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ACTIVE VIBRATION ANALYSIS OF GAS TURBINE WITH TI-ALLOY BLADE ROTATION FOLLOWING SURFAC DAMAGE GRIND-OUT REPAIR

ANORAMA SUBUDHI, *Gandhi Institute of Excellent Technocrats, Bhubaneswar, India*
SHASHIKANTA BALIYARSINGH, *Adarsha College of Engineering, Angul, Odisha, India*

ABSTRACT

Vibration examination of gas turbine sharp edge adds to advance in Aerospace and Aeronautics enterprises. Most regularly, recognizable proof and concealment of undesirable vibration is fundamental need. Methods of vibrations and regular frequencies are affected by harms brought about by outside item sway. These are progressively articulated for variation break geometry close to the foundation of cutting edge. Factual report and its post fix execution capacity are lacking in writing. It gives data on subject of dynamic nature of patch turbine cutting edges at working condition. Edge harm geometry and selection of areas can be characterized for the fastidious turbine edge helps in normal support.

Key words: *Ti-Alloy, Vibration Analysis, Threshold Frequency, Numerical Analysis*

NOMENCLATURE

[M] = Mass matrix of blade

[K] = Stiffness matrix of blade

x

{x} = Displacement vector

{F(t)} = External force vector

ω = Natural frequency

$\varnothing^{n}$

K_l = longitudinal Stiffness of blade

K_t = Torsional Stiffness of blade

$K_{b\Theta}$ = Bending Stiffness of blade for angular deflection

$K_{b\delta}$ = Bending Stiffness of blade for linear deflection m

= mass of blade

I_g = Mass moment of inertia of blade about geometry axis

I_r = Mass moment of inertia of blade about rotor axis δ_l =

Longitudinal deformation

δ_b = Linear bending deflection

Θ_t = Torsion angle

Θ_b = bent angle

P = Axial Load due to inertia about radial direction

T = Torque due to inertia about blade axis

M = Moment due to inertia about rotor axis

L = Blade length

A = Area of cross section of blade

E = Modulus of elasticity of blade material

I = Moment of inertia of cross section

J = Polar moment of inertia of cross section

G = Modulus of rigidity

U = Strain Energy

ρ = Density of the material

1. INTRODUCTION

Modern gas turbines are widely used large commercial aircraft and are more popular in the business jet market. It is the most resourceful today in several different modes in critical industries such as power, aviation, oil and gas, process plant and defense. These turbines have to perform under major climate changes of many countries. Damage that often occurs on turbine blades may reduce the structural stiffness and strength and consequently their static and dynamic behavior is altered, and may cause serious failure of turbine. The increased use of turbines requires a better compassionate of vibration characteristics for high standard of safety. Determination of the dynamic characteristics of turbine blades is essential not only in design stage but also in performance analysis of structure. Vibration analysis is a tool used to detect defects and offers an effective, inexpensive non-destructive testing. Presence of crack, its location and its size are important issues since such discontinuities may cause catastrophic failures due to vibratory motion. Behaviors of blade include investigation of cracks based on structural damage identification; abnormality detection, crack localization, quantification, noise immunity etc. [1]. The categorization of turbine blade failure by mechanical, metallographic and chemical analysis is very important. Characterization of blade material, stress localized areas and identification of probable grounds of failure and recommendations to ease incidents [2].

This research investigated characteristics of foreign object damage, which caused serious accidents in numerous recurrent cases with similar. These failures are due to foreign object damage creates stresses confined to a small area on blades. Titanium alloy blade with grinded foreign object damage is considered for analysis at 15,000 rpm. The results are related with size of damage, position and aiming to understand causes to hint improvements required in blade maintenance procedure.

2. FAILURE OF GAS TURBINE BLADES

In order to find the root causes and to seek the countermeasures, turbine blades are investigated to prevent accidents in future. Failures are mainly due to electrochemical reaction which causes corrosion in the molecular level, corrosion fatigue, stress corrosion and fatigue during the operation. In gas turbine corrosion failure is less compared with steam turbines, where as fatigue failure is major due to the flying conditions and found that failure mechanism of blades is the environment-assisted fatigue fracture [3]. It depends on the material quality, molecular arrangements, alternating and residual stresses. The fatigue failure of blade originates during transient vibrations and close to resonance of assembled blades [4].

