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Influence of Cracks on Shaft: A Review

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Abstract- *Cracks are a threat to uninterrupted operation and performance of modern day machines. Cracks occur in rotating shafts where its detection is challenging due to inspection difficulties. The problem of rotating cracked shafts has two main features have been recognized as: (i) the local flexibility introduced by the crack in the surrounding of the affected shaft sections; (ii) 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 and the work on the diagnosis of cracks has mainly been based on the vibration signatures. Changes in vibration response in the form of frequency composition have been found to be useful crack indicators. These vibration-based techniques have been applied to a variety of engineering structures, such as beams, trusses, rotors, etc. In this paper we have reviewed the influence of transverse cracks on a shaft.*

***Key Words*: Shaft, Fatigue, Catastrophic Failures, Cracks, Vibration Signatures.**

1. INTRODUCTION

Rotating shafts are primarily used in applications like engines, pumps and turbines. It has been reported that high speed and heavy duty shafts develop transverse cross-sectional cracks due to various reasons during their life period [1]. Material irregularities, uncertain usage patterns (e.g. random overloads and sudden jerks) and environmental conditions (e.g. changes in temperature and humidity) may adversely affect the life of mechanical systems leading to performance degradation and unanticipated failures [2]. In failures because of corrosion, stress is due to environmental action. Corrosion can be concentrated locally to form a pit or it can extend over a wide area, uniformly corroding the surface [3, 4]. Diagnostics for machine maintenance can be done using accelerometers by monitoring amplitudes of frequency response of machine. Transverse cracks in the shaft change the dynamic behavior of the system resulting in reduction of the rotor stiffness which affects the modal parameters (natural frequencies and mode shapes) and the acceleration amplitudes along the shaft [5]. Various theoretical and experimental studies have been carried out over the last few decades which indicate that the change in modal properties can be used for the detection of a crack as well as for the identification of both crack depth and location.

2. FRACTURE MECHANICS AND FATIGUE

It has generally been observed that the fatigue process involves the following stages: (1) crack nucleation, (2) short crack growth, (3) long crack growth and (4) final fracture. Cracks start on the localized shear plane at or near high stress concentrations such as persistent slip bands, inclusions, porosity or discontinuities. The localized shear plane usually occurs at the surface or within grain boundaries. Once nucleation occurs and cyclic loading continues, the crack tends to grow along the plane of maximum shear stress and through the grain boundary [1].

Fig. 1 shows the fatigue damage process where crack nucleation starts at the highest stress concentration site(s) in the persistent slip bands. The next step in the fatigue process is the crack growth stage. This stage is divided between the growth of Stage I and Stage II cracks. Stage I crack nucleation and growth are usually considered to be the initial short crack propagation across a finite length of the order of a couple of grains on the local maximum shear stress plane. In this stage, the crack tip plasticity is affected to a great extent by the slip characteristics, grain size, orientation and stress level, because the crack size is comparable to the material micro-structure. Stage II crack growth refers to long crack propagation normal to the principal tensile stress plane and in the maximum shear stress direction locally. In this stage, the characteristics of the long crack are less affected by the properties of the micro-structure than the Stage I crack. This is because the crack tip plastic zone for Stage II crack is much larger than the material micro-structure.

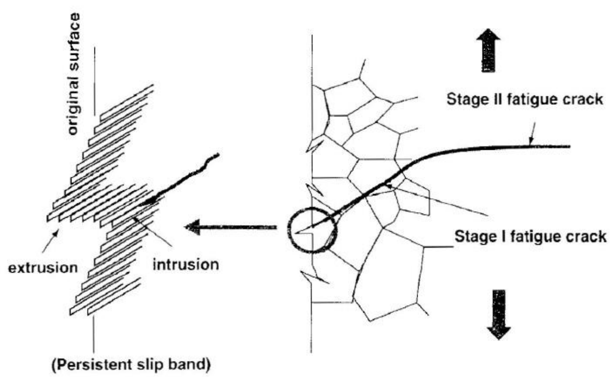

Fig. 1 The fatigue process

2.1 Damage Tolerant Design

The following are the three most important considerations for component or structure design to minimize the risk of failure by crack formation:
1. Eliminate all stress concentrators so that no cracks are ever initiated. This is impossible to achieve in practice, but good design practice will endeavor to avoid features that might initiate cracks.
2. Design to avoid propagation or at least control the rate of propagation of a crack. In service inspection then allows damaged components to be replaced or repaired prior to failure of the entire system. This is extremely challenging, if not impossible, in practice.
3. Design the structure to be safe even when one or more components have completely failed by cracking. This involves redundant components with an associated increase in weight and cost. A variation of this "safe design" theme is the use of visible and/or audible warning prior to failure.

2.2 Crack Modes

There are three (common) possible crack modes (Fig. 2). Almost all of the theory of crack propagation has been developed for Mode I. It is the most common crack mode found in practice.

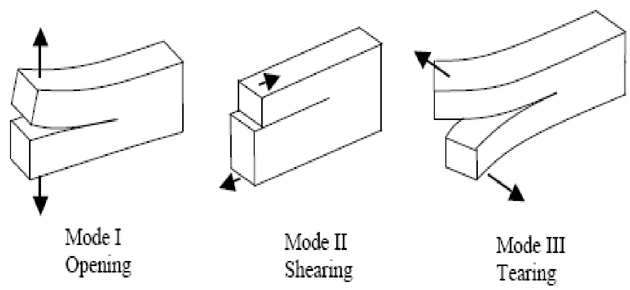

Fig. 2. Three possible crack propagation modes.

