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Detection and localisation of multiple cracks in a shaft system: An experimental investigation

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ABSTRACT

Experimental verification of an algorithm for detection and localisation of multiple cracks in a simple shaft system is presented. Cracks in a shaft cause the slope discontinuity in the shaft elastic line. The algorithm is based upon detecting the slope discontinuity due to cracks. Two simply supported non-rotating shafts are used for the experimentation. Both the shafts are tested with single as well as double artificially introduced open cracks. Transverse deflections of the shaft due to sine-sweep excitation force through an exciter are measured at regular axial locations of the shaft. The slope discontinuity is obtained by fitting shaft deflections at regular axial locations in a quadratic polynomial. The algorithm uses shaft deflections at several excitation frequencies to incorporate adequate modal information in the response to improve the crack identification. A scheme is proposed to improve the working of the algorithm in low signal to noise ratio conditions. The algorithm identifies the presence of crack and successfully locates the crack along the shaft length.

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1. Introduction

A fluctuating load over long time causes fatigue cracks in a shaft. Timely detection of these cracks is important for the safe and uninterrupted running of machines. Presence of a crack changes the dynamics of the rotor. Accurate mathematical modelling of the crack is required to extract key features from the cracked shaft dynamics. These key features include: the coupling between different motions such as the bending, longitudinal and torsional vibrations, the splitting of natural frequency due to presence of crack, the non-linearity in stiffness due to breathing, and the friction between cracked surfaces. These key features, along with modal parameters and the free and forced vibrations have been explored by several researchers for development of cracked-shaft diagnostic methods.

All the crack models invariably involve reduction in the stiffness at the location of crack. Dimarogonas and Massouros [1] considered the effect of a crack on the torsional dynamic behaviour of a shaft. They used the strain energy release rate approach to calculate the local flexibility of the shaft due to the presence of the crack. Gudmundson [2] represented the crack by static flexibility matrix and it was calculated by two different methods. He showed that if the static stress intensity factors are known, the flexibility matrix can be determined from the integration of these stress intensity factors. Otherwise, the flexibility matrix can be calculated by the static finite element calculations. A review on modelling a crack, based on the strain energy release rate was presented by Papadopoulos [3].

For a weight dominated shaft where the static deflection due to self-weight is more than deflections due to unbalances, the crack breaths, i.e. the crack opens and closes with the rotation of the rotor. Grabowski [4] suggested the switching of stiffness values from those of the

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uncracked rotor (fully closed crack state) to those of the cracked rotor (fully open crack state) at a particular rotor angular position. Nelson and Nataraj [5] developed the finite element formulation of a cracked element. The presence of crack was taken into account by a rotating stiffness variation. The stiffness variation was considered as a function of the rotor's bending curvature at the crack location. Al-Shudeifat and Butcher [6] presented two breathing functions to obtain the time varying stiffness matrix of the cracked element in finite element formulation. Finite element equations of motion were solved via the harmonic balance method for the responses, whirl orbits and the shift in the critical and subcritical speeds. Al-Shudeifat [7] presented a finite element model for the time varying stiffness of single cracked rotor. It was found that the whirl orbits with inner loops are unique feature of breathing cracks which are absent in the case of open cracks. Few researchers have considered other factors such as: thermal effect was considered by Bachschmid [8], and damping properties of crack was discussed by Wauer [9].

The local flexibility at the crack location reduces the stiffness of the rotor thereby reducing the natural frequencies. Several researchers have used the change in natural frequencies for the diagnosis of the cracked rotors. Morassi [10] derived an explicit expression of the sensitivity of the natural frequency to an open crack in a beam in the bending vibration for a simple spring-line model of a crack. He concluded that the sensitivity was proportional to the potential energy stored at the cross-section where the crack occurs in the beam. Nahvi and Jabbari [11] proposed a method based on measured frequencies and mode shapes of the beam. They used contours of normalised frequency in terms of normalised crack depth and location to detect the crack in cantilever beams. The intersection of contours with the constant modal natural frequency planes was used to relate the crack location and depth. Lu et al. [12] presented a method based on mode shape curvature and response sensitivity for the identification of crack in beam structures. In the first step, difference between the mode shape curvature of the cracked and intact beams were used to locate the crack. In the second step, a response sensitivity based model updating method was used to get the size and location precisely. Karthikeyan et al. [13] presented a method for the localisation and sizing of crack in a beam based upon free and forced responses. It uses the Tikhonov regularisation to get the bounded value of the crack flexibility coefficients. Guo et al. [14] used empirical mode decomposition along with wave transform spectrum to study the vibration signature of cracked rotor. It was found that the variations of the 2× and 3× super-harmonics components give accurate vibration signature of breathing crack.

Number of unknown crack parameters is far more for a multi-cracked shaft; namely the size, location, and orientation of cracks. A review on the multi-crack detection and localisation is presented by Sekhar [15]. There is a growing use of soft computing techniques (such as neural networks, fuzzy logic and genetic algorithms) and signal processing techniques (such as Hilbert transform and wavelet transform) for the diagnosis of multi-cracked shaft. Guo and Li [16] presented a two-stage method of determining the location and extent of multiple structural damages by using the information fusion technique and the genetic algorithm. In the first stage, evidence theory integrating natural frequencies and mode shapes are used to find out the location of damage. Then in the second stage, a micro-search genetic algorithm (MSGA) was used to determine the damage extent. Chang and Chen [17] presented a technique for the identification of cracks in a multiple cracked beam using the spatial wavelet analysis. First, locations of cracks were determined using the wavelet transform of the mode shape and then knowing the location, the size of cracks were determined using the change in natural frequencies. Patil and Maiti [18] used natural frequencies for the estimation of size and location of multiple cracks in cantilever beams. They used slender cantilever beams with the two and three cracks for the experimental verification.

As mentioned above, several reported work on crack identification is based upon changes in first few natural frequencies. Some of them have been verified in laboratory conditions also [18,19]. But for an industrial application, where measurements have to be taken over large time scales, the change in natural frequencies of transverse vibrations can be due to some more reasons such as change in bearing properties, seal ring locking and rub [20]. Algorithms such as wavelet based methods work by searching the effect of crack locally, i.e., detecting the slope discontinuity in the elastic line of shaft. For a successful application of the wavelet transform, the signal-to-noise ratio in the measured vibration signal should be high [21].

Researchers across the globe are putting efforts towards multiple crack identification and have elaborated its difficulty [15]. Methods based on the single-cracked shaft may give wrong estimation of the size and the location of crack for shafts with multiple cracks. Diagnosis of a multi-cracked shaft is more difficult because number of unknown crack parameters is more and different combination of these crack parameters may result in similar change the shaft dynamics. Authors [22,23] have previously developed a multi-crack detection and localisation algorithm (MCDLA) and tested the same with only numerical simulations. The algorithm is based upon forced responses of the cracked shaft, measured at regular axial locations of the shaft. The problem is compounded because the measurements are contaminated with noise. It uses the forced responses of the cracked shaft at several frequencies to incorporate more modal information for better predictions. Experimental verification of the MCDLA is presented in the present work. Single- and double-cracked non-rotating shafts are taken for the experimental verification. Also, a scheme is presented to improve the working of the algorithm in low signal-to-noise ratio conditions.

2. The MCDLA

In this section for completeness the MCDLA [20] is briefly presented. The algorithm uses shaft deflections at regular axial locations of the shaft and at several excitation frequencies. Let the number of locations at which linear DOFs are measured/known is n, and the number of

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