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Dynamic Behavior of a Disc-Rotor System Subjected to Different Crack Location & Different Speed – FEM Investigation: A Review

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Abstract— A theoretical analysis of the dynamics of a rotor-bearing system with a transversely cracked rotor is presented. The rotating assembly is modeled and the presence of a crack is taken into account. Rotor dynamics is the study of vibrational behaviour in axially symmetric rotating structures. The vibration in rotating machinery is mostly caused by unbalance, misalignment, mechanical looseness, shaft crack, and other malfunctions. A strong interest has developed within the past several years in the dynamic behavior of turbo machinery with cracked shafts. An excellent review of the field of the dynamics of cracked rotors and of different detection procedures to diagnose fracture damage has been presented. In literature, several studies are available for cracked rotor systems, and few authors have addressed the issue of multi-cracked rotor system. These statistics indicate that this is a very dynamic area of research, and the main focus of present article seeks to provide comprehensive review of previous and recent research work published on dynamic analysis of a cracked rotor.

Key words: Disc-Rotor System, FEM Investigation

I. Introduction

The dynamic response of a rotating shaft containing a transverse crack was initially investigated in 1970s. Heavy loaded rotating components of various machines (such as steam and gas turbine, pumps, generators and high speed compressor etc.) being diversely used in various fields such as aircraft, automobile and power generation. Rotor shaft is considered as one of the important part of various rotating machines. Due to manufacturing defect or cyclic loading, fatigue crack frequently appears in rotating shaft. Fatigue crack is considered as one of the main reasons for catastrophic failures in rotating shaft. In thermal machinery such as steam turbines, thermal stresses and thermal shocks are also accountable factors for high stress intensity which is also a cause of crack initiation and its propagation. The influence of a transverse crack on the vibration of a rotating shaft has been at the focus of attention of many researchers. More recently, several researchers have studied the dynamic response of cracked rotors using theoretical or experimental methods alone, or by combining both approaches. Cracks may be initiated and subsequently propagated in shaft subjected to dynamic loadings. Failure may result if the history of these cracks is not recorded and precautionary measures are not taken. Some Other techniques of non-destructive testing are used. An ultrasonic pulse technique has been used successfully to detect the positions of cracks in structures and welds. In some materials, this technique may not work due to the large attenuation of the signal at all except a particular frequency. Radiographic techniques have also been used for crack detection in structures. These Techniques, however, require higher radiation energy input for increasing material thickness, which increases the cost of operation. In addition, crack detectability is small for a small crack width/depth ratio and for cracks not parallel to the material surface. Though most studies in the field focused on the rotors with single crack, investigations on the rotor systems with multi-cracks are also available. Based on the existing studies, however, almost all the existing studies available in the current literature are found on the rotor systems that neglect the mass of the shaft and do not consider the geometric nonlinearity of the cracked rotor. The crack reduces the critical speed of the rotor system and produces changes in the amplitude of the vibrational harmonics. Depending on the size and location of the crack, the amplitudes may increase or decrease. A slight increase in the crack depth may induced a strong increase in the harmonic response. The main idea of these approaches is that a change in a rotor system due to damage crack will manifest itself as changes in the rotor dynamic behaviour: First of all, the presence of a transverse crack induces a slight decrease of the natural frequencies. Secondly, resonances appear when the rotational speeds of the shaft reach 1/2 to 1/3 of the critical speeds of the rotor system. Therefore, with the increase of the crack depth, the 1/2 and 1/3 sub-critical resonant peaks increases.

II. Literature review

V. Sudheer Kumar [1] examine the vibration characteristics of cracked shaft, a steel shaft with disk mounted at its center and supported by two bearings. An artificial crack was introduced to detect the vibration characteristics of the rotor. Initially, the signature data was obtained with no crack using spectrum analyzer. There after crack was introduced with depths ranging from 1mm to 6mm on the rotor of 25mm diameter. A significant change in vibration characteristic was examined when the crack depth has exceeded 3mm. On observing the first three peak amplitudes of right and left bearings, a different in the values was observed. A Significant increase in deflection was observed when the crack depth had reached 4mm when compared to no-crack condition. The results were well focused with the aid of displacement curves, and subcritical curves.

