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Diagnosis for Structural Health of Rotor Dynamic Systems: a Review

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Abstract*:* The ability to monitor the structural health of rotor dynamic systems is becoming increasingly important, as critical components continue to be used despite aging and the associated potential for damage accumulation. A shaft is a means of transferring energy; therefore any type of failure in one, such as fatigue cracks, causes serious damage to the system. The damage may lead to plant shutdown and great economical loss. Thus, many attempts in recent years have been made to deal with shaft crack detection methods. Cracks present in any structure deteriorate its performance. For detecting a crack present in the structure, many vibration-based methods include non-model-based and model-based methods have been widely used from the last few years. A comprehensive survey of available literature on cracked structures is carried out. In this paper the development of discontinuities in the shaft, the effect of crack on vibration behavior and its stiffness have been discussed. Also the review of analytical and experimental based techniques of crack detection has been carried out.

Keywords: Crack, Crack Detection, Fatigue, Catastrophic Failure, Vibration

I. INTRODUCTION

Rotating machinery is widely used in the modern industry, its applications ranging from domestic appliances to power plants and aerospace equipment. Shafts are amongst components subjected to perhaps the most arduous working conditions in high-performance rotating equipment used in process and utility plants such as high-speed compressors, steam and gas turbines, generators, pumps, aeronautics, aerospace and automobile. Which are vital for any economic development. Although usually quite robust and well designed, shafts in operation are sometimes susceptible to serious defects that develop without much apparent warning. They are prime candidates for fatigue cracks because of the rapidly fluctuating nature of bending stresses, the presence of numerous stress raisers and possible design or manufacturing flaws. Fatigue cracks are an important form of rotor damage which can lead to catastrophic failures if undetected early. They can have detrimental effects on the reliability of rotating shafts [1].

A Crack

Crack is a surface defect. Cracks are defined as any unintentional discontinuities in the shaft material. Fatigue type of loading of engineering structures and machine parts is likely to introduce cracks at highly stressed regions. Many times, manufacturing methods like welding may also introduce a crack. Crack reduces the strength of the structure or the machine part.

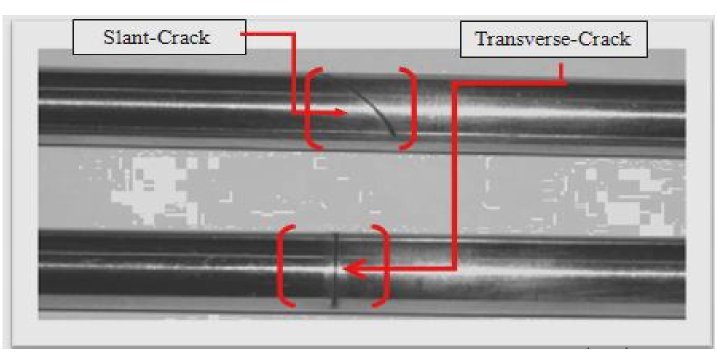

Fig. 1 Transverse-cracked shaft and slant-cracked shafts

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It can be classified based on their geometry and orientations are as follows:
Transverse cracks: - cracks perpendicular to the shaft axis are known as transverse cracks;
Longitudinal cracks: - cracks parallel to the shaft axis are known as longitudinal cracks;
Slant crack: - cracks at an angle to the shaft axis are known as slant cracks;
Breathing crack: - cracks that open and close, when the affected part of the material is subjected to alternating stresses, are known as breathing cracks;
Gaping crack: -cracks that primarily remain open are known as gaping cracks or notches;
Surface cracks: -cracks that appear open on the surface are known as surface cracks; cracks which are not visible on the surface are known as subsurface cracks [4].

II. RELATED wORK

Today, most of the works on the cracked shafts vibration analysis are concerned with investigating more deeply certain particular points such as the phase of acceleration or deceleration of the shaft, the passage through the critical speed or the coupling between diverse modes of vibrations to high light parameters facilitating the online cracks detection when dealing with machines monitoring. The vibration analysis of cracked beams or shafts is a problem of great interest due to its practical importance. In fact, vibration measurements offer a non-destructive, inexpensive and fast means to detect and locate cracks. Thus, vibration behavior analysis and monitoring of cracked rotors has received considerable attention in the last three decades. It has, perhaps, the greatest potential since it can be carried without dismantling any part of the machine and usually online avoiding the costly downtime of turbo machinery.

III. DEVELOPMENT OF DISCONTINUITIES IN SHAFT

There are two stages in crack development such as crack initiation and crack propagation. The crack initiation caused by mechanical stress raisers, such as sharp keyways, abrupt cross-sectional changes, heavy shrink fits, dents and grooves, and/or metallurgical factors, such as flaws, fretting, and forging. The latter stage namely crack propagation, can accelerate the growth rate under different conditions operating faults generated during sustained surging in compressor negative sequence current or grounding faults in generators and coupled turbines, the presence of residual stresses in the rotor material, thermal stresses, and environmental conditions, such as the presence of a corrosive medium [3].

