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Numerical and Experimental Study of Vibrations Caused by Defects in Fan Blades

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Abstract

Damage monitoring of rotating blades is becoming increasingly important, because blades in many applications like turbine engines, marine propellers, and turbo engines are exposed to high temperatures, high strains, and severe vibrations. Due to continuous operations of these blades fatigue cracks can emerge after an hour of service, these causes a blade failure and can potentially ruin an entire engine. The damage identification of blades by vibrational analysis is discussed in this paper, numerical analysis is carried out using ANSYS Workbench program to simulate a FEM model, and results are compared to the experimental analysis, where fault simulation machinery equipment used to know the vibration responses of a healthy and defective blades. Multiple distinct peaks were observed at the blade resonance region in case of blades having a defect when compared to healthy blades showing one distinct peak in the blade resonance region which helps in analysis helps in understanding the damage detection of blades early, reducing the likelihood of catastrophic accidents.

Keywords: *Vibration, Damage in fan blades, Mathematical modelling, Blade Health Monitoring.*

1.0 Introduction

Blade vibration can be caused by unstable aerodynamic loads, centrifugal force, rotor imbalance, and other aspects when rotating machines operate at high speeds. High cycle fatigue (HCF) of a blade is caused by these vibrations, which can result in blade fracture and possibly fatal accidents. As a necessary consequence, safe and robust blade vibration monitoring and fault alerting plays an important role in rotating machinery health management. To understand the blade vibrations and its nature of defects Kunpeng Xu et al. used the technique of mistuning identification to identify the hard-coated blisk blade substrate crack parameters that includes size and position of the cracks. The detection accuracy at the center distance is higher than the detection accuracy of the crack size at the crack length[1]. Mengyao Yu et al., proposed a method for identifying damage to fan blades based on a discrete mathematical model and a fluid-structure analysis, natural frequencies of data for each mode are obtained for various locations and sizes of a single crack in a blade the changes in natural frequencies were used to detect blade damage[2]. Emilio Di Lorenzo et al. performed operational modal analysis earlier and after buckling test and gathered the vibration data, which resulted in good relations between the experimental and numerical results[3]. S Hoell, P Omenzetter showed the acceleration responses as Damping scale factors (DSFs) by using partial autocorrelation coefficients and DSFs are converted into scores by Principal component (PC) analysis. PCs are selected based on the results obtained for the healthy and damaged blades that are more sensitive to extent damage[4]. Hwanhee Lee., et al develop a computational model for the dynamic properties of a rotor-blade system which showed the results that the blade pre-twist angle and shaft torsional flexibility have a notable effect on the system's varying response[5]. Neri, B. Peeters, et al., investigated the Non-Harmonic Fourier Analysis(NHFA) approach for

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detecting blade cracks quantitatively. Following that, a data processing algorithm for obtaining frequency shift information from short time samples is described, and NHFA produced good frequency estimate results in both numerical testing and experimental noise-affected testing[6]. Rama Rao et al., investigated casing vibration signal analysis, in which the reaction of the casing generated by blade pass frequencies at various stages is recorded in order to understand and evaluate blade conditions[7]. K. Ravi Prakash Babu et al., examined the modal behaviour of a shaft-hub-blade system with a cracks emerging in the shaft or the blade by using ANSYS software to determine mode shapes and natural frequencies for the system's healthy and damaged conditions[8]. Ding Zhang et al. obtained the crack faults in the turbine blades for various sizes and shapes by representing the data of modelling turbine and studying on the sonic IR imaging of the blades[10]. A K. Batabyal et al using Ansys software conducted different parametric studies to evaluate modal parameters such as natural frequencies and mode shapes for various crack parameters and cracks are identified by plotting the contour lines of crack beam frequencies by taking crack location and crack depth as its axis[10]. Mark Mollineaux et al. presented a case study of identifying and pinpointing damage in actual wind turbine blade for smaller ones utilizing ultrasonic Non-Destructive Evaluation/ Structural Health Monitoring (NDE/SHM) techniques. The second of the two techniques, nonlinear acoustics and guided-wave 'pitch-catch' techniques, was shown to be more effective in identifying and pinpointing blade damage[11]. H. D. Nelson et al. developed analytical procedure for the simulation of dynamic characteristics of rotor bearing assembly having crack of transverse by Finite Element Method FEM representation and perturbation parameter to understand the local stiffness changes caused due to the presence of the crack[12]. Ming-Chuan Wu and Shyh-Chin Huang using the method of released energy examined the dynamic characteristics of a blade which is rotating and has a transeverse crack, displacement responses of the blades having cracks are discussed under uniform lateral forces[13]. A. Joshuva and V. Sugumaran, et al suggested fifteen tree classification-based machine learning techniques for locating and detecting wind turbine blade cracks. These models were developed by computing the blade's vibration response when aroused with a piezoelectric accelerometer[14]. Jun Lin et al implemented novel Blade Tip Timing (BTT) analysis method which measures the arrival time of vibrating blade tip when the blades are passing through a BTT probe, and reconstructs unknown two or more mode blade vibration signals[15]. Thomas Krause Jörn Ostermann et al., used an AE (Aucostic Emission) approach to find damage to wind turbine rotor blades via airborne sound, with a close match to the recorded damage occurrences, the real-time operating algorithm determines the significance of the identified damages[16]. Ken Maynard1 and Martin Trethewey in the lab, developed approaches for measuring torsional natural frequencies to a jet engine that had experienced disc breaking near the blade root, as well as blade cracking by resampling method[17]. Xu Jinghui et al., based on the synchro extracting transform approached a a crack propagation monitoring for the rotor blades which has the benefit of high time-frequency resolution for extraction of time frequency aspect of the cracked blade's vibration signal[18]. E.A. Ogbonnaya et al., studied on the dynamic response of marine GT rotor shaft systems when they are subjected to force harmonic excitation[19]. F.L.M. dos Santos et al., used coordinate modal assurance criterion (COMAC) and the modal strain energy methods for a damage detection of an entire-size composite helicopter main rotor blade, in these methods the detection is based on the comparison of vibration modes and modal strain energy of the beam[20].

