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Crack Simulations in Shaft-Hub-Blade System using Modal Analysis

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Abstract: ***Mostly turbo machines encounter failures like cracks, unbalance, mechanical looseness, misalignment, etc. as they are subjected to fatigue loads. Any of these failure conditions lead to change in the dynamic behavior of these machines. The shaft assembled with hub and blades is considered as the turbo machine rotor for which vibrations response is analyzed. This work includes modal analysis of shaft-hub-blade system with crack developed either in the shaft or in the blade. Analysis was carried out using ANSYS software to evaluate natural frequencies and mode shapes for the healthy and cracked conditions of the system. From the analysis, it was observed that the presence of crack in any component of the system has appreciable effect on the natural frequencies of the system. But the decrease in the natural frequencies of the system is more for the crack located in the shaft compared to that of crack present in the blade. So it is evident that the vibration response of the individual components of the shaft-hub-blade system needs to be measured to identify the actual cracked component.***

Index Terms**:** ***crack simulation, Finite Element Analysis, Natural Frequencies, shaft-hub-blade system.***

I. INTRODUCTION

Rotating components of a machine are subjected to fatigue loads which lead to their failure. These loads generally produce faults such as misalignment, unbalance, looseness, crack etc. Because of these faulty conditions, rotating components vibrate with varying natural frequencies which will affect the designed life of the component. So, it must be ensured that the regular measurement of natural frequencies of such components helps to detect the fault and later to diagnose. This technique is commonly known as vibration based condition monitoring.

Condition monitoring should help to detect any type of the fault and quantify its magnitude. For instance, a crack present in any component of a machine must be identified with its location and severity. This can be achieved by utilizing advanced tools available in the field of condition monitoring. Sekhar and Prabhu [1] developed finite element models of damaged components to evaluate the effect of crack on vibrational characteristics. Krawczuk [2] studied the static and dynamic behavior on a cracked composite cantilever beam by applying finite element method. Orhan [3] modelled the shear compliance of crack with finite elements in a beam of composite material to study the vibrations in transverse direction. Ostachowicz and krawczuk [4] studied the changes in the natural frequencies of the cantilever beam under the influence of two cracks. The type of crack introduced was double sided open crack which is practical situation of fracture produced due to cyclic loading. Dimarogonas [5] reported a complete review of crack effects on dynamic behavior of structures like beams, rotors, blades, pipes, bars, plates etc.

The damage in a beam was considered as the reduction in the cross sectional area with definite depth at a certain location [6,7]. It was then analyzed for the changes in the natural frequencies and mode shapes. Gasch [8] established equality between two shafts with one having crack and other having unequal cross sections. Mayes and Davies [9] employed reduction in cross section of the shaft to analyze the damage. Grabowski [10] utilized the model formulation to derive an analytical model and obtained a set of discrete, periodic time varying coefficients equations for a cracked shaft. Chondros and Dimarogonas [11] investigated a cantilever beam with a welded support for the change in natural frequency with varying crack depths. Dimarogonas and Paipetis [12] developed a coupled stiffness matrix of a cracked beam with rectangular cross section subjected to axial and bending loads Waikar and Katekar [13] observed the change in the dynamic behavior of a rotor system due to cracks developed in the high stress regions when subjected to fluctuating loads. Vaibhav et. al [14] carried out the modal analysis to study the harmonic and transient dynamic response of structures. Patil and Varna [15] conducted experiments of cracked beams of various cross sections and analyzed natural frequencies for locating the crack using fuzzy logic.

The aim of this paper is to evaluate the natural frequencies of the shaft-hub-blade system for both healthy and cracked conditions. Then comparison is made to study the effect of crack in any of the component of the system.

II. GEOMETRIC AND FINITE ELEMENT MODELLING OF SHAFT-HUB-BLADE SYSTEM

A. Geometric Modelling of rotor with blades

A Shaft is modelled with a diameter of 20mm and length of 600mm to which four blades each having a length = 200mm, width = 20mm and thickness = 5mm are attached on a hub with an outer diameter of 50mm, inner diameter of 20mm, and length of 50mm. Assembly of all the components is done and is shown in Fig. 1.