Several investigations are carried out from molecular level and mechanical point of view. It generally starts from visual and microscopic observations to determine failure mechanism. During exposure to high cycle fatigue, temperature and stress, crack initiates from the surface of damage and propagates to a critical length resulting in terrible failure. The absence of crack closure effect is not only the reason for propagation rate when compared with long cracks [5]. Mating surfaces of blade root undergo excessive fretting wear. Even slight amplitude of cyclic motion can cause welding spot with the mating surfaces. The Presence of cuboidal, structural changes occurs in the matrix and fractal dimensions of the metallographic images which can correlate the progressive damage accumulation at various locations of the blades [6].

But foreign object impact causes severe changes the characteristics of the blades like factor of safety, fatigue life, natural frequency and structural integrity during the operation. It is due to birds, animals, any foreign particles mainly during takeoff or landing and volcanic ash found at high amplitude of eruption but these locations are normally avoided. Volcanic ash clouds contains high amount of sulphur can cause corrosion damage and the influence of microstructure on the vulnerability to high cycle fatigue failure following foreign object damage cause crack growth behavior [7-9]. These damaged blades are often machined to investigate and to know the crack root. Damages are to be machined to semicircular notch and U-notch with clean surface and no crack on the surface. Sharp V-notches in the leading edge of blades creates stress concentration region, so dislocation density method is a convenient and accurate way of carrying out elastic stress analysis of a V-notch with a radii used root [10].

3. HEALTH MONITORING

Health monitoring of turbine blades is of great interest in the field of flight technology. Unexpected failure of turbine blades can stop the missions in cases of military, results in the death and threat to the nation. In maintenance plan or technique health monitoring is an integral part, which results in accurate with good ample of failure data and significant cost saving. Turbine blades are operating in highly variable environment for which more comprehensive source of design, manufacturing, operation and random operations to be considered. It is necessary to understand the combined effect of sources with the variable environment. It enables the development of robust fault detection methods, and explores the deterministic as well as variation characteristics of failure signatures [11]. Vibration monitoring involves analysis of blade passing frequencies, dynamic signals using most appropriate method for fault diagnosis in practical field conditions. It is a model based analysis, which extracts the dynamic signals correctly. Methods like signal processing; noncontact measurements may perhaps detect blade faults at engine operating speed [12-13].

Fault Diagnosis and post-repair performance analysis is most versatile approach in health monitoring of blades. It involves describing the limiting factors for high cycle fatigue failures limiting to the microscopically small threshold flaw sizes for the worst case, in which limiting the premature crack initiation caused by stress concentration due to foreign object indentation and presence of tensile residual stresses [14]. Even offline diagnosis methods gives preventive to predictive maintenance approach like Gibbs sampling in Bayesian models, laser strain techniques, grind-out repair eventually reduce the maintenance cost [15-16]. In laser stain techniques all cracks highlighted by Fluorescent penetrant inspection able to find the small defects on complex turbine blade shapes.

Grind-out repair to various depths allows studying subsurface metallurgical damage might affect in future in-service performance [17]. To overcome this, the new effective technologies like finite element method in effect can be used for dynamics of turbine blade with real working environment. A most promising approach for developing complete solution for vibration problems is provided by advanced mathematical discretization scheme. The basic concept in finite element method is subdivision of mathematical model into disjoint or non-overlapping components of simple geometry which are expressed in terms of finite number of degrees of freedom characterized at set of nodal points. The response of mathematical model is considered to be approximated by that of discrete model obtained by linking or assembling collection of all elements.

4. MATHEMATICAL ANALYSIS

High speed rotating blades are normally subjected to high cycle fatigue and vibration problems, which are intern concerned with performance and safety. Mechanical and high temperature accelerates the damage. HCF induces undesirable vibration stress due to resonant vibration, but in low cycle fatigue crack initiation and propagation takes place during throttle cycle. Desirable blade dimension, orientation and material properties are required to find the remaining life of component from allowable crack. Blades can be considered as continuous system subjected to free or forced vibration in which mass is distributed along with the stiffness. In rotating blades, speed, density of material used, blade dimension and shape influence the vibration nature. Continuous rotor speed variation and mass distribution over the blade causes longitudinal vibrations due to inertia effect, torsional vibration due to twist and untwist effect, and bending transversely due to inertia effect and gas bending. The general equation of motion for any undamped multiple degrees of freedom system is given by

$$M x + K x = F t \quad (1)$$

Where and x are respective acceleration and displacement vectors for whole blade and {F(t)} is the external excitation force vector. Force vector is due to inertia effect, traction force,

