

An Experimental and Numerical Investigation on Static Vibration Response of Multi-Cracked Rotor Shaft

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Abstract. Many process industries make wide use of rotating machineries such as engines, pumps and turbines. It is seen that heavy-duty and high-speed shafts develop cracks due to fatigue at some time during their life cycle. Under certain conditions, the catastrophic failure of shaft unavoidable as stress required for propagation is smaller than that required for crack initiation. The above conditions mean that the detection, diagnosis and analysis of crack plays important role in reliable operations. Using measurement of vibration characteristics condition of the machine periodically monitored. Many researchers have analyzed the nonlinear dynamic analysis of cracked rotors. In this paper, the experimental investigation has been carried on single and multi-transverse cracked rotor shafts by measurement of static vibration characteristics. The present study aims to, experimental investigation of the vibration response of uncracked, single cracked and multi-cracked rotor shaft with different size and locations of cracks. The experimental setup has been developed for measurement of natural frequency. The changes in the shaft's natural frequencies are investigated experimentally. Natural frequencies have been obtained through vibration analyzer system using impact hammer test under static conditions. The results obtained through experimentation conform to the numerical results obtained in ANSYS.

1. Introduction

Many process industries make wide use of rotating machineries such as pumps, engines and turbines. Rotating machineries consists of shaft carrying disks are broadly used in many different applications. It is seen that heavy-duty and high-speed shafts develop cracks due to fatigue at some time during their life cycle. There are some constraints, such as sharp keyways, sudden cross sectional change, metallurgical factors, different types of fits, grooves, and other stress concentration factors that endorse the crack initiation, which lead to cracks. Under certain conditions, the catastrophic failure of shaft unavoidable as for propagation of crack stress required less than that necessary for initiation.

To investigate the behaviour of a cracked shaft and to avoid catastrophic failure, the dynamic behaviour of cracked rotor studied exhaustively since 1970's in various aspects. J. Wauer [1], R. Gasch [2], A. D. Dimarogonas [3] and G. Sabnavis [4] presented reviews on dynamic behaviour of cracked rotor shaft and damage detection with different diagnostic techniques.



Tong Zhou Zhengce considered one transverse crack due to fatigue based on the Jeffcott rotor model. A. S. Shekar [6] analyzed response of cracked rotors with two open cracks. S.C. Huang [7] and A. K. Jain et al. [7] investigated on vibration and stability of shaft with single transverse and multi cracked rotor shaft. In this present study, the possible approach presented which provide the prediction of changes dynamic behaviour of rotor shaft which real time based diagnosis method to predict the behaviour of a crack in order to avoid catastrophic failure. T. Ramesh Babu et al. [12] have considered transient analysis for rotor bearing system with transverse breathing open crack. Zhou [13] studied vibration response in frequency demine and suggested method of diagnosis at critical speed of cracked rotor. Davies [14], Imam [15], Lee [16] carried out experimental vibration analysis and compared with theoretical results. However, in many research papers results are obtained by simulation analysis. It is found very few papers deals with experimental analysis of multi-cracked rotors.

In this paper, the experimental study has been carried to present the possible approach, which provides the prediction of changes static behaviour of single, and multi cracked rotor shaft. This paper describes methodology and analysis carried out to predict the fault in multi cracked rotor, which was very few authors addressed. T Rastogi V. [08] has used the concept of analysis of vibration by measurement of natural frequencies for analysis of single and multi-cracked rotor shafts. In this paper the concept of experimental measurement of natural frequency has been used further to different cases of single and multi-cracked rotor shaft. The analyses of vibration response of the rotor shaft have been carried out in static condition by measurement of change in natural frequency by impact hammer test. The results obtained by experimentation validated using numerical results obtained in ANSYS.

2. Experimentation Study

The impact hammer test used to obtain natural frequencies at different crack condition. The experimental set up used for finding the natural frequency is shown in Figure 1. The experimental setup consists of shaft specimen for which measurement has been carried out. The one end of shaft is held in chuck of the lathe machine and other end overhang as shown in figure 1. The FFT Analyzer used to measure natural frequency as shown in figure. The impact hammer test gives natural frequencies of any component in static conditions as the hammer impulse are of constant force and applied over wide range of frequency so that it capable for excitation in all resonances in that range. The obtained Frequency Response Function (FRF) imparts the modal parameters which are necessary in calculating natural frequency of component.