This study focused on the blade health monitoring for the detection of damages in the blade through vibration responses. The experiments are set out on Tiera Fault simulator machinery for four blade conditions, acceleration data is collected by accelerometers at the two ends, in which blades are positioned in the middle of the two bearing pedestals. Tiera software is used for FFT analysis for measuring the changes at different phases connected to the blade resonance frequencies to access the dynamic behaviour of the blades under different cases.

2.0 Geometric modelling of shaft-hub-blade system

In order to understand proper suitable dimensions for the Tiera fault simulator machinery test rig, blade-hub-shaft is firstly developed and analyzed using Finite element to know the natural frequencies and mode shapes. For analysis the modelling of a blade-hub-shaft system is done in the solid works for both healthy and a damaged blade. The material

Table 1: Model Parameters of the System

Parameter, symbol (unit)	Blade dimensions
Length of blade (L)	75mm
Width of blade (b)	15mm
Thickness of blade (Hb)	2mm
Thickness of disk (Hd)	35mm
External diameter of disk (r2)	35 mm
Internal diameter of disk (r1)	20 mm
Radius of shaft (rs)	20mm
Length of shaft (S)	320mm

properties of mild steel is considered. The model parameters of the system is represented in the Table 1. All the components are assembled in a way as in the Figure 1.

Faulty blade for 6 mm crack length is modelled in the software, The width and depth of the crack damage for the blades is considered as 0.2 mm width and 0.2 mm depth. The model of blades is shown in the Figure 2

