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Research paper

Vibration behavior of a two-crack shaft in a rotor disc-bearing system

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ABSTRACT

The vibration response characteristics of a rotor disc-bearing system with one and two cracks are analytically investigated using a modified harmonic balance method. The analytical model is formulated considering rigid-short bearing supports to study the effects of cracks' characteristics such as depth, location and relative angular position on selected vibrational properties, namely, critical speeds, harmonic and super-harmonic components of the unbalance lateral response and the shaft center orbit. Each crack is initially described by a breathing function proposed by Mayes and Davies, which is subsequently modified as a softly-clipped cosine function to accurately describe saturation in breathing phenomenon. The response characteristics of the cracked shaft are also compared with those of the system with an intact shaft in order to identify potential measures for detecting cracks. The results show that the presence of a second crack emphasizes changes in the critical speeds of the rotor disc-bearing system, while relative angular position of the cracks influences the shaft center orbit. The validity of the proposed analytical model and the solution method is also investigated through simulations of a finite element model of the system.

1. Introduction

Emergence and propagation of fatigue cracks in rotating machines could adversely affect their operational efficiency and may lead to catastrophic failures. Considerable efforts have been made to identify various crack detection measures based on vibration responses of the rotor disc-bearing systems, which have been thoroughly reviewed in [1–3]. The changes in vibrational properties of the rotor system in the presence of a crack have been widely proposed for identification of crack parameters in majority of the studies. Changes in modal parameters, transient responses, shaft center orbit evolutions in sub-critical speeds, torsional-lateral vibrational coupling and equivalent fictitious loads have been applied to evaluate effects of crack parameters on vibrational properties of the rotor disc-bearing systems [4–8].

The effects of a single crack on vibrational properties of different structural systems have been widely reported, while the effects of double/ multiple cracks have been addressed in a relatively fewer studies. This may be due to the fact that the presence of multiple cracks on a shaft happens rarely and as the authors know, no case study has been reported. Different combinations of properties of single or multiple crack such as depth and location may yield similar effects on vibrational properties of the system. Sekhar [9] conducted a review of methods for identifying two or more cracks in components

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such as beams, rotors and pipes and concluded that efficiency of identification of single or multiple cracks mostly depends on the applied signal processing techniques. Fourier transform is a suitable signal processing method for analyzing signals, which their frequency content does not change in time. However, in case of time-variable frequency contents of vibration responses of cracked mechanical systems, their features should be extracted using advanced signal processing techniques such as wavelet transform (WT) and Hilbert-Huang transform (HHT) [e.g., 10–13].

Some studies have presented changes in preselected vibrational properties due to known multiple crack parameters [e.g., 14,15], while others have presented inverse problem of determining multiple cracks' parameters from known changes in vibrational properties [e.g., 16,17]. Sekhar [14] investigated the effects of two open cracks on the eigenfrequencies, mode-shapes and threshold speed of a rotor system using Finite Element (FE) method. Darpe et al. [15] studied the effect of two breathing cracks on unbalance response of a simple Jeffcott rotor. Both studies suggested that relative angular position of the two cracks may exhibit significant changes in the shaft center orbit. Saridakis et al. [16] formulated an inverse problem of identifying cracks' properties (depth, location and relative angular position) from known changes in vibrational properties of a flexible cantilever shaft with two breathing cracks. The inverse problem was solved using artificial neural networks, genetic algorithm and fuzzy logic methods. The study suggested that the method could provide real-time identification of crack parameters.

Ramesh and Sekhar [17] proposed an alternate crack indicator, referred to as 'amplitude deviation curve (ADC)', based on the concept of operational deflection shape (ODS) and concluded that the method outperforms that based on the continuous wavelet transform (CWT) reported in [18] for detecting two breathing cracks. Sekhar [19] subsequently considered both forward and inverse problems to investigate the effects of two cracks on vibration responses of a shaft-rotor system. The method employed fictitious loads obtained from a FE model for identifying the depths and locations of the cracks.

