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Sweep excitation with order tracking: A new tactic for beam crack analysis

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ABSTRACT

Crack detection in beams and beam-like structures is an important issue in industry and has attracted numerous investigations. A local crack leads to global system dynamics changes and produce non-linear vibration responses. Many researchers have studied these non-linearities for beam crack diagnosis. However, most reported methods are based on impact excitation and constant frequency excitation. Few studies have focused on crack detection through external sweep excitation which unleashes abundant dynamic characteristics of the system. Together with a signal resampling technique inspired by Computed Order Tracking, this paper utilize vibration responses under sweep excitations to diagnose crack status of beams. A data driven method for crack depth evaluation is proposed and window based harmonics extracting approaches are studied. The effectiveness of sweep excitation and the proposed method is experimentally validated.

1. Introduction

Condition monitoring and maintenance planning of beam and beam-like structures are critical in various industrial applications, such as civil engineering, aerospace and automotive. Detection and evaluation of beam cracks caused by mechanical fatigue and chemical corrosion become important issues for structural health monitoring and maintenance [1]. Among various monitoring techniques, vibration monitoring has been reported to be both practical and effective for many fault diagnostic problems including beam crack evaluation [2–4].

Vibration based monitoring may be classified into model based and data driven categories. Model based methods construct mathematical models to study the dynamic behaviour of the beam under different crack status [5,6], while data driven methods use historical data to match vibration patterns [7–9]. Both two approaches involve extracting effective features, such as natural frequencies and harmonics, from vibrational signals.

Early researchers developed many ways for beam modelling. Dimarogonas [10] (1996) and Bovsunovsky and Surace [11] (2015) surveyed beam models for crack detection. In Refs. [12–14], the cracks are assumed to be open. Many other works, e.g. Refs. [15–18], took the closing effect into account and established breathing crack models. It is found that the stiffness changes as the two bodies of the beam on either hand of the crack come into contact and depart. Beam models with breathing crack are reported to be more sensitive to small cracks [19] and exhibit non-linear characteristics of the system. The non-linearity caused by breathing phenomenon are often been studied as a key to crack analysis in beams. Some diagnostic methods monitor the non-linear changes of modal shapes [20,21] or natural frequencies [5,22,23] to determine crack status. However, Loutridis et al.

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[24] and Kim and Stubbs [25] pointed out that these changes are fractional to crack conditions. Instead, many papers, such as [26,27], use non-linear characteristics of the response to diagnose the beams. Sub and super harmonics are typical non-linear features that are used to indicate crack status of the beam [17,28]. In Section 2.1, an analytical demonstration is given in order to explain the relationship between crack status and the harmonics in its vibration response.

To vibrate the beam, most reported researches use impact force (hammer test) [29,30] or sinusoidal force (harmonic excitation) [31–33]. Hammer tests usually involve human operations and become some what impractical when the damping of the system is huge. For harmonic excitations, the excitation frequency is commonly fixed. Papers [11,28,32] reported that different excitation frequencies have different diagnostic performances for big and small cracks. This mean that fixed excitation frequency may not be enough for all situations. There is an alternative but forsaken way, namely sweep excitation, that can be used to discover the non-linear dynamic properties of a beam. Giannini et al. [17,34] found that more solid crack detection results can be obtained by using a slow-varying sweep excitation. However, their sweep ranged only a few Hz around the resonance frequency. Referring to the start-up operations that are usually implemented to diagnose faults in rotating machines [35], a wider sweep excitation range for beams may capture richer non-linearity information relevant to crack. In this paper, we will explore the benefits of using a wider sweep range to detect breathing cracks.

Apart from non-linearities, sweep excitations induce non-stationarities in vibration responses. This makes it hard to retrieve frequency harmonics with normal Fourier Transforms (FT). Order Tracking (OT) is an effective solution to non-stationary signals and has been successfully used for diagnosing rotating machines [36,37]. Typical OT techniques include Computed OT (COT) [38], Vold-Kalman Filtering OT [39] and etc. Among them, COT gives us order domain spectrum that are similar to frequency spectrum. It resamples the signals by a constant rotational angle increment and uses the main shaft rotating frequency as the reference to track the signal contents. The ratio of a frequency to the main shaft rotating frequency is called order. In order spectrum, order harmonics can be graphed and are potential non-linear features for crack detection. In our previous work [40], we adopted the angular resampling in COT for processing beam vibration signals. Based on this, we can track the order harmonics of beam vibrations under sweep excitations and utilize them as features for beam crack evaluation.

To summarize, extracting non-linear features from vibrational signals are important in beam crack status evaluation. Sweep excitation and harmonics are effective ways to respectively energize and capture the non-linearities introduced by crack. Using the resampling idea in COT, non-linear order harmonics can be retrieved from the beam's vibrations under sweep excitations. In this paper, we aim to investigate the effectiveness of order harmonics in beam crack evaluation, and we also study the details of extracting harmonics from spectrum. The contributions of this paper can be highlighted as follows:

1. Sweep excitation across many Hz is implemented to capitalize on the non-linearity introduced by breathing cracks;
2. Order spectrum for beam vibrations are constructed and window based harmonics extracting techniques are studied for crack evaluations;
3. Experimental data together with Support Vector Machines (SVMs) are used to assess the ability of extracted harmonics in evaluating cracks.

Remaining parts are organized as follows: Section 2 introduces related theories, Section 3 proposes the diagnostic method. Section 4 gives experimental demonstration and discussions of the proposed method. Finally, Section 5 concludes this study.

2. Related theory

2.1. Crack breathing non-linearity

The deflection of a simply supported beam, as shown in Fig. 1, under harmonic excitation can be written as:

$$x(t) = A(\omega)\sin\omega t \tag{2.1}$$

$$A(\omega) = \frac{2f_0}{\rho d\Pi}\sum_{n=1}^{\infty}\frac{1}{\omega_n^2-\omega^2}\sin\frac{n\pi l}{L}\sin\frac{n\pi d}{L} \tag{2.2}$$

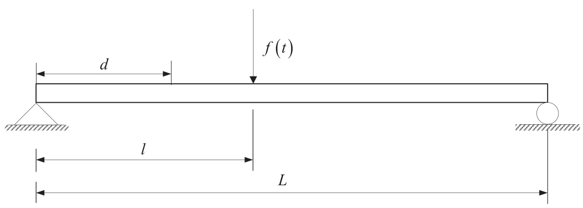

Fig. 1. Simply supported beam under excitation.