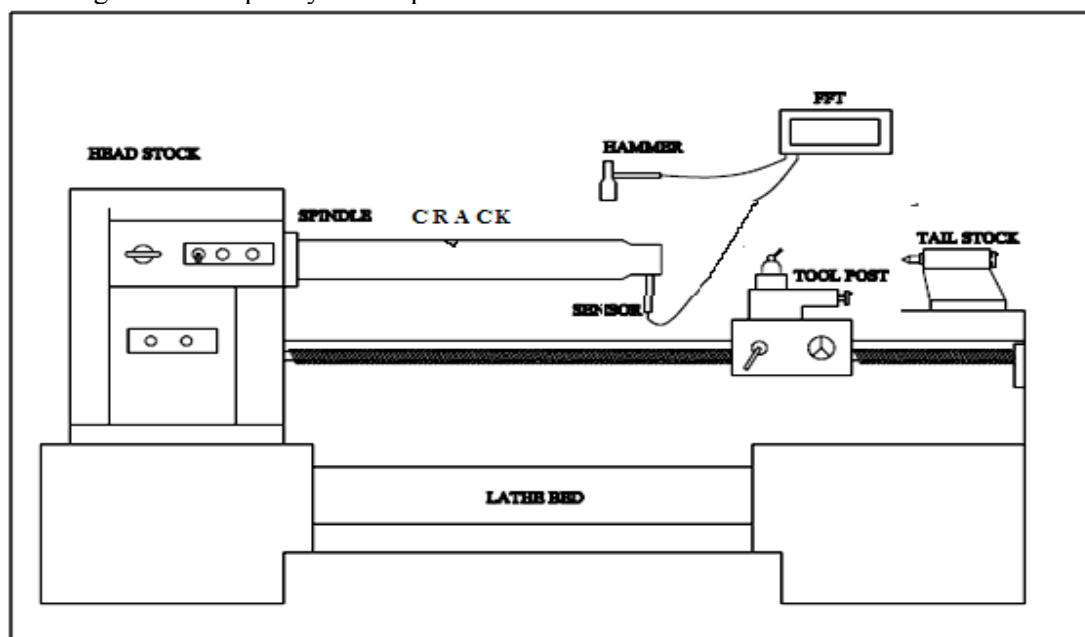


Figure 1. Experimental set up used for finding the natural frequency



Figure 2. Different cases of shaft

The shaft specimens as shown in figure 2. Following are the cases selected for the static experimental analysis:

- 1 Case I: Uncracked Shaft
- 2 Case II: Single Cracked Shaft(5mm*3mm)
- 3 Case III: Multi-Cracked Shaft (6mm*3mm ; 5mm*3mm)
- 4 Case IV: Multi-Cracked Shaft (7mm*3mm; 6mm*3mm)
- 5 Case V: Multi-Cracked Shaft (8mm*3mm ; 7mm*3mm)
- 6 Case VI: Multi-Cracked Shaft (9mm*3mm; 8mm*3mm)
- 7 Case VII: Multi-Cracked Shaft (10mm*3mm; 9mm*3mm)

The specifications of shaft used in the experimentation are shown in Table.1

Table 1. Shaft specifications	
Shaft material	Mild Steel
Effective length (Bearing to bearing)	660 mm
Overhang (Each side)	175 mm
Diameter of shaft	22 mm
Weight of shaft	1.80 Kg
Density	7900 Kg/m ³
Stiffness	275 N/mm

The transverse cracks are created with the help of fine jewel saw. The dimensions for single cracked considered of 3 mm of diameter and in the range of 0-14 % of the diameter of shaft. The above mentioned cases of crack depth have been considered for analysis.

The present study categories the measurement of natural frequency at crack condition on shaft as mentioned above. The experiments are performed with the help of ADASH VA4 FFT analyzer, which is shown in figure 4 and 5.



Figure 3. VA4 FFT Analyzer

Figure 4. Accelerometers

Figure 1. Shows an experimental set up in which the shaft hold on lathe chuck. The one of shaft is fixed to minimize the effect of weight of accelerometer on the natural frequencies of the shaft. An accelerometer is mounted on lathe chuck and the impact hammer is connected to FFT analyzer with the help of cables as shown in figure. The output of FFT analyzer is connected to computer system which displays required results. This test has been performed with the help of ADASH VA4 FFT Analyzer.

The each specimen stroked at centre of shafts with the impact hammer, the resultant response measured by an accelerometer. Similarly, tests are carried out for different cracked specimens and uncracked specimen. The experiments have been performed at different cases as mention above and FRF's obtained on the screen of the FFT analyzer shows the natural frequencies obtained. Some of the FRF's are shown Figure.6-7.