IV. EFFECTS OF CRACKS ON VIBRATION BEHAVIOR AND STIFFNESS

From the review of papers following ill effects of the crack present in the shafts have been observed. Paolo Pennacchi [5] shown that the overall behavior of a horizontal axis heavy cracked shaft is linear. Only in extreme operating conditions, the non-linear effect of the breathing crack, which is weak in normal conditions, may influence its behavior. The stiffness of a cracked shaft is periodical due to the breathing and the rotation of the crack. Zdzis aw gosiewski, jerzy t. Sawicki [6] shown that the difference of the vibration signals of cracked and uncracked shaft one can obtain the relative increase in amplitudes of combined resonances which are closely related with the crack. After 40% crack the rotor stiffness in crack direction is reduced by 9%, while in the perpendicular direction it is reduced by 4%. M. S. Lebold [7] shown that the maximum vertical and horizontal amplitudes are drastically affected by the variation of the crack depth and crack location. The reduced stiffness which changes the system natural frequencies, resulting from the presence of the crack. A.K. Darpe [10] under the open crack condition, the local flexibilities remain constant along with the shaft rotation angle. Among the crack orientation, the crack breathing behavior depends on the depth of the crack and the shape of the crack front. A. Tlaisi1 [11] the frequencies of the cracked shaft decrease as the crack depth increases. Impedance and mobility were measured and simulated in the vertical direction. The amplitudes of all the mobility curves increase for the resonant frequencies for increasing crack depth. In contrast, the amplitudes of impedance at all the anti-resonant frequencies either decrease (at the first anti-resonance) or increase (at the third anti-resonance).

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V. NEED OF DETECTION OF CRACK

Fatigue cracks are an important form of rotor damage which can lead to catastrophic failures if undetected early. They can have detrimental effects on the reliability of rotating shafts .Safe and reliable operation of equipment relies on proactive maintenance aided by newly emerging diagnostic technologies. Operators and maintenance personnel of critical plant machinery are particularly interested in early detection of symptoms that can lead to in-service failure of shafts. [6]. Early papers documenting crack occurrences in real machines date back to the end of 1960s and to 1970s. Propagating transverse cracks have been discovered in the last 20 years in several rotors of steam turbines or generators of European power plants. The importance of early detection of cracks, possibly by means of an automatic diagnostic methodology that uses the information furnished by standard monitoring systems, which generally analyze the vibrations measured in correspondence of the bearings only, appears to be significant [5].

VI. CRACK DETECTION TECHNIQUES

Detection of the crack in a rotating shaft of machine is one of the most challenging problems in equipment predictive maintenance .There are several predictive maintenance techniques used to monitor and analyze critical rotating machinery. Some of the techniques are as follows visual inspection, thermography, tribology, ultrasonic, vibration analysis and other non-destructive analysis techniques. The vibrational behavior of cracked shafts has received considerable attention in order to prevent significant rotor faults. Vibration analysis technique is used mostly because of mainly two reasons. It is non distractive and it does not interfere with the machine's normal operation [3].

A. *Analytical Based Techniques*

The main objective of this review is to the presentation of a method of construction of a cracked beam finite element. The stiffness variation of the element is deduced from three-dimensional finite element computations accounting for the unilateral contact between the cracks lips. Based on an energy approach, this method could be applied to cracks of any shape. The validation of the approach on a case of a cracked rotating shaft has been carried out and its stability analysis is verified using the Floquet theory. The approach is quite simple and comprehensive and can be applied to any geometry of cracks [1]. The Harmonic Balance Method can also apply in order to save time and to be able to undertake parametric numerical studies. The dynamic behavior due to the presence of the breathing crack, particularly the behavior of the 2X and 3X harmonic component of the system and the evolution of the orbit near one-half and one-third of the first critical speed. Parametric studies considering the influences of the crack depth and location has been investigated in order to examine the possibility of detecting the presence of a crack even if the crack depth is small or the crack is situated in an unfavorable position [8].The proposed detection methodology exploits both the typical nonlinear breathing phenomenon of the crack and the coupling of bending–torsional vibrations due to the presence of crack for its diagnosis. A transient torsional excitation is applied for a very short duration at specific angular orientation of the rotor and its effect in the lateral vibrations is investigated. Wavelet transforms (WTs) is used in revealing the transient features of the resonant bending vibrations, which are set up for a short duration of time upon transient torsional excitation. Variation of peak absolute value of wavelet coefficient (of the transient lateral vibration response) with angle at which torsional excitation is applied can be investigated. The correlation of this variation with the breathing pattern of the crack is verified [9].

A quasi-static approximation has been used to study the effect of the crack breathing mechanism on the time-variant flexibility due to the crack in a rotating shaft. The deflections of a circular cross-section cantilever beam presenting a crack of different depths, due to bending or torsion loads are analyzed with the aid of an advanced nonlinear contact-FEM procedure in order to predict accurately the time-variant flexibility of a fractured shaft. This method predicts the partial contact of crack surfaces, and it is appropriate to evaluate the instantaneous crack flexibilities. [10]. A local compliance matrix of different degrees of freedom is also used to model the transverse crack in a shaft of circular cross section, based on available expressions of the stress intensity factors and the associated expressions for the strain energy release rates. It is known that when a crack exists in a structure, such as a beam, then the excitation in one-direction causes coupled vibrations in other directions. This property is used here to identify the crack. [12].