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and point force. Under free vibration, the natural frequencies and the mode shapes of a multiple degree of freedom system are the solutions of the Eigen value problem.

$$M - \omega \quad K = 0 \qquad (2)$$

Where ω is the angular natural frequency and Φ is the normal mode shape corresponding natural frequency. Mass and stiffness of material characterizes vibration modes and it is very important to consider the materials with high strength to weight ratio for high operating conditions, structural stability and safety. Titanium alloy has high yield strength and low density than steel. Vibration modes and natural frequencies are characterized by the material properties such as density, elastic modulus and geometric properties like cross section and moment of inertia. Steel has high elastic modulus to density ratio of 25.47, nickel alloys of 21.18 and least value of titanium alloys is 20.77, which are commonly used for construction of gas turbine blades. Titanium alloy gives least frequency and much variation with nickel and steel; because frequency is depend on Elastic modulus to density ratio.

Table 1 Summary of Natural frequency, deflection, stiffness, Factors Influence, Energy Equation for uniform cross section cantilever vibration analysis.

	Longitudinal	Torsional	Transverse (Angular Deflection)	Transverse (Linear Deflection)
Natural Frequency	$\omega = \sqrt{\frac{K}{m}}$	$\omega = \sqrt{\frac{K}{I}}$	$\omega = \sqrt{\frac{K}{I}}$	$\omega = \sqrt{\frac{K''}{I}}$
Deflection	$\delta = \frac{PL}{AE}$	$\theta = \frac{TL}{GJ}$	$\theta = \frac{ML}{EI}$	$\delta = \frac{ML}{2EI}$
Stiffness	$K = \frac{P}{\delta} = \frac{AE}{L}$	$K = \frac{T}{\theta} = \frac{GJ}{L}$	$K = \frac{M}{\theta} = \frac{EI}{L}$	$K'' = \frac{M}{\delta} = \frac{2EI}{L}$
Factors Influences	P, A, m	T, J, Ig	M, I, Ir	
Energy Equation	$U = \int \frac{P}{2AE} dr$	$U = \int \frac{T}{2GJ} dr$	$U = \int \frac{M}{2EI} dr$	

Titanium alloys are more dominant material than Nickel alloy and steel without affecting vibration characteristics in turbine blades due to its high strength to weight ratio. Table-1 gives information about natural frequency, energy equations and factor influences vibration for an equivalent mechanical system. Factors like blade cross section 'A', Polar moment of inertia 'J', moment of inertia 'I' are dimensional parameter, where as load 'P', torque 'T', moment 'M', mass moment of inertia 'I_g' about geometry axis and 'I_r' about rotor axis are forcing functions depends on the mass distribution and working conditions, but modulus of rigidity 'G' and elastic constant 'E' are totally material constant and temperature dependent.

5. RESULT AND DISCUSSION

Titanium alloy blade is considered in fixed-free condition rotating at 15,000 rpm without-with damage at the leading edge. When the blade is running with constant high speed of rotation, the frequency ratios to which without with notch of blade are found. This helps in utilizing blade even

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after damages occur during operation, and are able to resist vibration caused in them after machining damaged portion as semicircular or U shaped notch figure 1. If the damage depth is small it is machined to semicircular notches and when the damage depth size is large it is machined to U- Notches. Notch radius of 2, 4, 6, 9 and 12mm are considered and positioned at 20, 40, 60, and 80 mm from the root of blade. Where as in U-notches are analyzed for depth of 1 and 2 mm from the leading edge of the blade with notch radius and position mentioned above.

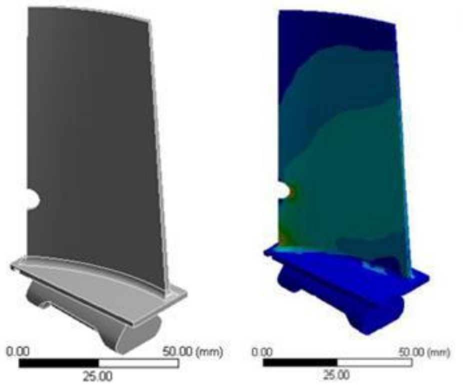
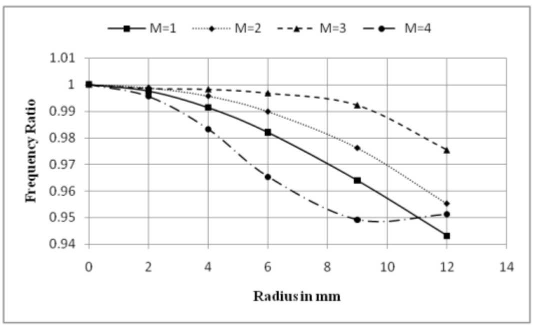


