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Study of Influence of Crack on Transmission Shaft by Finite Element Analysis

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Abstract: *Cracks are most common defects which can develop due to fatigue in structure and machine elements. Fatigue cracks are responsible for catastrophic failures. Cracks are the threat to an uninterrupted operation and performance of the modern day machines. The crack occurs in rotating shafts where detection of cracks is difficult due to inspection difficulties. The problem of rotating cracked shafts has been investigated for a long time. Two main features have been recognized: (1) the local flexibility introduced by the crack in relation to the affected shaft sections; (2) the opening–closing phenomenon of the crack during rotation called as breathing mechanism of the crack. Various researchers have studied the response of cracked shafts. The work on the diagnosis of crack has been mainly based on vibration signature. The changes in the vibration response in the form of changes of frequency composition have been found to be some of the important crack indicators. These vibration-based techniques have been applied to a variety of engineering structures, such as beams, trusses, rotors, etc. In this work, the influence of transverse crack in a shaft is analyzed. Vibration parameters are obtained from a simulation employing the Finite Element Method using modal analysis for different crack depths. The unique relation between the natural frequencies and modes shapes with crack depths is employed to relate failure patterns of different points of the shaft.*

Keywords: *Crack, Vibration Parameters, FEA*

I. Introduction

Rotating shafts are broadly used in many mechanical applications like pumps, engines and turbines. Material irregularities, uncertain usage patterns (e.g. random overloads and sudden jerks) and environmental conditions (e.g. fluctuations in temperature and humidity) may adversely affect the service life of mechanical systems to cause performance degradation and unanticipated failures. It is observed that high speed and heavy duty shafts develop transverse cross-sectional cracks due to fatigue at some time during their life period. Cracks present a serious threat to an uninterrupted operation and performance of the machines. In order to reduce the possibility of failure in operation, the investigation and prediction of the dynamic behavior of such rotating machines have become increasingly important in the early stage. Once a crack is initiated it propagates and the stress required for propagation is smaller than that required for crack initiation. After many cycles operating stresses may be sufficient to propagate the crack. The crack propagation takes place over a certain depth when it is sufficient to create unstable conditions and fracture take place [1]. It is important to develop new non-destructive techniques to predict the behavior of a crack in order to avoid human and economical disasters. Machinery diagnostics for maintenance of a structure or machine can be done using accelerometers by monitoring its amplitudes of frequency response. Transverse cracks in the shaft modify the dynamic behavior of the system results in reduction of the rotor stiffness which changes the modal parameters and the acceleration amplitudes along the shaft [2]. Establishing a relation between these vibration parameters and the failure characteristics of the system will be useful to characterize and predict a failure in a rotor system. The influence of a transverse crack in the shaft of rotating machines on the associated dynamic behavior has been a focus of attention for many researchers. Generally, two different approaches are attempted to identify the presence of a crack in rotating structures. The first approach is based on the fact that the presence of a crack in rotating shaft reduces the stiffness of the structure hence reducing the natural frequencies of the original uncracked shaft [3]. Various theoretical and experimental works performed over the last three decades have indicated that the change in modal properties (natural frequencies and modes shapes) may be useful for the detection of a crack as well as for the identification of both crack depth and location.

II. Literature Overview

Many researchers investigated and tackled effect of cracks in the system. The wavelet-based crack detection method is used for measuring natural frequencies of cracked shaft with suitable vibrometer (Jiawei Xiang et. al. 2007). To gain the accurate frequencies this method utilizes combination of wavelet-based elements and genetic algorithm [2]. Itzhak Green and Cody Casey (2005) utilized two theoretical analyses consists of global and local asymmetry crack models to identify characteristics of the system response that may be directly attributed to the presence of a transverse crack in a rotating shaft [3]. A model consisting of an overhung whirling rotor is utilized to match an experimental test rig. A 2X harmonic component of the system response is the primary response characteristic resulting from the introduction of a crack. Once the unique characteristics of the system response are identified, they serve then as important observations for the monitoring system. A.S. Sekhar in the year 2007 proposed the identification techniques on multicracks in structures such as rotors, beam etc. using finite element model [4]. Xuanyang Leia et al. (2005) studied a vibration analysis of a crankshaft with slant crack in crankpin and prepared finite element model which can be applied for simulation and analysis of crankshafts with or without cracks [5]. A.K.Darpe (2007) developed a noval way to detect transverse surface crack in shaft which utilizes transient external torsional excitation at specific angular position of cracked shaft model and non-linear breathing phenomenon of cracks [6].