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B. Finite element modelling of the shaft

The objective of the present work is to evaluate the natural frequencies and mode shapes of a shaft-hub-blade system to study the effect of crack on its dynamic behaviour.

The modal analysis was carried out based on finite element method using ANSYS Software. For the meshing of the shaft-hub-blade system an 8-noded rectangular solid brick element with the edge length of 4mm was used as shown in Fig. 2

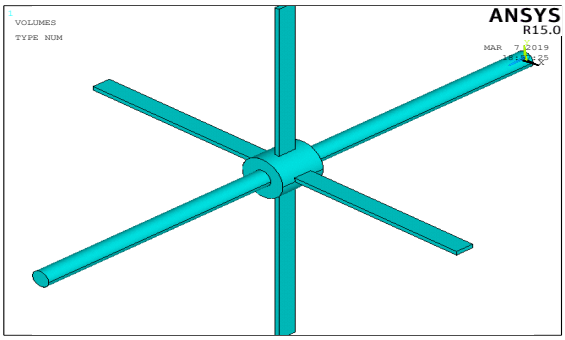

Figure 1: Geormetric model of shaft-hub-blade system

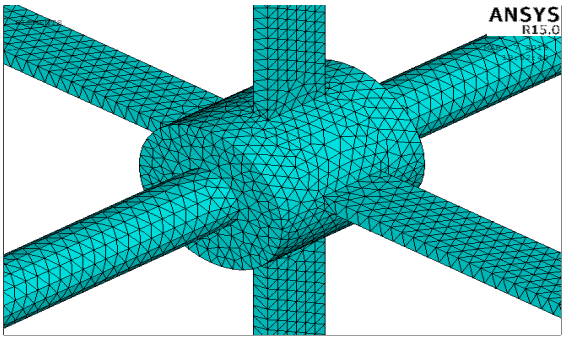

Figure 2: Finite element model of rotor with blades

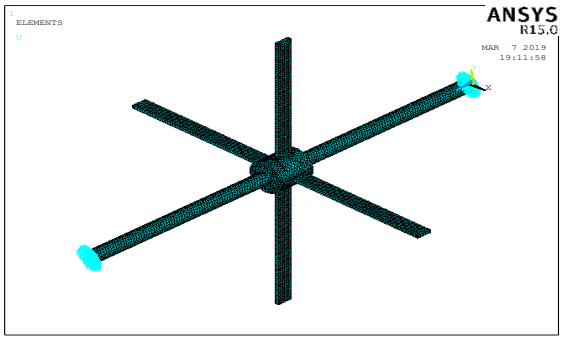

Figure 3: Simply supported supports at both ends

Appropriate boundary condition for the shaft-hub-blade system was provided in order to specify the real time support provided by bearings.

C. Geometrical modelling of blade with a crack

For the shaft, a U shaped slot has been made by saw cut as shown in Fig. 4. The zoomed portion of the crack on the shaft and the blade are shown in the Figs. 4(a) and 4(b) respectively.

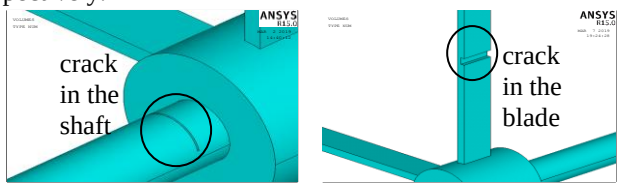

Figure 4: Crack in the (a) shaft and (b) blade

III. RESULTS AND DISCUSSIONS

A. Healthy system

The finite element modal analysis was carried out to determine the natural frequencies. According to the results obtained from the ANSYS, the natural frequencies for the shaft-hub-blade system are 75.012Hz, 599.04Hz and 893.71Hz. It is observed from the results that no vibration was recorded in the blades when the system is vibrating in the first mode as shown in Fig. 5. But for the second and third mode shapes of the shaft, blades are vibrating in the first and second modes as shown in Figs. 6 and 7 respectively.

B. Crack simulation in the shaft

The natural frequencies of the system with a crack having dimensions of depth = 2.5mm, length = 20mm and width = 10mm located at a distance of 10mm from one end of the hub was considered. The natural frequencies of the cracked shaft are found to be 72.08Hz, 597.12Hz and 868.28Hz for the first, second and third modes respectively.