Figure 1 Turbine Blade with Notch

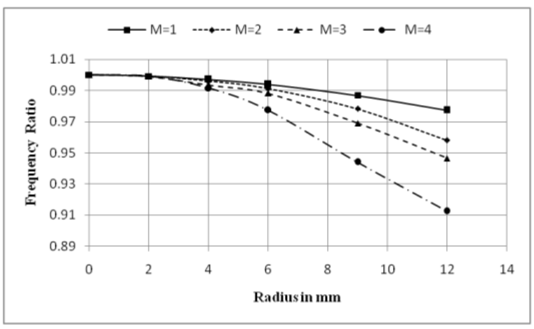
5.1. Semicircular Notches Radius at Constant Position

When the semicircular notches are nearer to the root of the blade i.e. at a distance of 20 and 40 mm, it is observed that as the notch radius increases, frequency ratio decreases. When the position of the notch is varies the frequency ratio also varies as shown in figure 2a & 2b. This gives very significant information in deciding the life of the turbine blade. It is observed that higher mode has lowest frequency and subsequently other modes of vibration. In case of figure 2c, the notch position is at a distance of 60 mm. For increase in notch radius, frequency ratio decreases in mode 2 and 4 only, where as in mode 1 frequency ratio is constant. In mode 3, frequency increases for the notch radius of 2 to 10 mm and decrease after 9 mm radius. This is mainly due to swirl shape effect of the blade. From figure 2d, at 80 mm distance from the root of blade, frequency ratio increase as notch radius increase in mode 1 and 2.

For mode 3, frequency increases for the notch radius of 0 to 6 mm and afterwards decreases. Frequency ratio decreases for mode 4. There need to be known frequency ratio for the variation of notch radius and position for different modes. Results show there is frequency variation of -0.09 to +0.02 factors for first four modes of vibration.



(a)



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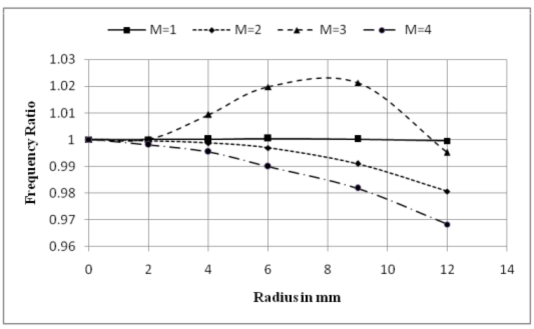
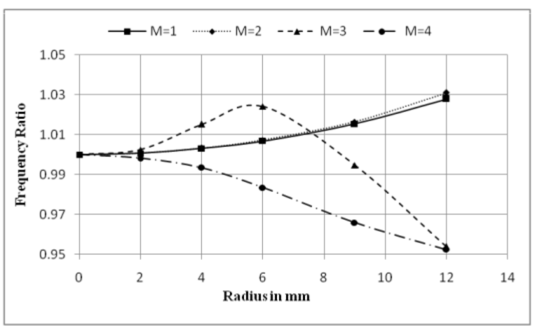


(c)



(d)

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Figure 2 Frequency ratio for variant semicircular notches at a distance of a). 20mm b). 40mm c). 60mm d). 80mm from the Root of Blade.

5.2. U-notches for depth b=1 & 2 mm at Constant Position

As the crack or damage depth is more, the damage can be machined to a U-notch. The results are plotted for the depth of 1 and 2 mm from the surface in the figure 3a to 3d. It is observed that as the notch radius increases at the root, the frequency ratio decreases. Frequency ratio decreases for each subsequent mode of vibration and for damage nearer to the root of the blade figure 3a, 3b, 4a and 4b. As the notch position is away from the root of the blade it is observed as different phenomenon. In this case as notch radius increases, frequency decreases in mode 2 and 4, but in mode 1 frequency constant as the increasing the notch radius.

Figure 3 Frequency ratio for variant U-notches for a depth b=1mm at a distance of a). 20mm b). 40mm c). 60mm d). 80mm from the Root of Blade.