Wayne C. Haase, Michael J. Drumm (2002) developed a system to detect, discriminate and track fatigue cracks in rotating disks [7]. They primarily focused at jet engines in flight applications. The system is also important for detecting cracks in a spin pit during low cycle fatigue testing and for monitoring the health of steam turbines and land-based gas turbine engines for maintenance purposes. The results of this system are used to produce a physics-based model that describes the changes in the center of mass of a rotating disk using damping ratio, initial unbalance and crack size as parameters. Mitchell S. Lebold, Kenneth P. Maynard, et al.(2003) developed the method which resolves and tracks characteristic changes in the natural torsional vibration frequencies that are associated with shaft crack propagation [8]. A laboratory scale rotor test bed was developed to investigate shaft cracking detection techniques under controlled conditions. The test bed provided a mechanism to evaluate sensing technologies and algorithm development. After each crack growth in step, the specimen was evaluated using ultrasonic inspection techniques. This was followed by installation of the shaft in the rotor test bed and the observing the change in shaft torsional vibration features. B.S. Wang, Z.C. He (2007) proposed the numerical simulation and the model experiment upon a hypothetical concrete arch dam for the research of crack detection based on the reduction of natural frequencies. The influence of cracks on the dynamic property of the arch dam is analyzed. A statistical neural network is then proposed to detect the crack through measuring the reductions of natural frequencies [9].Shalabh Gupta et al. (2007) presents a novel analytical method for early detection of fatigue damage in polycrystalline alloys that are commonly used in mechanical structures. Time series data of ultrasonic sensors have been collected for detection in the statistical behaviour of structural materials [10].

The performance of this method has been evaluated relative to existing pattern recognition tools, such as neural networks and principal component analysis for detection of small changes in the statistical characteristics of the observed data sequences. J.R. Jain,T.K. Kundra (2003) proposed a model based technique for online identification of malfunctions in rotor systems [11]. Presence of fault changes the dynamic behavior of the system. This change is taken into account by equivalent loads acting on the undamaged system model. The mathematical representation of equivalent loads is referred to as Fault Model. This work focuses on developing a fault model for a transverse fatigue crack in shaft and testing it through simulated studies. T. Ramesh Babu, A.S. Sekhar (2008) studied effect of multi-crack on shaft and developed the solutions or the combinations of parameters characterizing the cracks consists of a new technique called amplitude deviation curve (ADC) or slope deviation curve (SDC) which is a modification of the operational deflection shape (ODS) [12]. Chong-Won Lee and Sung-Woo Kang developed the complex model testing method for linear rotor systems in which the directional frequency response is used for identification of system asymmetry as open crack. They initially generate unbalance force to keep the crack open and then proposed the complex model testing and its effectiveness is experimentally demonstrated for detecting breathing crack [13]. Robert Gasch (2008) studied the dynamic behaviour of a one disc rotor (Laval rotor) having a transverse crack in the elastic shaft. With the help of a simple crack model the non-linear equations of motion are derived but due to the effect of weight in the elastic deflection of the horizontal shaft, the equations can be simplified to linear but time-variant equations [14]. The work was focused on forced vibrations due to crack and unbalance, the orbit decomposition into forward and backward whirls which can be helpful tool for understanding the complicated dynamic phenomena. A.K. Darpe and K. Gupta et al.(2006) developed the equations of motion of the rotor with a transverse surface crack with a bow are formulated and steady state and transient response analysis of the rotor is studied [15]. The purpose of the study is to assess the effect of the residual bow on the stiffness characteristic of the rotating cracked shaft and changes if any.