Table 1: Comparison of natural frequencies of healthy and cracked shaft

Natural Frequency	Healthy shaft (Hz)	Cracked Shaft (Hz)
First mode	75.012Hz	72.08Hz
Second mode	599.04Hz	597.12Hz
Third mode	893.71Hz	868.28Hz

It can be observed from the table 1 that the natural frequencies of the cracked shaft got reduced compared to that of the healthy shaft and the deviation is quite appreciable in third mode and is shown in Fig. 8.

C. Crack simulation in the blade

As the first case a small cut of 1 mm width was modelled in the single blade at three different locations of 50mm, 100mm and 150mm from the hub. In the second case cracks were modelled in two blades adjacent or opposite to one another. Crack simulation details for each case are discussed in the following sections. And later one cracked blade is analyzed for the dynamic behaviour.

The natural frequencies of the first three mode shapes of the shaft-hub-blade system with crack in the single blade at three different locations are given in the table 2 and the third mode of the cracked shaft-hub-blade system is shown in Fig. 9.

Table 2: Natural frequencies of shaft-hub-blade system with crack in a blade

Natural Frequency	50mm	100mm	150mm
First mode	74.78	74.99	75.11
Second mode	597.8	596.7	599.1
Third mode	894.2	886.2	893.9

To understand the dynamic behavior of the shaft-hub-blade system with two cracks in the adjacent blades, natural frequencies were evaluated with cracks located at 100mm from the hub in both the blades and are given in table 3.

Table 3: Comparison of natural frequencies of healthy and cracked blades adjacent to each other

Natural Frequency	Healthy Shaft (Hz)	Cracks in adjacent blades (Hz)
First mode	75.012Hz	74.92Hz
Second mode	599.04Hz	596.88Hz
Third mode	893.71Hz	884.11Hz

In some cases cracks may occur in the blades opposite to one another. So, natural frequencies are also evaluated for the shaft-hub-blade system with two cracks located at 100mm length of the each blade opposite to one another.

The deviation of the natural frequencies of the first three modes with respect to the healthy system is given in the table 4 and the second mode of the faulty system is shown in Fig. 11.

Table 4: Comparison of natural frequencies of healthy and cracked blades opposite to each other

Frequency	Healthy shaft	Cracked Shaft
First mode	75.012Hz	74.91Hz
Second mode	599.04Hz	594.60Hz
Third mode	893.71Hz	878.05Hz

From the analysis of shaft-hub-blade system with crack simulation either in the shaft or the blades, it is observed that the deviation of the first and second mode natural frequencies is very negligible and the third mode natural frequency got reduced with appreciable value. So, any decrease in natural frequencies of the system is observed it indicates the presence of crack in any one of the component in the system. Thus to locate the crack further analysis is to be carried out for individual components.