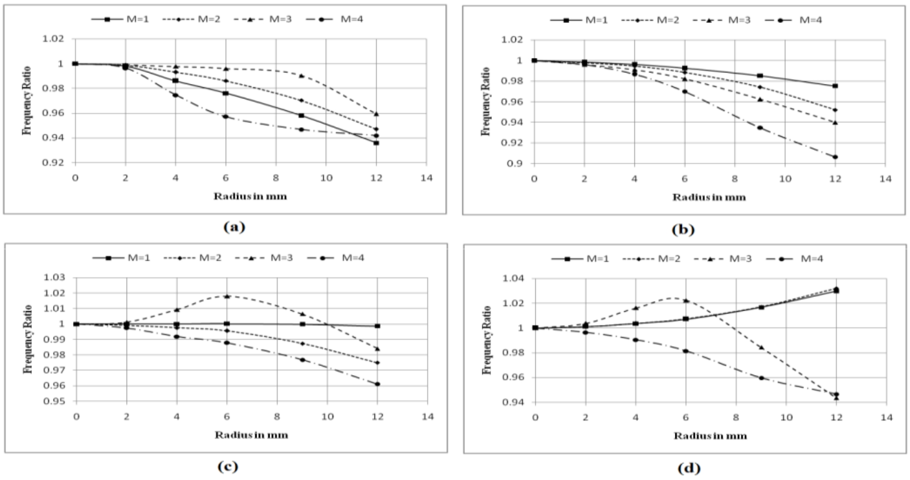
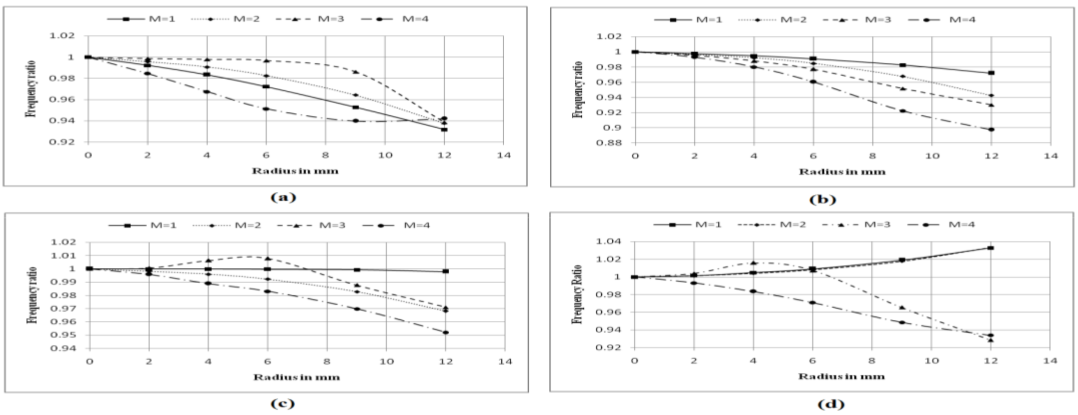


Figure 4 Frequency ratio for variant U-notches for a depth b=2mm at a distance of a). 20mm b). 40mm c). 60mm d). 80mm from the Root of Blade.



In mode 3, frequency ratio increases for notch radius 2 to 10 mm, and decrease after 9 mm radius figure 3c and 4c. When the damaged is distant from the root of the blade figure 3d and 4d, the frequency increase as notch radius increase in mode 1, 2 and frequency decrease in mode 4 as radius increase but in mode 3 frequency increase 0 to 6mm radius after decrease. It is observed that for first four modes of vibration, frequency varies by -0.09 to +0.03 factor for the maximum depth of 13mm and subsequently by -0.11 to +0.03 factor for the maximum depth of 14mm.

5. CONCLUSION

This paper discussed about vibration analysis and its importance while defining safety and health monitoring. Stresses due to vibration cause severe damage to the engine and in this paper results shown for turbine blade made of Titanium alloy material with and without notches at constant speed of rotation. Smaller the depth of damage is modeled as semicircular or else U-notch during the period of maintenance. The list of results gives the information to the engineer to decide the blade life for the further usage. As radius of notch increases at root, the frequency decreases for semicircular notches. Where as in U- notches as depth of notch increases with respect to crack size, the frequency variation is more and random compared to semicircular notches. The frequency variation of -0.11 to +0.03 by factor for the first four modes of vibrations and for the maximum damage depth of 14 mm is observed. The effect of crack is more pronounced near the root of the blade than at far free end. The natural frequencies are most affected when the cracks located near to the root, the middle and then free end, respectively.

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