It has been observed that the usual level of bow may not significantly influence the stiffness variation and the nonlinear nature of crack response is not significantly altered. However, the bow completely masks the sensitivity of orbital response of cracked rotor to unbalance phase at half the critical speed and the use of influence of unbalance phase on orbital response at half critical speed of cracked rotor cannot be used for the detection purposes. N. Bachschmid, P. Pennacchi and E. Tanzi (2007) obtained some results in laboratory tests for the dynamical behaviour of cracked rotating shafts and also analyse its typical static and dynamic behaviours which is used to formulate the models which allow the behaviour of cracked shafts to be accurately simulated [16]. Andrew L. Gyekenyesi at al (2003) describes the analytical results concerning the detection of a crack in a rotating disk. The concept is based on the fact that the development of a disk crack results in a distorted strain field within the component [17]. As a result, a minor deformation in the disk's geometry as well as a change in the system's center of mass occurs. They also conducted Finite element analyses concerning a notched disk in order to define the sensitivity of the method. The notch was used to simulate an actual crack and will be utilized for upcoming experiments. J. Howard Maxwell and Darryl A. Rosario (2001) developed a model to predict the vibration caused by a pump shaft crack that combined a crack propagation model and a rotor dynamics model which is calibrated by the actual vibration data. An inspection of the pump rotor during replacement revealed a completely different kind of crack not previously seen on this type of pump [18]. The modeling performed that indicated that the surface rolling would slow crack growth and a description of the actual crack found.

III. Finite Element Analysis

Finite element analysis (FEA) has become commonplace in recent years. Numerical solutions to even very complicated stress problems can now be obtained routinely using FEA and the method is so important that even introductory treatments of Mechanics of Materials should outline its principal features. Finite element codes are less complicated than many of the word processing and spreadsheet packages found on modern microcomputers. Nevertheless, they are complex enough that most users do not find it effective to program their own code. A number of prewritten commercial codes are available representing a broad price range and compatible with machines from microcomputers to supercomputers [16]. In practice, a finite element analysis usually consists of three principal steps:

1. **Preprocessing:** The user constructs a model of the part to be analyzed in which the geometry is divided into a number of discrete sub regions, or elements, connected at discrete points called nodes. Certain of these nodes will have fixed displacements and others will have prescribed loads. These models can be extremely time consuming to prepare.
2. **Analysis:** The dataset prepared by the preprocessor is used as input to the finite element code itself which constructs and solves a system of linear or nonlinear algebraic equations
   $Kijuj = fi$

Where, u and f are the displacements and externally applied forces at the nodal points. The formation of the K matrix is dependent on the type of problem being solved. One of FEA's principal advantages is that many problem types can be addressed with the same code merely by specifying the appropriate element types from the library.

3. **Post processing:** A typical postprocessor display overlays colored contours representing stress levels on the model showing a full-field picture similar to that of photoelastic or moire experimental results. In this study, Finite Element Method is employed to model the cracked and uncracked shaft to verify theoretically the sensitivity and uniqueness of the acceleration response in the frequency domain for different crack depths. Figure 3.1 shows model of uncracked shaft. The shaft is considered with a transverse open crack of upto 0.8 mm width for the purpose of the analysis as shown in figure 3.2. The open crack is considered as a small element with reduced stiffness within the finite element model. Only one crack is assumed for this study and external damping was neglected.
4. **Model Geometry and Properties:** A finite element model of the shaft is developed using Preprocessor: FEMAP as shown in Figure 3 and Solver: NX/Nastran. Tetrahedron 10-noded element used was used. The model inputs were given based on dimensions and properties.