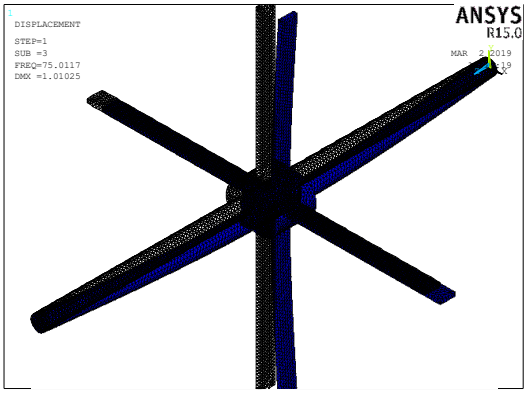

Figure 5: First mode of the healthy system

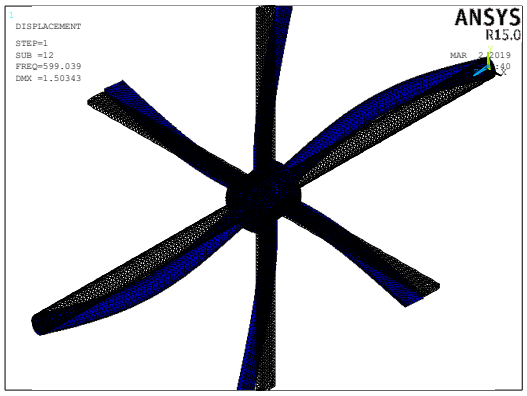

Figure 6: Second mode of the healthy system

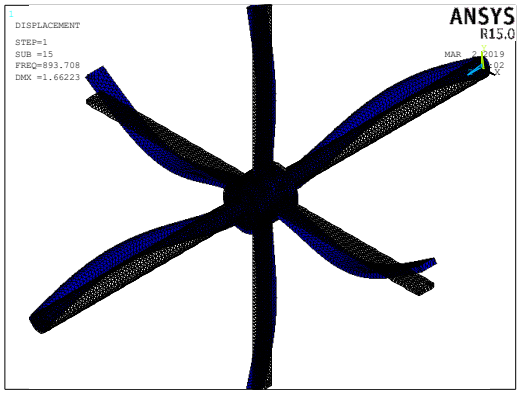

Figure 7: Third mode of the healthy system

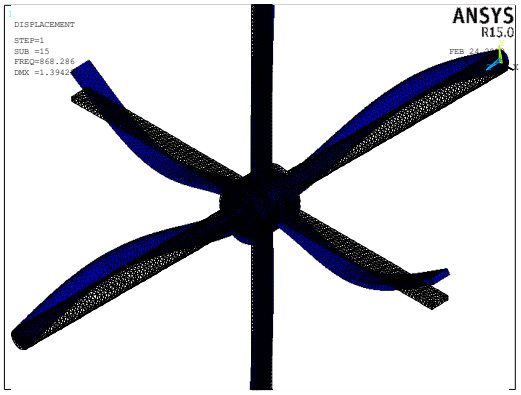

Figure 8: Third mode of the system with crack in shaft

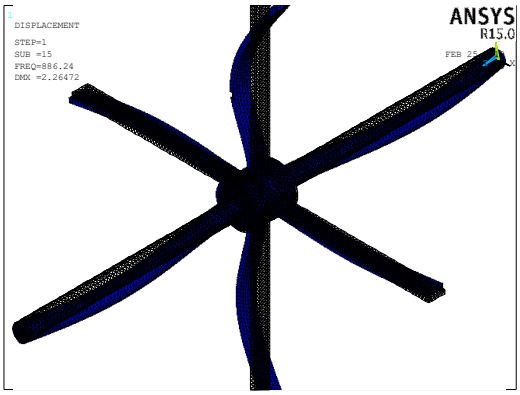

Figure 9: Third mode of the system with crack in single blade

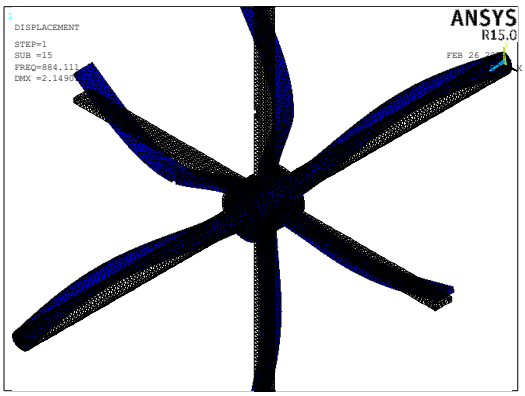

Figure 10: Third mode of the system with two cracks in the adjacent blades

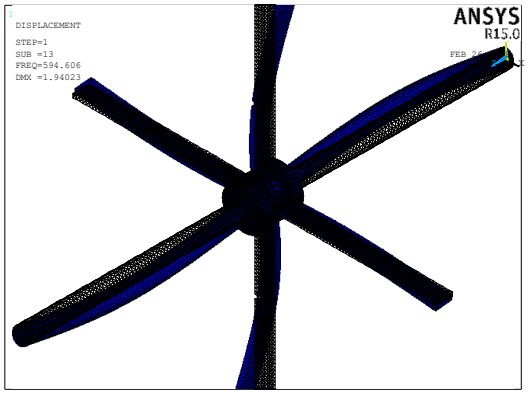

Figure 11: Second mode of the system with two cracks in the opposite blades

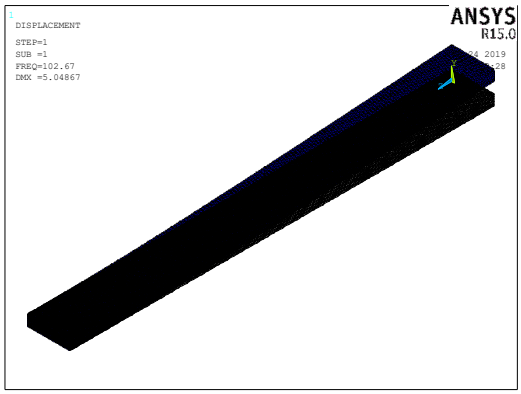

Figure 12: First mode of cracked blade

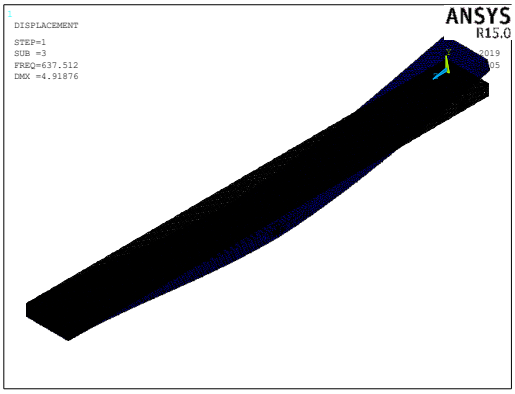

Figure 13: Second mode of cracked blade

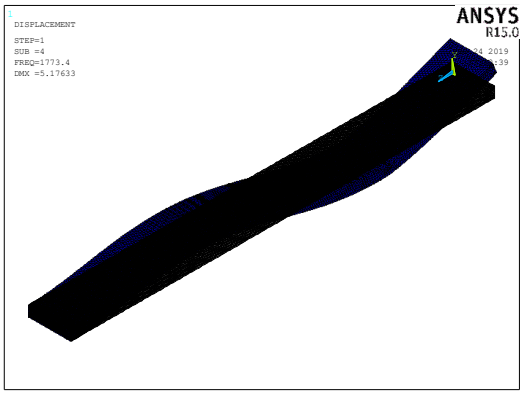

Figure 14: Third mode of cracked blade

D. Crack Simulation in an individual blade

To study the effect of crack in the blade, modal analysis was carried out on the blade taken out from the shaft-hub-blade system. Crack is introduced in the blade at three different locations i.e. 50mm, 100mm and 150mm from the fixed end. The natural frequencies for the first three modes are given in the table 5. The decrease of first, second and third mode natural frequency is more for the crack located at 50mm, 100mm and 150mm and are shown in Figs. 12, 13 and 14 respectively.

Table 5: Comparison of natural frequencies of healthy and cracked individual blade

Natural Frequency	Healthy blade	50mm	100mm	150mm
First mode	107.85	102.67	106.80	108.37