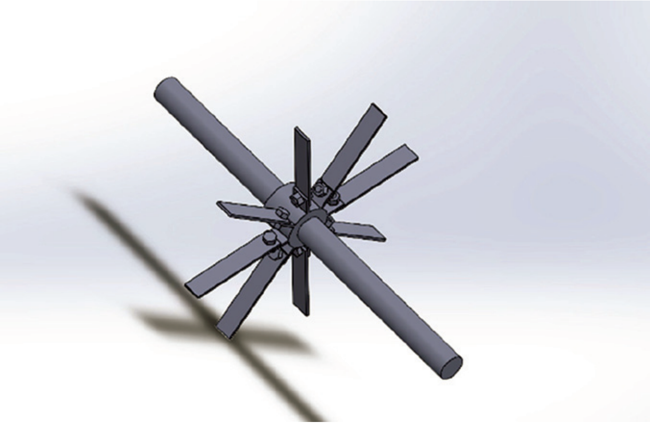


Figure 1: Geometric figure of the system

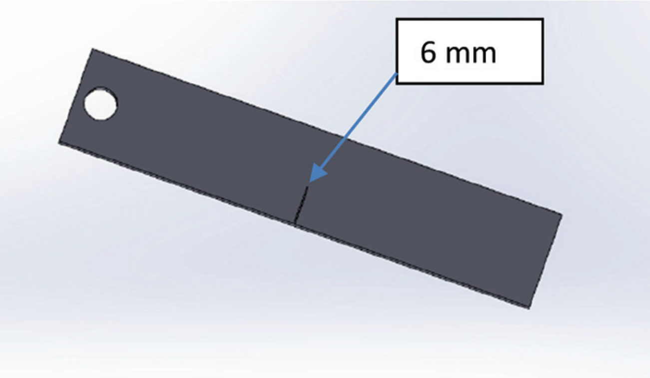


Figure 2: Blade with 6mm crack length modelled in software

3.0 Finite Element Analysis

The design model of a blade-hub-shaft system is imported from the SOLIDWORKS Software to ANSYS Workbench to carry out the model analysis and harmonic analysis using finite element method. Meshing is done for an element size 2mm, as shown in Figure 3. In order to define the real-time support formed by bearings in experimentation, boundary conditions for the shaft-hub-blade system is ANSYS Software is provided, simply supported supports are provided at the two ends of the shafts making transitional and rotational of all axis constrained, except one axis making rotational free.

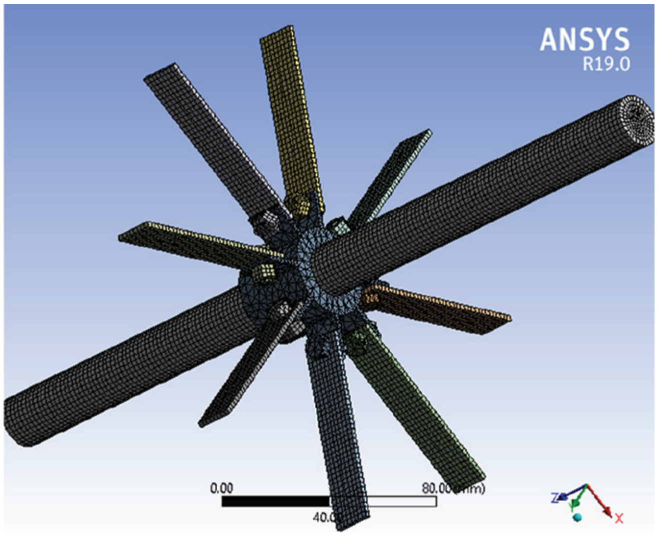


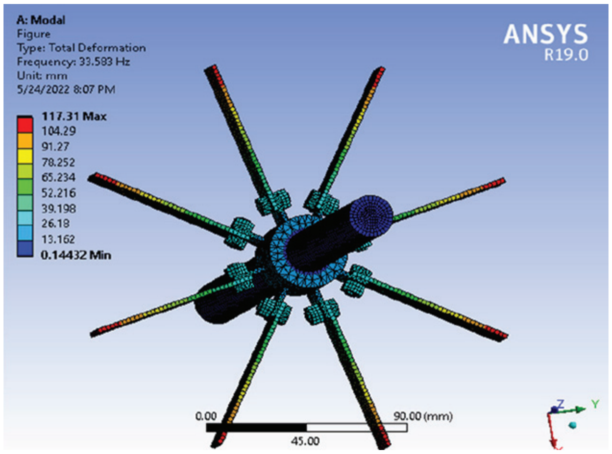
Figure 3: Meshed model of the system

3.1 Simulation for Healthy System

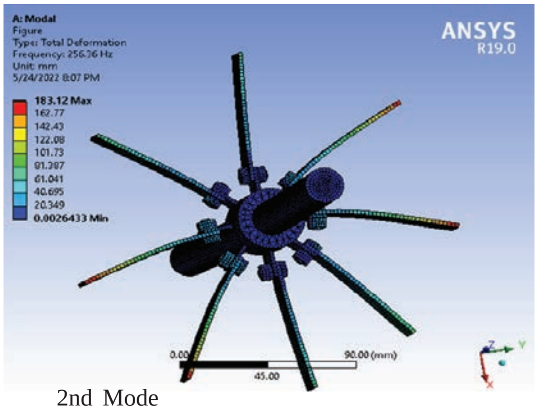
The modal and harmonic analysis for simulation is carried out to note the natural frequencies and harmonic response of healthy blades, the natural frequencies acquired from the Ansys are 33.42 Hz, 256.36 Hz ,256.45 Hz, and, it is found that no vibration of the blade occurs when system is vibrating in first mode, but blade and shaft both are vibrating at the second and third mode as shown in the Figure 5 shows the first five modes of the system. Fig 6 shows the first harmonic response of the system.