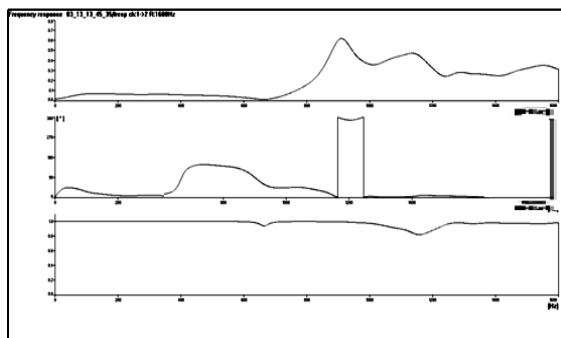


Figure.5. FRF's obtained uncracked shaft

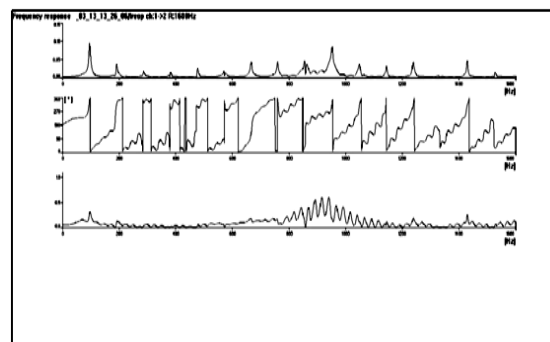


Figure.6. FRF's obtained Single cracked shaft

By observing, the FRF's obtained for different cases the condition of change of phase at peak amplitude has been selected. For each case natural frequency has been obtained with impact hammer test and the values of natural frequency noted in Table 3.

3. Simulation Study

The numerical investigation has been carried out with finite element analysis. The finite element model of each case has been developed using CATIA solid modeling software. The element convergence has been carried out with considering different element length for tetrahedral element as shown in Table 3. After modelling, analysis was carried out to find the natural frequency and deflection for each of shaft as above mentioned. Mode shapes can be defined by the amplitude of displacements of all the mass points during the vibration of the structure at natural frequencies. The analysis was carried out in the absence of damping and load. Twelve modes and its natural frequencies were determined. The above analysed mode shapes give information about behaviour of each cases which have been considered for investigation. FEA gives 12 mode shapes of each cases in which first six mode having negligible value so these were neglected. The mode number eight used for comparison as experimentation have been carried out in that direction. The modal data and results were used for the comparison of experimental results shown in table 2. Figure 7-14 shows behaviour of all cases at fundamental frequency mode shapes.

Table: 2 Element convergence with deformation for FEA	
No. of Element	Deformation
11	39.32
09	37.08
8	36.11
6	31.79
4	31.75