Mode I is known as the opening or tensile mode, where the in-plane stresses and strains are symmetric with respect to the X- axis. Mode II which is the sliding or in-plane shearing mode, the stresses and strains are anti-symmetrical with respect to the X-axis. In Mode III which is known as the tearing or anti-plane shearing mode, the out-of-plane stresses and strains are anti-symmetrical with respect to the X-axis. Mode I is the most common, Mode II is extremely rare, Mode III can occur in composite materials when there is a pre-existing crack [20].

3.Review of Research and Development in the Subject

Wayne C. Haase, Michael J. Drumm (2002) developed a system to detect, discriminate and track the fatigue cracks in rotating disks [6]. They primarily focused on jet engines used in flight applications. This 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.

J.R. Jain, T.K. Kundra (2004) proposed a model based technique for online identification of malfunctions in rotor systems [7]. 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.

Andrew L. Gyekenyesi et. al. (2003) discussed the analytical results concerning the detection of a crack in a rotating disk. This concept is based on the fact that the development of a disk crack results in a distorted strain field within the component [8]. 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 (FEA) of a notched disk in order to define the sensitivity of the method. The notch was used to simulate an actual crack.

Itzhak Green, Cody Casey (2005) utilized two theoretical analyses consisting 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 [9]. A model consisting of an overhung whirling rotor was 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 then serve as important observations for the monitoring system.
Xuanyang Leia et al. (2006) studied vibration analysis of a crankshaft with slant crack in crankpin and prepared a finite element model which can be applied for simulation and analysis of crankshafts with or without cracks [10].

A.K. Darpe, K. Gupta (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 [11]. The purpose of the study was to measure the effect of the residual bow on the stiffness characteristic of the rotating cracked shaft and changes if any. They 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 upto unbalance phase at half the critical speed. The use of influence of unbalance phase on orbital response at half critical speed of cracked rotor cannot be used for the detection purposes.

Jiawei Xiang et. al. (2008) proposed the wavelet-based crack detection method which can be used for measuring natural frequencies of cracked shaft with suitable vibrometer. To gain the accurate frequencies, this method utilizes combination of wavelet-based elements and genetic algorithm [12].

A.S. Sekhar (2008) proposed the identification techniques on multi-cracks in structures such as rotors, beams etc. using finite element model [13].

A.K.Darpe (2007) developed a novel way to detect transverse surface crack in a shaft. This method utilizes the transient external torsional excitation at specific angular position of cracked shaft model and non-linear breathing phenomenon of cracks [14].

B.S. Wang, Z.C. He (2007) proposed numerical simulation and model experiment on 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 was analyzed. A statistical neural network has been proposed to detect the cracks by measuring the reductions in natural frequencies [15].

Shalabh Gupta et. al. (2007) presented 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 was collected for detection in the statistical behavior of structural materials [16]. The performance of this method was evaluated relative to the existing pattern recognition tools, such as neural networks, principal component analysis for detection of small changes in the statistical characteristics of the observed data sequences.

N. Bachschmid, P. Pennacchi and E. Tanzi (2007) obtained useful results in laboratory tests for the dynamical behavior of cracked rotating shafts. They also analyzed its typical static and dynamic behaviors which was used to formulate the models which allow the behavior of cracked shafts to be accurately simulated [17].

T. Ramesh Babu, A.S. Sekhar (2008) studied the effect of multi-cracks on shaft and developed the solutions or the combinations of parameters characterizing the cracks. This 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) [18].

Robert Gasch (2008) studied the dynamic behavior 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 were 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 [19]. The work focused on forced vibrations due to crack and unbalance. The orbit decomposition into forward and backward whirls which can be a helpful tool for understanding the complicated dynamic phenomena.

Qinkai Han et. al. (2012) studied the dynamic behavior of a geared rotor system with a slant cracked shaft. They investigated the effects of slant crack on the whirling characteristics, parametric instability and steady-state response for the system under unbalance force and tooth error excitations[20].

Binglin Lv et. al. (2016) proposed an indirect method to measure torsional vibration of shaft structures. A T-like beam structure is attached to one end of a shaft structure due to which the torques are produced by ordinary forces and linear accelerometers at a various positions of the beam structure were used for monitoring. This method improves accuracy in measuring receptances of torsional vibration of shaft structures. Data from numerical simulation of a test structure with noisy parameters and noisy simulated receptance was used to validate the method. [21]

4. CONCLUSION

Cracks are very dangerous and frequent faults in rotary machines. It is difficult to locate and configure the cracks and if undetected early, they can lead to extended breakdowns, heavy damages and severe economic consequences. Vibration analysis method is the best and most accurate method for damage detection.

The frequency spectrum provides valuable information about the condition of a shaft. By comparing the frequency spectrum of the shaft in cracked condition with the reference frequency spectrum of a shaft in good condition, the nature and depth of the cracks can be detected. The relation between the natural frequencies of cracked shaft and different crack depths shows a unique pattern. By knowing only the natural frequencies prediction of depth of crack depth is possible.

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