B. *Experimental Based Technique*

A model-based transverse crack identification method suitable for industrial machines is validated by experimental results obtained on a large test rig, which was expressly designed for investigating the dynamical behavior of cracked

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horizontal rotors. The identification method and the relative theory are briefly presented, while three different types of cracks are considered. The excellent accuracy obtained in identifying position and depth of different cracks proves the effectiveness and reliability of the proposed method [5]. Vibroacoustical signals of rotating machinery are used for the identification and diagnostics purposes. Such signals can be generated by phenomena connected with operational state of the machinery or can be excited by additional devices added to the machinery. The devices are typically the force generators. They should be able to generate forces in desired frequencies range called a frequency bandpass. Presently there are a few such devices like electro hydraulic or electromagnetic exciters, magnetic bearings, or piezo-electric actuators with sufficient bandpass for diagnostics or identification procedures. Many authors have looked for symptoms for detection of earlier stage of the shaft crack. All models of crack leads to nonlinear description of rotor dynamics because of asymmetric rigidity of the rotor and because of the additional parametric excitations of the rotor vibrations [6].The laboratory test bed uses a simple shaft which is fabricated with a seeded fault. The crack is initiated and grown by fatiguing the shaft for a specified number of cycles with a 3-point bend machine. Once grown, the crack is nondestructively characterized. The shaft is installed and operated in the torsional test rig to extract the Torsional vibration signature (refer Figure 2). The fatigue cycling process is repeated until the crack is grown to a critical length or shaft deformation occurs. The torsional vibration signature is used in conjunction with a crack characterization model to examine the sensitivity of the process [7].In order to identify the crack existence in shafts using the mechanical impedance approach crack presence could be definite detected when the non-dimensional crack ratio is greater than 0.20 to 0.25. In addition monitoring of the lower torsional frequency indicated the crack presence even from the beginning stages [11]. The current work is focused on the investigation on the vibrational response of a cracked rotating shaft. A phenomenological model that incorporates the breathing of the crack, nonlinear shaft bending stiffness, and the external forces from the AMBs is used to represent the response of the shaft. This model is then analyzed, a combination resonance is identified, and the response of the system under these forcing conditions is characterized. Most importantly for this work, when the system is operated at this resonance, the amplitude of the response at the fundamental shaft frequency is proportional to the amplitude of the time-dependent stiffness, which is assumed to be proportional to the shaft damage [13].

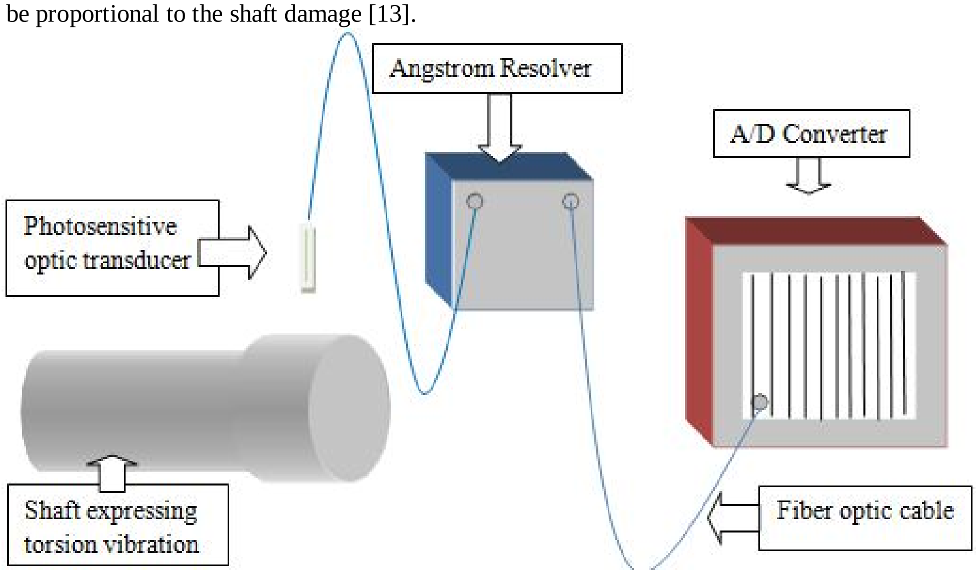

Fig. 1 Torsional vibration measurement instrumentation using a fiber optic probe approach

VII. DISCUSSION

This paper discusses the significance of crack detection and its severity, if they remain undetected. The technique will help to create the awareness in the community to technicians, engineers and researchers to motivate them for further study in the area of crack detection. A crack in a structural member introduces local flexibility that would affect vibration response of the structure. This property may be used to detect existence of a crack together its location and depth in the structural member. The presence of a crack in a structural member alters the local compliance that would affect the vibration response under external loads.

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