4.1 Various modes vibration of the uncracked shaft is as follows:

Modes are further characterized as either rigid body or flexible body modes. All structures can have up to six rigid body modes, three translational modes and three rotational modes. If the structure merely bounces on some soft springs, its motion approximates a rigid body mode. Many vibration problems are caused or at least amplified by the excitation of one or more flexible body modes. The fundamental modes are given names like Bending (as shown in figure 3 and 4) and Twisting as shown in figure 5.

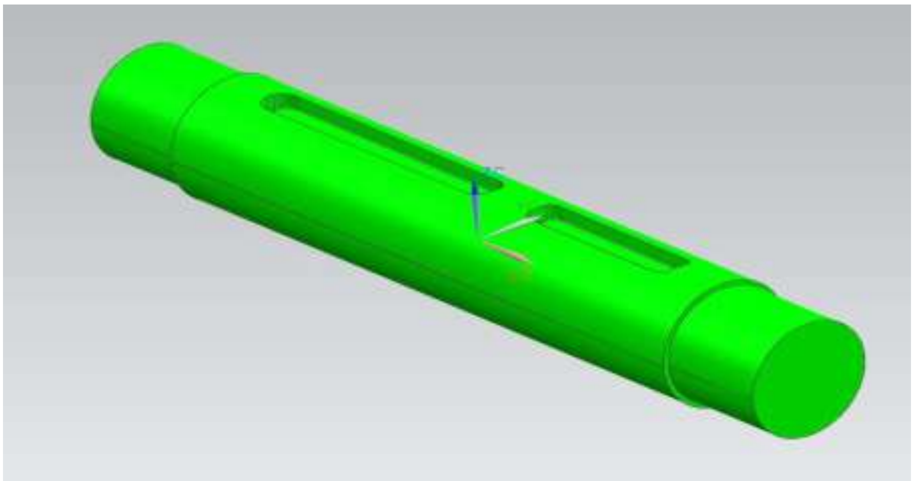

Fig. 1 Uncracked Shaft

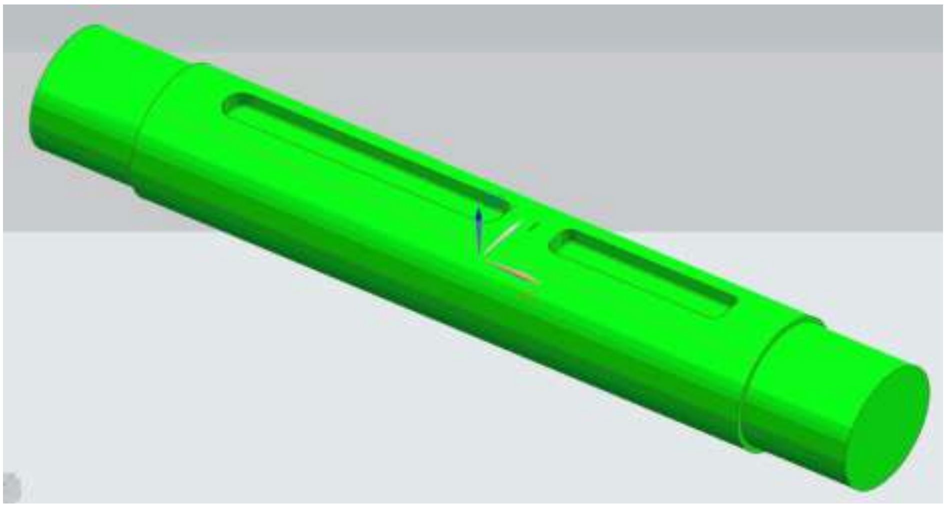

Fig. 2 Cracked Shaft with 1mm crack depth

1. Bending Mode in ZX Plane

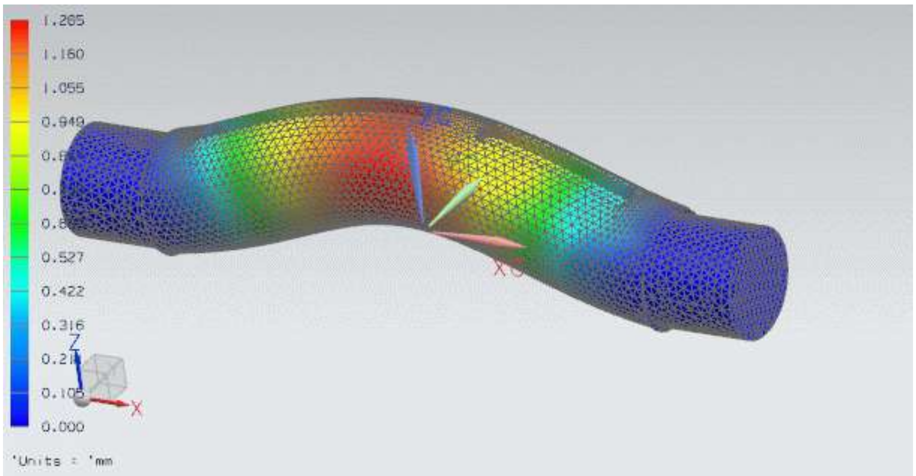

Fig. 3 Bending Mode in ZX Plane

Figure 3 and 4 shows vertical bending in ZX plane and bending in XY plane respectively. Due to vertical bending the crack gets open and close when the crack is near the center of the shaft. This is known as breathing behavior. Study of uncracked as well as cracked shaft model shows that the shaft likely to get fracture due to vertical bending hence it is considered as critical mode.