Second mode	693.64	677.25	630.51	660.74
Third mode	1878.72	1869.8	1891.22	1773.4

From the results obtained from the modal analysis of the shaft and the blade, their vibration response with crack simulations help to predict the fault like crack in the shaft-hub-blade system.

IV. CONCLUSION

Modal analysis of shaft-hub-blade system is performed using ANSYS software. The natural frequencies of the system were evaluated with crack in the shaft and the blades. Shaft was given with simply supported boundary conditions and the blade as cantilever boundary condition. From the analysis it can be concluded that

- Appreciable reduction of natural frequencies was observed for the cracked shaft compared with that of the healthy shaft
- The modes of vibration of the blades are not matching with that of the shaft. For the given mode of vibration of the shaft, blade is vibrating in the previous mode
- Reduction of natural frequencies was negligible for the shaft-hub-blade system when the crack is in the single blade, adjacent blades or opposite blades
- Natural frequencies of the blade are to be measured to study the influence of crack in the blade
- First mode natural frequencies of the blade are effected when the crack is located near the fixed end, second mode natural frequencies are effected when the crack is in the middle of the blade and third mode natural frequencies are effected when the crack is near the free end

This analysis helps in identifying the effect of crack in the vibrational behavior of applications like turbo machineries, air compressors, pimps and fans that are similar to shaft-hub-blade system.

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