Mohammad A. AL-Shudeifat [2] investigates the effect of crack depth of a rotor-bearing-disk system on vibration amplitudes and whirl orbit shapes through a general harmonic balance technique and experimental verification. Finite element models and general harmonic balance solutions have derived for breathing and open cracks which are valid for damped and un damped rotor systems. It is found via waterfall plots of the system with a breathing crack that there are large vibration amplitudes at critical values of crack depth and rotor speed for a slight unbalance in the system. The high vibration amplitudes at the backward whirl appear at earlier crack depths than those of the forward whirl for both crack models.

Debabrata Gayen [3] developed Finite element formulations for dynamic analysis of a functionally graded shaft having a transverse crack. Two nodded Timoshenko beam element with four degrees of freedom per node has been used where effects of translational and rotary inertia, transverse shear deformations, and gyroscopic moments are considered. Local flexibility coefficients (LFCs) of the cracked FG shaft are determined analytically as a function of crack size, power-law gradient index (*k*), and temperature using the Castigliano's theorem and Paris's equations which are used to compute the stiffness matrix in the FE analysis. Temperature dependent thermo-elastic material properties of the FG shaft are considered graded in the radial direction following power-law gradation. He found that the power-law gradient index has significant influence on the whirl frequencies and critical speed both for cracked and un-cracked FG shaft and could be judiciously chosen in designing FG shafts.

Changping Chen [4] Established a new approach for analyzing the nonlinear behavior of a cracked rotor system. Nonlinear governing equations of motion developed for the cracked rotor system with asymmetrical viscoelastic supports. In this approach, the masses of the rotational shaft and a disc mounted on the shaft, geometric nonlinearity of the shaft, and the rotor's extra displacements due to the existence of the crack are all taken into account. The effects of the crack and the other system parameters on the dynamic stability of the rotor system is also investigated.

Oh Sung Jun [5] studied the additional slope and bending moment at crack position in analyzing the dynamic behavior of a general cracked rotor. The nonlinear motion of the cracked rotor, which results in the harmonic vibration, is simulated using the response including bending moment and the additional slope recursively. He found that At the high speed range where the dynamic bending moment is enough large to affect the total bending moment, the change of additional slope occurs with the speed change and it becomes one of the causes of the drastic orbit change. The continuous operation of the cracked rotor at such speed range having large dynamic bending moment may produce the fast crack propagation. Also he analyzed that the second vibration mode happens when the speed closely approaches half of the second critical speed.

Huichun Peng[6] worked on the Stability analysis of an open cracked rotor with the anisotropic rotational damping in rotating operation.The motion equations of the cracked rotor system are formed by Lagranges principal. The anisotropic system with the multi periodical varied coefficients is simplified by the moving frame method such that the stability analysis based on the root locus method can be applied. The effects of anisotropy of stiffness on the decisions of the critical range are presented. He also suggests that the increased proportion and the aggravated anisotropy of the rotational damping due to the crack of the fatigue rotor should been taken into consideration on the modeling of cracked rotor system.

H.D Nelson [7] worked on theoretical analysis of the dynamics of a rotor-bearing system with a transversely cracked rotor. The rotating assembly is modeled using finite rotating shaft elements and the presence of a crack is taken into account by a rotating stiffness variation. This stiffness variation is a function of the rotor's bending curvature at the crack location and is represented by a Fourier series expansion. The resulting parametrically excited system is nonlinear and is analyzed using a perturbation method coupled with an iteration procedure. The system equations are written in terms of complex variables and an associated computer code has been developed for simulation studies.

Fangyi Wan [8] investigates the vibration of a cracked rotor sliding bearing system with rotor–stator rubbing using harmonic wavelet transform (HWT). non-linear oil film forces, rotor–stator rubbing and the presence of crack, are taken into account. According to Newmark method, the dynamic response of the rotor is calculated. Using HWT method, the effect of these non-linear factors is analyzed simultaneously in both time and frequency domain. The numerical simulated result shows that HWT will be available to analyze this multi-non-linear factors rotor effectively and can reveal the exact fault characteristics in detail.