2.Bending Mode in XY Plane

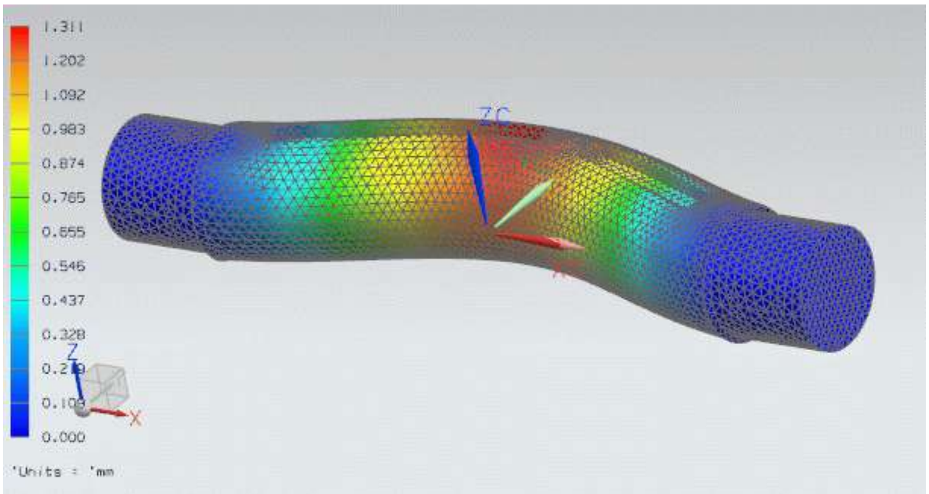

Fig. 4 Bending Mode in XY Plane

3. Twisting Mode about X- axis

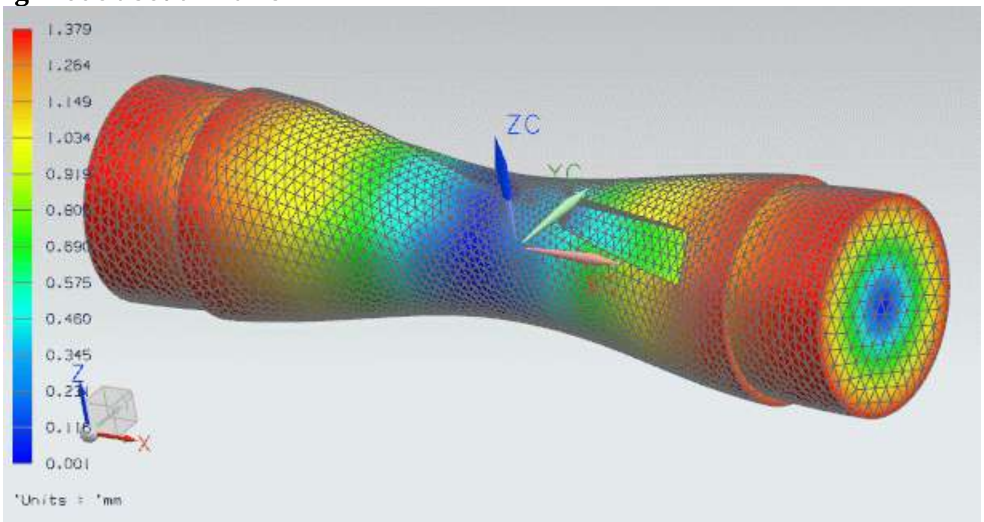

Fig. 5 Twisting Mode

Figure 5 shows twisting mode in X axis. Twisting mode results into torsional vibrations. Most of the machines used in industries are rotary in nature and hence are subjected to torsional vibrations. These vibrations can damage the machine components. Torsional vibrations are harder to detect and hence are more dangerous.

4 Bending Mode in ZX Plane with two nodes

Fig.6 shows the higher frequency mode shape. These modes are usually more complex in appearance and therefore don't have common names. The mode shapes with two and three nodes are examples of higher frequency mode shapes. Figure 7 shows the graph of variation of natural frequency in Hz with the crack depth in mm obtained from Finite Element Analysis.

