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Development of residual operational deflection shape for crack detection in structures

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ABSTRACT

Excitation of a cracked structure at a frequency always generates higher harmonic components of the exciting frequency due to the breathing of the crack. In this paper, the deflection of cracked structures at the exciting frequency and the second harmonic component is mapped by a new method based on the operational deflection shape (ODS) for the purpose of crack detection. While the ODS is helpful in understanding dynamic behaviour of structures and machines, it is not always possible to determine the location of cracks in structures or machines based on the ODS itself. Therefore, a new concept called residual ODS (R-ODS) has been defined for crack detection in beam-like structures. This paper presents the details of the proposed method and its results when applied to numerical and experimental examples.

1. Introduction

One of the important tasks of structural health monitoring systems is the detection of cracks in structures such as buildings and bridges. A number of vibration-based methods are available in the literature [1] that can identify the presence and location of cracks globally in any structures.

The presence of crack in a structure changes flexibility in the vicinity of the crack. This change causes the dynamic behaviour for the whole cracked structure to be different from the healthy one [2]. Vibration-based crack detection methods generally consider either open or breathing crack in their approaches. Gentile and Messina [3] identified open cracks in beam structures by minimising measurement data and baseline of the structures and using continuous wavelet transform (CWT). Although the ability of this method to efficiently identify locations of open cracks was shown, the method was not verified experimentally. Khaji et al. [4] presented an analytical approach for identifying cracks in uniform beams with open edge cracks based on vibration measurements. The method was able to predict the crack location and depth with errors less than 8% and 25% respectively. Xiang et al. [5] proposed a model-based crack identification method to estimate the crack location and size in a static shaft with an open crack. The method investigated the effects of rotary inertia on the natural frequencies of the rotor system to construct B-spline wavelet on the interval and was verified experimentally.

While some approaches use open cracks in their analysis, the existence of breathing fatigue crack in a structure can be represented accurately by considering its non-linear behaviour. Yan et al. [6] identified breathing-fatigue cracks in beams by employing the difference between natural frequencies of each stiffness region of a beam according to the stiffness interface. Surace et al. [7] used higher order frequency response functions (FRFs) based on the Volterra series for the purpose of fatigue crack detection in a cantilever beam. Tsyfansky and Beresnevich [8] used the higher harmonic components of

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external harmonic excitation to identify fatigue cracks in flexible geometrically bars. Same approach was utilised by Semperlotti et al. [9] to locate a breathing fatigue crack in an isotropic rod.

In this paper, vibration responses at the higher harmonics of exciting frequency for the structure, generated due to the breathing of fatigue crack (opening and closing), have again been considered. These responses can be analysed by considering either amplitude of deflection (AOD) or operational deflection shape (ODS). Ullah and Sinha [10] utilised the AOD method to map the deflection of E-glass fibre and epoxy resins composite plates with centre and off-centre delaminations. It was shown based on the experimental results that the normalised summation of higher harmonics (NSH) of the exciting frequency at each mode and its cumulative NSH (CNSH) were able to detect and locate the delamination respectively. The disadvantage of the AOD method at higher harmonics is that only absolute values of vibration amplitude at a specific mode are considered. Therefore, a true representation of the deflection shape of the structure which requires both the amplitude and phase information cannot be constructed. The other drawback of the AOD method at higher harmonics is that it may not be successful in detecting cracks in all types of structures [11]. Therefore, a new method for identifying and locating the crack based on the ODS at higher harmonics, which considers both amplitude and phase, is presented here.

Vibration amplitudes need to be measured at a number of locations along a structure during external excitation in order to construct the ODS for that structure. This can be done practically using a scanning laser Doppler vibrometer (SLVD). The key advantage of the ODS is that it uses both the amplitude and phase of vibration responses at a frequency to map the deflection pattern of structures. This results in realistic vibration patterns of structures and/or machines at a specific frequency. The ODS method is well-known in the vibration analysis [12,13]. Applications of the ODS analysis to different structures e.g., machines, bridges, gearboxes, and wind turbines are presented in the literature for different purposes. Pai and Young [14] investigated the use of a boundary effect detection (BED) method for identifying small damages in beams based on ODSs. Boundary layer solutions were extracted from experimental ODSs using a sliding-window least-squares curve-fitting method. It was showed both numerically and experimentally that the BED method is reliable for locating small damages; however, some difficulties and limitations were observed during the application of this method. Sundaresan et al. [15] used a scanning laser vibrometer to compute and then compare the ODSs of healthy and damaged turbine blades. Changes in curvature of the ODSs were used to locate the damage. Zhang et al. [16] proposed a new damage detection algorithm called global filtering method (GFM) for beam and plate like structures based on ODS curvature (ODSC). A vehicle was used to move along a line on damaged structure as an exciter. The ODSCs were then constructed from dynamic responses of the vehicle and not the structure. The GFM which is based on wavelet decomposition was employed to make the experimental ODSC smoother so that it can be used as baseline data. Then, the effect of damage could be detected through comparing the ODSC and the filtered one. The method does not require a number of preinstalled sensors on the structure which can be considered as an advantage; however, optimum velocity of the vehicle needs to be discovered since the detection quality of the GFM depends on it. Moreover, the results from the GFM were sensitive to the chosen decomposition level of filtering and the method may not be helpful in detecting small damages.

The ODS method is generally helpful in identifying vibration related problems in structures and machines; however, it may not be straightforward to locate cracks in structures by using only the ODS. Recently, the residual ODS (R-ODS) has been defined for the purpose of crack detection [11]. The preliminary study on simulated numerical examples showed encouraging results for identifying cracks in beam-like structures. In this paper, details of the R-ODS method as well as the results of applying it to both numerical and experimental examples are presented.

2. Proposed method

A breathing crack opens and closes alternatively during every cycle of loading and consequently produces non-linear dynamics of the cracked structure (Fig. 1). Due to this phenomenon, excitation of the cracked structure at a frequency always generates higher harmonic components of the exciting frequency. A typical spectrum for the beam with a breathing crack is shown in Fig. 2 where the exciting frequency ($1\times$) as well as its higher harmonics ($2\times$, $3\times$, $4\times$ ...) can be seen.

The ODS of the cracked beam can be generated at the exciting frequency and the second harmonic components to map the deflection of the cracked structure. However, it has been observed from numerical simulations [11] that the ODSs at the

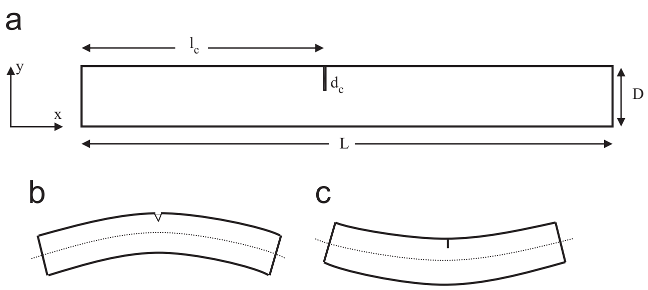

Fig. 1. (a) A typical cracked beam, (b) open crack and (c) closed crack.