Jean-Jacques Sinou [9] the dynamic characteristics and stability of the non-linear periodic solutions for a cracked rotor are analysed in this paper. The stability analysis is carried out by applying a perturbation to the non-linear periodic solution. firstly, the influence of a transverse crack on the dynamic characteristics of a cracked rotor is discussed. It is shown that the shaft executes, respectively, two or three loops per shaft revolution, when the rotational speed of the cracked rotor passes through one-half or one-third of the critical speed. Secondly, it is shown that the rotor system may in some cases lose its stability when cracks appear. The influence of crack size and location is significant for the main regions of dynamic instability, which expand with the crack increases in depth. Disk location and support stiffness influence the main regions of dynamic instability when cracks appear, whereas flexible rotor supports can reduce both the threshold speed limits and the extent of the regions of instability.

Mohammad Hadi Jalali [10] found that the high speed rotors are vulnerable to vibrations resulting in the failure of the whole operating system. To avoid resonant conditions at operating speeds, modal analysis of such rotors is very important in the design and development of the system. He also explained that full rotor dynamic analysis during operating conditions is also mandatory to investigate the dynamic behavior of the rotating structure. In this paper, the full dynamic analysis of a high speed rotor with certain geometrical and mechanical properties is carried out using 3D finite element model, one-dimensional beam-type model and experimental modal test. There is a good agreement between the theoretical and experimental results which indicates the accuracy of the finite element models. The Campbell diagram, critical speeds, operational deflection shapes, and unbalance response of the rotor are also obtained in order to completely investigate the dynamic behavior of the rotating system.

Qinkai Han [11] investigates the dynamic response of cracked rotor-bearing system under time-dependent base movements. Three base angular motions, including the rolling, pitching and yawing motions, are assumed to be sinusoidal perturbations superimposed upon constant terms. Both the open and breathing transverse cracks are considered in the analysis. The finite element model is established for the base excited rotor-bearing system with open or breathing cracks. He used an improved harmonic balance method to obtain the steady-state response of the system under both base and unbalance excitations. The response spectra, orbits of shaft center and frequency response characteristics, are analyzed accordingly. Also, the effects of various base angular motions, frequency and amplitude of base excitations, and crack depths on the system dynamic behaviors are considered in the discussions.

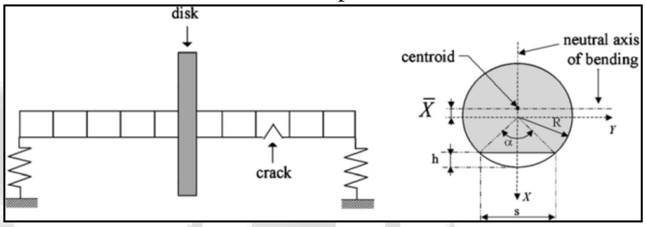
M. A. Mohiuddin [12] introduced a general dynamic model for a large-scale rotor-bearing system with a cracked shaft. A finite shaft element with a crack is developed using a consistent finite Element approach. The model utilizes the powerful finite element method while accommodating the crack effects within a consistent finite element formulation. It accommodates shafts with tapered portions, multiple disks and anisotropic bearings. The formulation is also applicable to rotor-bearing systems with different practical design configurations including intermediate bearings, shaft overhang, and stepped shaft assemblies. The model utilizes the powerful finite element method while accommodating the crack effects within a consistent finite element formulation. It is also hoped by him that the developed computational scheme offers an efficient and essential core module in establishing other specialized crack detection schemes for rotor-bearing systems.