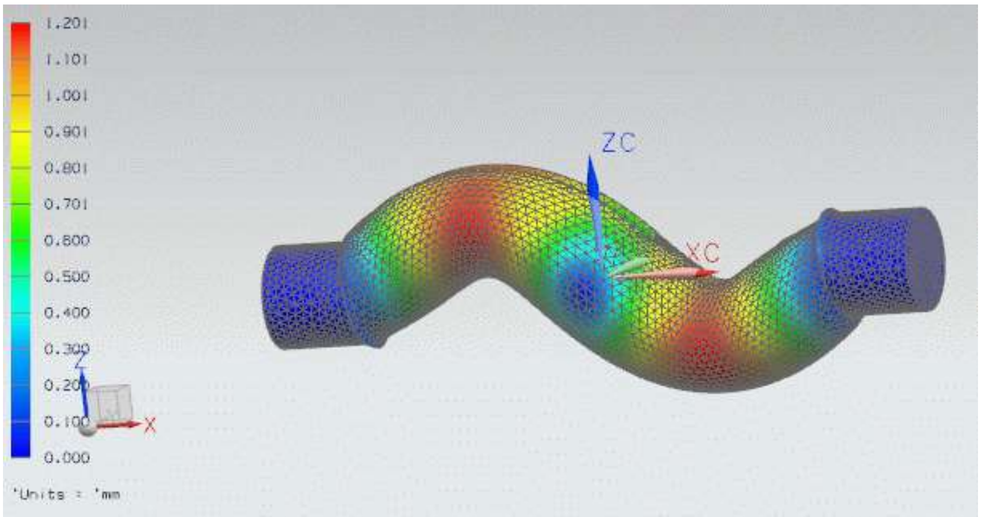

Fig. 6 Bending Mode in ZX Plane with two nodes

Table 1 Natural frequencies for the uncracked shaft and cracked shaft with the variation of the crack depth using FEA

Mode	Natural frequency (Hz)	Uncracked shaft	Cracked Shaft					
			1mm crack depth	2mm crack depth	4mm crack depth	6mm crack depth	8mm crack depth	10mm crack depth
1	1st Natural frequency	2756.99	2755.674	2753.619	2749.850	2741.883	2726.124	2694.672
2	2nd Natural frequency	2930.99	2928.228	2928.237	2926.964	2926.775	2926.007	2922.132
3	3rd Natural frequency	6944.39	6938.158	6934.243	6933.535	6917.183	6905.704	6880.481
4	4thNatural frequency	6989.54	6986.727	6986.139	6982.859	6980.084	6973.718	6958.896
5	5thNatural frequency	7387.94	7380.336	7384.696	7378.200	7376.069	7377.746	7372.502
6	6th Natural frequency	11100.4	11100.71	11100.65	11098.80	11092.15	11075.40	11037.57

