4 Stress intensity factor $K_I$ for $b = 0.32$ mm and $a = 0.8$ mm

Figure 4.5 shows the mode I stress intensity factor at the location of the crack, the maximum SIF is 40.9 MPa$\sqrt{\text{m}}$ at the surface interception points for $b = 0.48$ mm and $a = 1.2$ mm.
Figure 4.5 Stress intensity factor $K_I$ for $b = 0.48$ mm and $a = 1.2$ mm

Figure 4.6 shows the Von-Mises stress distribution at the crack tip in presence of crack depth of 0.8 mm. It is also observed that larger part of the blade is subjected to elastic stresses. Close to crack tip stress is large, of the order of 8009 MPa. Figure 5.16 shows the stress intensity factor $K_I$, the maximum SIF is 46.2 MPa√m and 46.5 MPa√m at the surface interception points for $b = 2$ mm and $a = 0.8$ mm

Figure 4.6 Von – Mises stress distribution and Stress intensity Factor $K_I$

Figure 4.7 shows the Von- Mises stress distribution at the crack tip in presence of crack depth of 1.6 mm. It is also observed that larger part of the blade is subjected to elastic stresses.

Figure 5.2 Von- Mises stress distribution at the crack tip for $a=1.6$ and $b = 4$mm

5. BENCHMARK PROBLEM

In order to validate the obtained stress intensity factor solution a benchmark problem whose solution is available in literature has been solved by using fracture module in ansys. The benchmark problem consists of a cylindrical bar having a semi-elliptical crack subjected to tension loading. The crack is defined by its crack length and cracks depth.

A rectangular flat plate having a breadth of 25.132 mm, the width of 20 mm, and height of 40 mm was considered for analysis. The analysis was done using the fracture module in Ansys workbench for the case of crack length $a = 4$ mm and crack depth $c = 2$ mm. the plate was subjected to a pressure of 200 MPa on one side while at the other side displacements were constrained.

The fine mesh was used near the crack region to obtain the accurate stress intensity factor solution. Assembly of the plate containing the crack is shown in figure 5.1
Figure 5.1 Rectangular plate containing crack

Von–Mises stress contour and crack opening due to the applied load is shown in figure 5.2.

For the benchmark problem, crack depth or semi-major axis is denoted by “a” and semi minor axis is denoted by “c” numerical stress intensity factor solution for the benchmark problem is shown in the graph obtained in figure 5.1 for stress intensity factor vs. crack front position.

Von–Mises stress contour and crack opening due to the applied load is shown in figure 5.2

Figure 5.3 Von-Mises stress at the crack tip

For the benchmark problem, crack depth or semi-major axis is denoted by “a” and semi minor axis is denoted by “c” numerical stress intensity factor solution for the benchmark problem is shown in the graph obtained in figure 5.2 for stress intensity factor vs. crack front position.

The stress intensity factor solution for this problem is given by M. Vorel and E. Leidich as shown in figure 5.4

6. CONCLUSIONS

Based on the finite element analysis and the analysis done with the help of fracture module, the following conclusions were drawn.
Static stress analysis for the operating conditions of axial flow compressor blade was performed. Crack zone in the compressor blade was identified on the pressure side of the blade near the fillet region of blade and root of the blade. The maximum Von – Mises stress of 781.58 MPa occurred in the region for the blade rotating at a rotational velocity of 20000 RPM. The same region was identified as critical for a crack for the blade rotating at 10000 RPM and 5000 RPM.

Semi-elliptical crack of crack depths of 0.2, 0.4, 0.6, 0.8, 1.2, 1.6, 2, 3, 4, 5, and 6 mm were considered for stress intensity factor evaluation. Fracture module in Ansys workbench was used for evaluation of stress intensity factor. Mode I stress intensity factor at the surface interception point varied from 6.57 MPa√m to 60.8 MPa√m. For crack 0.2 mm for 0.8 mm crack length, mode I stress intensity factor becomes negative. It indicates that the crack depth is subjected to closing mode or compression.

Fatigue crack growth rate at the crack depth increase with the increase in crack length. For a more accurate solution, a method which takes care of crack closure effect and propagation of a crack along an arbitrary, solution dependent path under fatigue loading conditions must be considered.

7. SCOPE FOR FUTURE WORK

In the present work, a single crack was considered for fatigue crack growth rate evaluation under different rotational velocity. The effect of multiple crack growth can be considered for future work. Also, the crack propagation path can be simulated automatically using software such as ZENCRAKC, AFGROW i.e without manual incremental at each iteration. Solution dependent path under fatigue loading conditions can be considered. Stress-based and strain based analysis to calculate the fatigue life of a compressor blade can be performed using software such as nCODE design life and MSC FATIGUE.

8. REFERENCES


BIOGRAPHY

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I Am vijayavithal M Ilal, completed my M.Tech in Product Design and Manufacturing in RVCE Bengaluru. Presently working as Assistant professor in Sambharam institute of technology