Zbigniew Kulesza [13] analyses the present paper on the possible application of the multisine excitation technique for an early shaft crack detection problem. This technique was previously used for identification problems where the influence of nonlinear distortions on the linear system behavior was to be evaluated and measured. a developing shaft crack manifests itself in the appearance of nonlinear effects resulting in higher harmonics in a vibration spectrum. However, such symptoms are characteristic not only for developing shaft cracks but also for other malfunctions such as a shaft bow, a coupling misalignment, etc. That is why novel shaft crack detection methods introduce a specially designed diagnostic force applied to the shaft in order to amplify the particular symptoms of the crack. Most often a simple harmonic force is used for such purposes, yet the results may not be reliable. The results demonstrate a potential of the presented method to detect the shaft cracks and to evaluate their severity.

Zhaohui Ren [14] used wavelet transforms method to diagnosis of crack fault in rotor bearing system. He said that As the traditional Fourier transformation method cannot process the non-linear and non-stationary vibration signal of the cracking rotor system, the 3-D waterfall spectrum in combination with reassigned wavelet scalogram method is presented to analyze the temporal frequency characteristics of the crack fault. The experiment results show that the present method is effective in determining the frequency structure of the signal, especially the twofold frequency component, which can be measured at half of the critical speed.

Jerzy T. Sawicki [15] This paper investigates the modelling and analysis of machines with breathing cracks, which open and close due to the self-weight of the rotor, producing a parametric excitation. After reviewing the modelling of cracked rotors, the paper analyses the use of auxiliary excitation of the shaft, often implemented using active magnetic bearings to detect cracks. This paper suggests an alternative approach based on the harmonic balance method, and validates this approach using simulated and experimental results. The simulations shown suggest that the use of an auxiliary active magnetic bearing (AMB) to help identify crack in the rotor has some merit, but further work is needed to produce a robust condition monitoring technique. The harmonic balance method proposed in this paper provides a fast and convenient method to predict the responses, and could be used with inverse methods for damage detection. Furthermore, the effect of adding an extra force to the system might encourage a faster crack growth, which is obviously a disadvantage.

Jean-Jacques Sinou [16] this paper investigate the use of the 2x and 3x super-harmonic frequency components for detecting the presence of a single transverse breathing crack in a non-linear rotor system. This procedure is based on the detection of the super-harmonic frequency components of the non-linear dynamical behaviour at the associated sub-critical resonant peaks.



It is demonstrated that for a given crack depth the unbalance does not only affect the vibration amplitude of the 1x amplitudes, but also the ½ and 1/ 3 sub-critical resonant peaks. it is also illustrated that the emerging of super-harmonic frequency components provides useful information on the presence of cracks and may be used on an on-line crack monitoring rotor system. Using this methodology, the detection of small levels of damage may be easily undertaken.

Ashish K. Darpe [17] In this paper a simple Jeffcott rotor model of a rotor with a slant crack is presented. Flexibility matrix of the rotor with slant crack is developed and the stiffness coefficients based on the flexibility values are used in the equations of motion. Response dependent nonlinear breathing crack model is used to evaluate unbalance response of the cracked rotor. Comparison between rotor with slant and transverse crack is made with regard to the flexibility/stiffness coefficients and the unbalance response characteristics. The response of the rotor with the two types of cracks (transverse and slant) is analysed at sub harmonic resonances to explore possibilities of distinctive features in their response. He found the flexibility matrix of the slant crack rotor is more populated and contains more non-zero off-diagonal elements than that of the rotor with transverse crack. Flexibility coefficients are also compared with the case of rotor with transverse crack. The lateral and longitudinal stiffness of the rotor is more for the slant crack than for transverse crack.

III. Conclusion

Intensive research work published on dynamic analysis of cracked rotor in rotor-disc-bearing system examine the effect of crack depth on the vibrational amplitude of shaft[1,2]. Debabrata Gayen [3] investigated the same effect on functionally graded shaft. Various researchers worked on same effect with different approaches with and without anisotropic effect. Few researchers worked on nonlinear behavior of cracked shaft. A few researchers presents work on slope and bending moment at crack position. From the above literature survey it is found that majority of published research work mainly focused on effect of crack and crack depth on vibrational amplitude with the help of different approaches ,softwere and experimental study. At the time of review, there is no comparative study found that relates effect of different crack position and different rotor speed on a cracked rotor.

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