3.2 Simulation for System with damaged blades

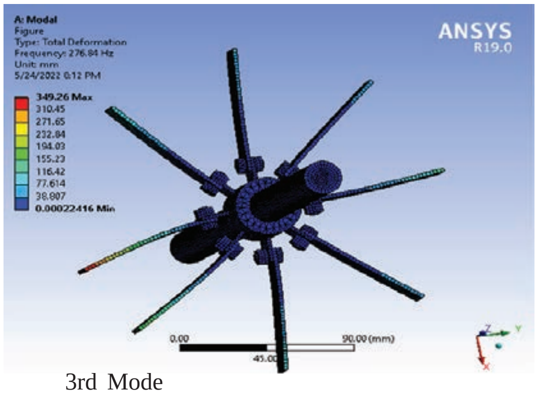
The one blade from blade-shaft-hub system is replaced by the one damaged blade i.e of 6mm, modal and harmonic



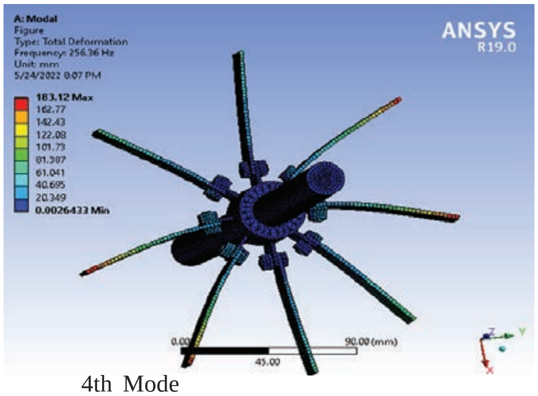
1st Mode



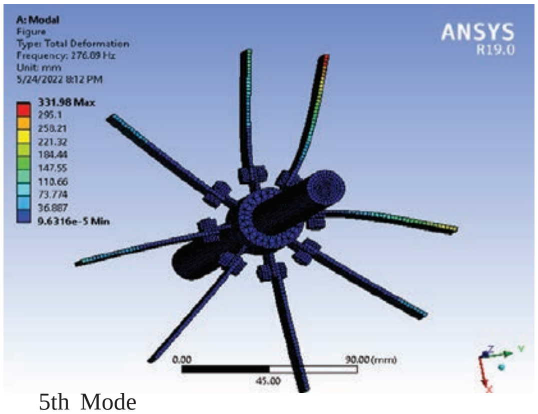
2nd Mode



3rd Mode



4th Mode



5th Mode

Figure 5: five modes of shaft-Hub-blades system using Finite Element (FE) method

analysis is performed to find out natural frequencies, the natural frequencies obtained for system with 6mm defect are 32.046 Hz, 256.1 Hz, 256.14 Hz, The natural frequencies variations is shown in the Table 2.

Table 2: natural frequencies of healthy anddamaged system for 6 mm defect

Mode Names	Healthy system (Hz)	Defect 6mm (Hz)
First Mode	33.42	32.046
Second Mode	256.36	256.1
Third Mode	256.45	256.14