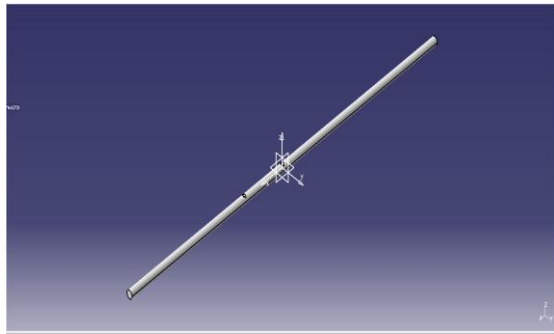


Figure 7. CATIA solid modeling

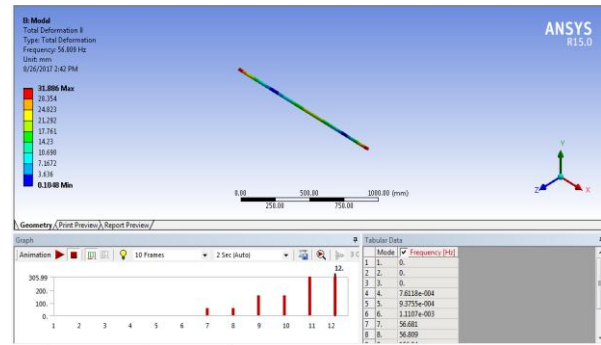


Figure 8. Case I: Uncracked shaft

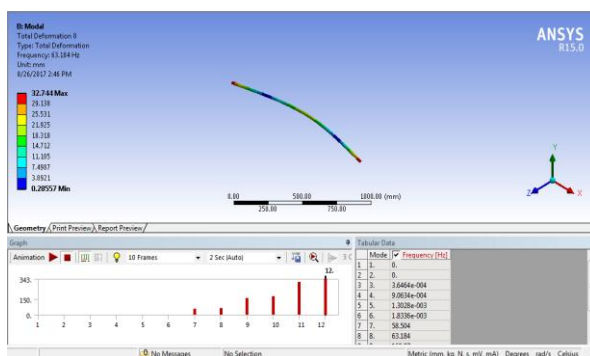


Figure 9. Case II: Single cracked shaft

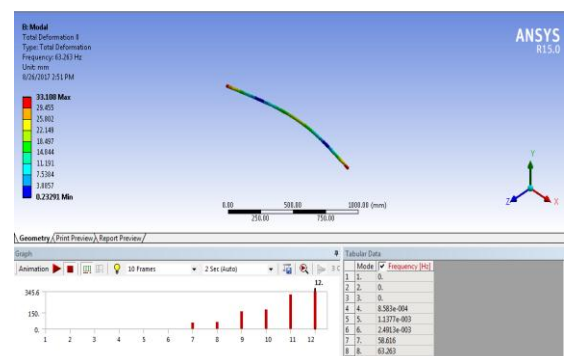


Figure 10. Case III: Multi-cracked shaft

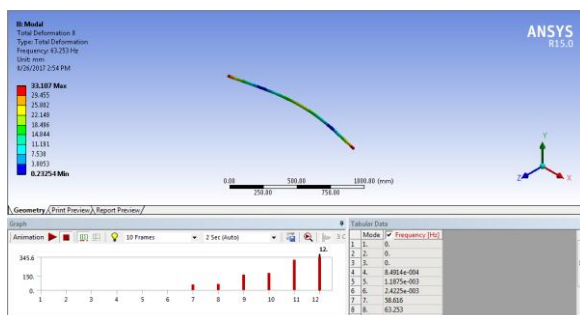


Figure 11. Case IV: Multi-cracked shaft

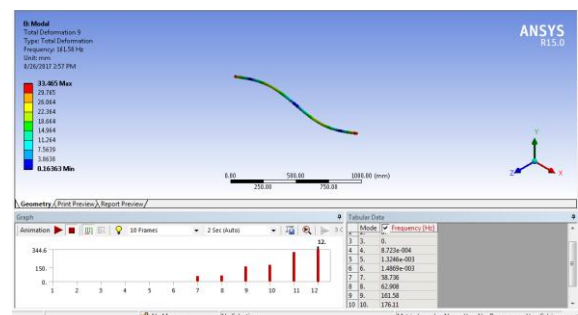


Figure 12. Case V: Multi-cracked shaft

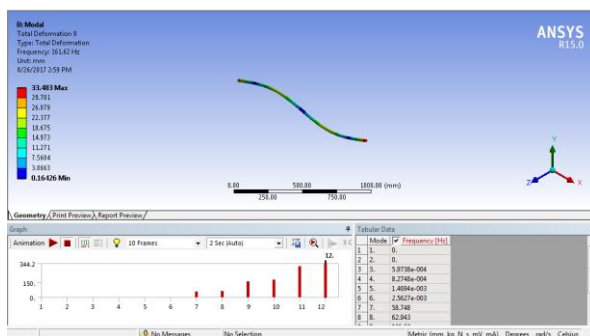


Figure 13. Case VI: Multi-cracked shaft

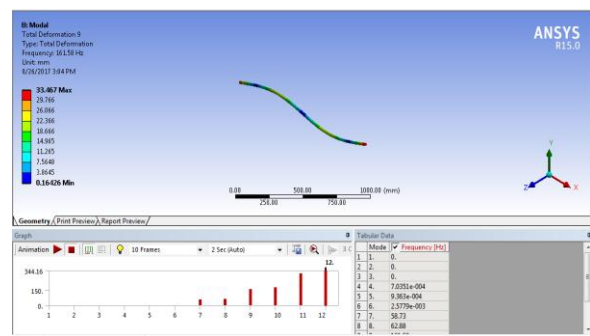


Figure 14. Case VI: Multi-cracked shaft

Table 3. Fundamental frequency by Experimentation and Numerical Analysis at 8th Mode shape

Cases	Experimental Frequency (Hz)	Simulation Frequency (Hz)
Case I: Uncracked Shaft	110.5	90.58
Case II: Single Cracked Shaft	95	76.22
Case III: Multi-Cracked Shaft (6mm*3mm ; 5mm*3mm)	86.5	71.08
Case IV: Multi-Cracked Shaft (7mm*3mm; 6mm*3mm)	85	70.92
Case V: Multi-Cracked Shaft (8mm*3mm ; 7mm*3mm)	85.3	70.79
Case VI: Multi-Cracked Shaft (9mm*3mm; 8mm*3mm)	85	70.49
Case VII: Multi-Cracked Shaft (10mm*3mm; 9mm*3mm)	83	70.22

4. Conclusions

The main objective of this paper is to investigate experimentally the vibration response of rotor shaft containing single and multi transverse crack of different size and locations. The main point is to put the effect of multi-cracked on rotor shaft under static condition. The vibration responses obtained by experimentation coincides with software results. The experimental investigation shows

1. It is observed that for the multi cracked shaft vibration amplitude increases than the single cracked shaft.
2. It is observed that in case of single cracked shaft vibration amplitude increases as the size and location of crack changes and for multi- cracked shaft vibration amplitude increases as the size and location of crack changes.
3. It is found as crack depth increases vibration amplitude increases.
4. The natural frequency difference is more for single and uncracked shaft but there is little difference in natural frequency of single and multi cracked shaft observed. [8]

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