It is observed from FEA results that as crack depth increases the natural frequency of the shaft decreases as shown in figure 7. Finite Element Analysis shows several modes of vibration hence it makes understanding of modal analysis easier. Modes are used as a simple and efficient means of characterizing resonant vibration. Resonant vibration is caused by an interaction between the inertial and elastic properties of the materials within a structure. Resonant vibration is often the cause of or at least a contributing factor to many of the vibration related problems that occur in structures and operating machinery. To better understand any structural vibration problem, the resonance of a structure needs to be identified and quantified.

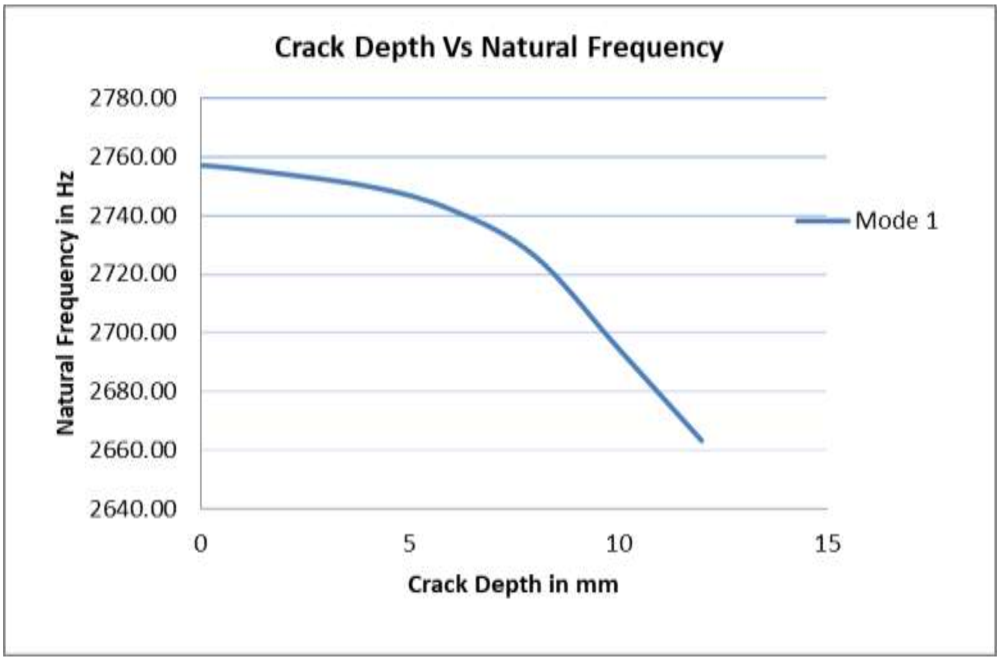

Fig. 7 Graph of Natural Frequency in Hz Vs Crack Depth in mm

IV. Conclusion

Shaft crack is very dangerous and frequent fault in a rotary machines but how to locate and configure it is not easy to tackle. If undetected early, such cracks can cause long out of service periods, heavy damages and severe economic consequences. Thus it is important to develop online monitoring technique. In this study, the influence of transversal cracks has been investigated that the change of the shaft frequencies affected due to the presence of a crack in a shaft. Modal parameters such as mode shapes and natural frequencies obtained from the finite element model resulted to be very sensitive to crack depth and crack location. It is observed that as crack depth increases the natural frequency of the shaft decreases. Modal parameters such as mode shapes and natural frequencies obtained from the finite element model resulted to be very sensitive to crack depth.

Conflict of interest The authors declare that there is no conflict of interests regarding the publication of this paper.

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