Han and Chu [20] investigated the stability of a rotor-bearing system in the presence of two transverse cracks on the shaft. They compared the effect of applying two different crack breathing models proposed by Mayes and Davies [21] and Al-Shudeifat and Butcher [22] on instability shaft speeds. Furthermore, they showed that the shaft speed instability regions are highly affected by the relative angular position of the cracks on the shaft.

The reported analytical studies have invariably shown that the changes in vibrational properties of a cracked shaft-rotor system are strongly affected by the crack model. Modeling the crack has thus been an important challenge in many studies. The changes in shaft cross-section geometry in the vicinity of the crack, and thereby changes in the local stiffness of the shaft strongly depend on the crack depth, which are generally obtained using the concepts of strain energy release rate and stress intensity factor [23,24] or changes in area moment of inertia about the transverse coordinates of the cracked shaft [25,26].

In a rotating shaft, the crack-induced changes are also a function of the shaft rotation, when the shaft static deflection dominates the lateral vibration and the crack thickness in axial direction is negligible [22]. The crack has been considered as an open-crack in a number of studies, assuming negligible effect of shaft rotation on changes in the shaft local stiffness [e.g., 14,15,27]. Alternatively, crack is modeled as a breathing crack to incorporate the effect of shaft rotation on the localized stiffness [e.g., 21,28,29]. The majority of the breathing crack models employ explicit breathing functions such as step and cosine to describe local stiffness changes with shaft rotation [e.g., 27,30,31]. Such functions, however, describe the breathing behavior of the crack neglecting the effects of its properties.

A few studies have employed linear fracture mechanics to evaluate local stiffness of the shaft cross-section near the crack location corresponding to different shaft angles of rotation and proposed breathing crack models considering the effects of crack depth and location [24,32,33]. Jun et al. [32] used the sign of the total stress intensity factor (SIF) at each point on the crack edge to determine whether the crack is open or closed. In compressive stress state, the sign of total SIF is negative and the crack is assumed to be closed, while in tensile stress state the sign of total SIF is positive and consequently the crack is considered to be open. Darpe et al. [24] introduced the concept of crack closure line (CCL), an imaginary line perpendicular to the crack edge, separating the open and closed parts of the crack, to study breathing behavior of the crack. The CCL position was obtained considering the sign of the total SIF at each point on the crack edge, as proposed by Jun et al. [32].

Owing to complexities associated with evaluations of the stress intensity factor for shaft angles corresponding to stress state transition between the vertical and horizontal moments, Chasalevris and Papadopoulos [33] employed B-spline curves to interpolate between the transient points. Al-Shudeifat and Butcher [22] used changes in area moment of inertia about the transverse coordinates of the cracked shaft cross-section area to obtain an accurate breathing function. The method considered exact locations of centroid and neutral axis of the cracked shaft cross-section at each shaft angle to estimate corresponding area moments of inertia and the local stiffness. Unlike the earlier studies [24,32,33], the breathing crack model employed an explicit breathing function.

The reported studies have employed different analytical [6,15,33–38] and numerical models [5,22,39] of the rotor disc-bearing systems for evaluating reference vibration responses and the effects of cracks. The analytical models are generally based on the simplified Jeffcott rotor model [e.g., 6,15]. Chasalevris and Papadopoulos [33] used the Timoshenko beam theory to develop a continuous shaft-disc model to study the effects of a crack on the vibrational responses. A number of FE models of the rotating cracked rotor disc-bearing systems have also been reported considering either Euler–Bernoulli and Timoshenko beam theories [e.g., 5,9,22,26,39,40].

The studies have also employed different solution strategies, which satisfy the continuity and boundary conditions to obtain steady-state and transient responses, and changes in the selected vibrational properties. Some studies have employed a solution function in exponential form, which is only limited to the first harmonic component [e.g., 33,35,36,41], while