



Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

The use of roving discs and orthogonal natural frequencies for crack identification and location in rotors



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ARTICLE INFO

Article history:

Received 10 July 2013

Received in revised form

3 April 2014

Accepted 22 May 2014

Handling Editor: I. Trendafilova

Available online 19 July 2014

ABSTRACT

A variety of approaches that have been developed for the identification and localisation of cracks in a rotor system, which exploit natural frequencies, require a finite element model to obtain the natural frequencies of the intact rotor as baseline data. In fact, such approaches can give erroneous results about the location and depth of a crack if an inaccurate finite element model is used to represent an uncracked model. A new approach for the identification and localisation of cracks in rotor systems, which does not require the use of the natural frequencies of an intact rotor as a baseline data, is presented in this paper. The approach, named orthogonal natural frequencies (ONFs), is based only on the natural frequencies of the non-rotating cracked rotor in the two lateral bending vibration x – z and y – z planes. The approach uses the cracked natural frequencies in the horizontal x – z plane as the reference data instead of the intact natural frequencies. Also, a roving disc is traversed along the rotor in order to enhance the dynamics of the rotor at the cracked locations. At each spatial location of the roving disc, the two ONFs of the rotor–disc system are determined from which the corresponding ONF ratio is computed. The ONF ratios are normalised by the maximum ONF ratio to obtain normalised orthogonal natural frequency curves (NONFCs). The non-rotating cracked rotor is simulated by the finite element method using the Bernoulli–Euler beam theory. The unique characteristics of the proposed approach are the sharp, notched peaks at the crack locations but rounded peaks at non-cracked locations. These features facilitate the unambiguous identification and locations of cracks in rotors. The effects of crack depth, crack location, and mass of a roving disc are investigated. The results show that the proposed method has a great potential in the identification and localisation of cracks in a non-rotating cracked rotor.

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1. Introduction

The early detection and diagnosis of incipient faults associated with rotating machines have aroused considerable interest from researchers over the decades. It is known that the presence of a crack in rotors gives rise to stress concentration in the vicinity of the crack tip which introduces local flexibility at the crack location. This consequent reduction in the rotor stiffness, which is associated with decrease in natural frequencies and mode shapes of the rotor, leads to considerable changes in the dynamic behaviour of the cracked rotor. This, in turn, causes dangerous and catastrophic problems on the dynamics of rotating systems and result in serious damage to the rotating systems. Therefore, the early

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detection of a crack has significant importance on the safety, reliability, performance and efficiency of a cracked rotor system [1–6].

A non-rotating rotor system with a transversal open crack can be considered as a simply- support beam. As a result, the investigations of the identification of an open crack in non-rotating structures such as beams, rods and columns is useful for identifying and locating cracks in rotating machinery (see [7–9]). Over the past three decades, the aforementioned dynamic behaviour and non-destructive techniques (vibration-based) have been utilised by many researchers for the identification and location of cracks in rotating machines and structures. Mayes and Davies [10,11], Friswell and Lees [12], Doebling et al. [13], Tsai and Wang [14], Lee and Chung [15] and Sekhar [16] conducted several investigations on the dynamics of rotating cracked shafts. They have indicated that the change in natural frequencies and mode shapes due to the presence of a crack may be useful for the identification and localisation of cracks in rotors.

Narkis [17] studied the behaviour of cracked simply supported uniform beams and uniform free-free vibrating rods in bending. He has shown that the variation of the first two natural frequencies is adequate to identify the crack location. The identification of a single crack in a vibrating rod which is based on the knowledge of the shifting of a pair of natural frequencies due to the presence of a crack has been presented by Morassi [18]. The analysis was based on an explicit expression of the sensitivity of frequencies to crack location which can be used for non-uniform rods under general boundary conditions. Messina and Williams [19] have introduced a new algorithm to improve the computational efficiency of the multiple damage location assurance criterion (MDLAC). This algorithm requires measurements of the changes in a few natural frequencies of an intact and cracked structure in order to provide good prediction for the location and size of single or multiple cracks. Zhong and Oyadiji [20–22] have investigated theoretically and experimentally the natural frequencies of a cracked simply supported beam with a stationary roving mass. The results have shown that the roving mass along the cracked beam increases the variation of natural frequencies. That is, using the roving mass provides additional spatial information for damage detection of the beam. From their results; they produced natural frequency curves, which show the variations of the natural frequencies with the location of the roving mass. Fan and Qiao [23] have presented a more comprehensive literature survey on using a variety of techniques which are based on the variation of natural frequencies for the identification of cracks in structures.

Some researchers have investigated the use of changes in the flexibility matrix to identify cracks. Zhao and Dewolf [24] have conducted a theoretical sensitivity investigation comparing the application of natural frequencies, mode shapes, and modal flexibility for the identification of damage in structures. The results indicate that model flexibility performs slightly better than the other two methods. Pandey and Biswas [25] have presented a new method for damage localisation based on the changes in the modal flexibility of a damaged beam. Lu and Zhao [26] have proposed the modal flexibility curvature method with higher sensitivity than Pandey's method for multiple damage localisations.

The identification of cracks through utilising mode shape measurements has been conducted by some researchers. Pandey et al. [25] have indicated that the damage location in structures can be detected by using the changes in the curvature mode shapes which are localised in the region of damage. These changes increase with increasing damage size. Ratcliffe [27] has shown that the location of damage can be identified by using the mode shapes associated with higher natural frequencies, but their sensitivity is less than the sensitivity of the lower mode. Zhong and Oyadiji [28] have used the derivatives of the mode shapes of simply supported beams for the identification and localisation of small cracks in beams. The results have shown that using the first, second and third derivatives of the displacement mode shape provide good indication of the presence of a crack.

Some non-model based algorithms which are presented as damage index methods require the characteristics of the intact structure as a baseline data. The baseline is used as a reference to determine the changes in the modal parameters due to a crack. Normally, the baseline data is determined by two ways: either from undamaged structure measurements or by modelling the intact structure using the finite element method (FEM). In the context of using this methodology, Al-Said [29] has proposed a new algorithm to identify the location and depth of a crack in a stepped cantilevered Bernoulli–Euler beam with two masses. The variation of the difference between the natural frequencies of the cracked and intact systems was utilised for the proposed algorithm. However, a finite element model and experimental responses were used to obtain the natural frequencies of the intact beam as a baseline data. Pandey et al. [25] have compared the mode shape curvatures of the intact and damaged structures to identify the damage location. Cornwell et al. [30] have extended the one-dimensional strain energy method which was presented by Stubbs and Kim [31] to two-dimensional structures, but these two approaches still require the baseline data of the intact structure.

Most of the previous reviewed methods depend on the comparisons of the baseline data of intact structures with the data of the cracked structures. In fact, this approach can give erroneous results about the location and depth of a crack if an inaccurate finite element model is used to represent an intact model. To overcome this problem, several approaches have been presented to identify the crack location in cracked systems without resorting to the data of the intact states. Law [32] has proposed an algorithm for the damage localisation in two-dimensional plates. The algorithm is based on changes in uniform load surface (ULS), which requires only the first few frequencies and mode shapes of the plate before and after damage, or only the damage state eigenpairs if a gapped-smoothing technique is implemented. Ratcliffe [27] has developed a method for the identification of damage in one-dimensional beams. The method is based on a modified Laplacian operator which operates only on the data of the damaged beam. The procedure is performed by applying a cubic curve fit to the modal data and determines the variation between the curve fit and the actual data to locate the damage. Recently, a new method for crack detection in beam-like structures has been presented by Zhong and Oyadiji [4]. The method is based on

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