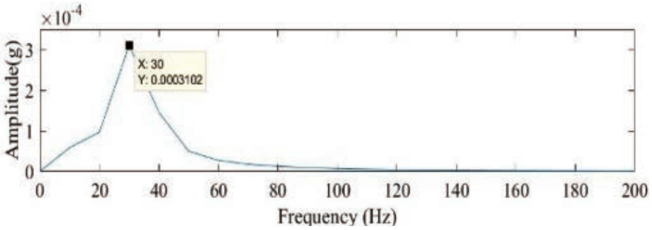


Figure 6: Harmonic blade response obtained in Ansys software

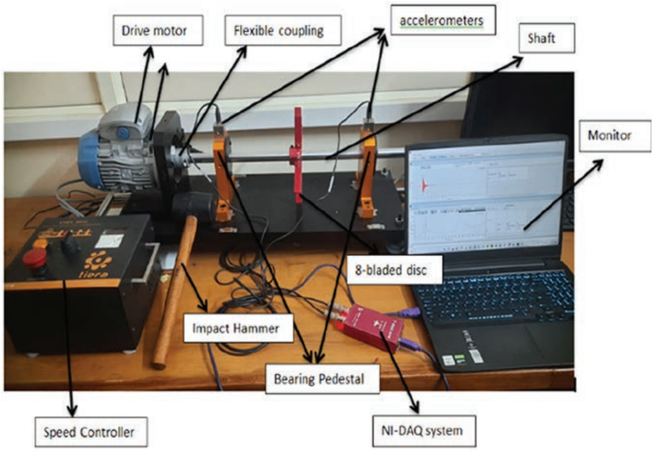


Figure 7: Experimental Test Rig

3.3 Modal Testing

To understand modal properties of system and resonance of the frequencies by experimentation, modal analysis is carried for the blade-hub-shaft system, test rig set up for analysis is shown in Figure 7. The system was excited using the impact hammer, vibration responses that is FFT (Fast Fourier Transformation) signals is noted which is obtained through accelerometer and by Tiera software. First blade resonance of the system is obtained at 32.5 Hz experimentally as shown in the Figure 8 when compared to numerical analysis response which is obtained at 30 Hz are almost same as shown in the Figure 6. There will be a small deviation of ±4 Hz is considered due to the mistuned effect that might be due to blade fabrication and fitting.

4.0 Experiments and Fault Simulation

The experiments performed when the system is in running condition at speed varying from 1000 rpm to 1500 rpm . Fault simulation tests is carried out for the conditions shown in the Table 3

Blades with defect having different crack length of 6mm is shown in the Figure 9, depth and the vibration experiments is performed for the conditions stated in the Table 3

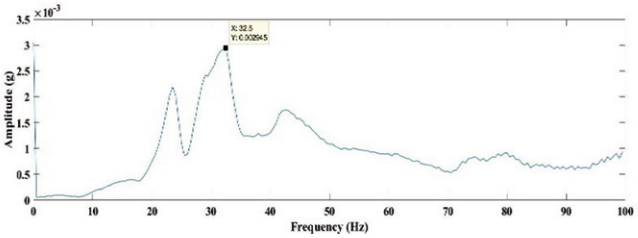


Figure 8: FRF plots of Blade-Hub-Shaft bladeresonance experimentally

Figure 9: Crack length of 6mm

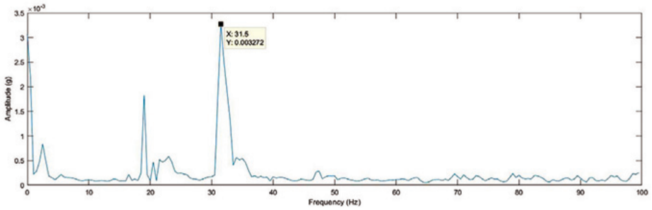


Figure 10: Measured FFT Spectra for Healthy Blades

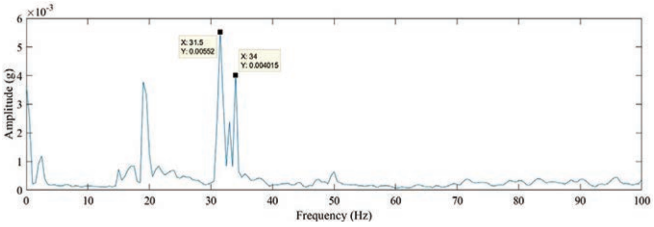


Figure 11: Measured FFT Spectra for 6mm fault blade condition

Table 3: Experimental Conditions

Condition no	Description
01	With all healthy blades
02	Blade with defect of crack length 6mm

5.0 Data Analysis Observation and Discussion

The accelerometers placed on the bearing pedestals is shown in the Figure 9. Signals measure from the accelerometers are analysed and understood by appearances of the blade resonances and by its dynamic behaviours, the vibration analysis is performed for the different cases and by using Tiera software the signals and processed and analysed, the Figures 10 and 11 shows the FFT spectrum for first blade resonance (BR) for the cases in the Table 3, and compared to understand faults in the blades.

5.1 Observation and Discussion

For the healthy blades it is observed that there is one distinct peak in the first blade resonance region, for condition 2 with the blade having 6mm crack length defect it is observed with the three distinct peaks at the first blade resonance region, as shown in the Figure 11. Thus having a more than one peaks in the blade resonance region or in higher harmonics when there is a defects in the blades can be considered as an observation feature for the blade health monitoring.

6.0 Conclusions

In this paper the dynamic nature of the rotating blades with and without faults were understood by obtaining the vibration response of the system using Tiera fault simulation machinery equipment during the machine run. Two different conditions were considered for the experimentation one with healthy blade and other having a defect blade with crack length of 6mm. It is observed that there is multiple distinct peaks in case of defect blade compared to healthy blade which is having a single peak at blade resonance region. This helps in understanding the fault in the blades, thus reducing the serious accidents or failure in the machineries.

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