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Kissing bond detection in structural adhesive joints using nonlinear dynamic characteristics

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ABSTRACT

In this paper, the effect of kissing bond on nonlinear dynamic behavior of structures with flexible adhesive joint is investigated. Bilinear characteristic due to opening and closing in kissing bond region results in nonlinear dynamic behavior of the structure such as harmonic distortion in response to harmonic excitation. So, the higher-order harmonics can be considered as Nonlinear Damage Indicator Functions (NDIF) for the purpose of damage identification. A two-dimensional (2D) finite element model of a beam connected to a rigid support via a flexible adhesive layer is used to investigate the efficiency of the proposed NDIFs in kissing bond detection. Kissing bond is introduced to the model via contact elements. NDIFs are extracted for the finite element model using single tone stepped-sine test simulation. Parameters such as amplitude of excitation, size and location of kissing bond region as well as friction between kissing surfaces, are studied. The results proved that the NDIFs are sensitive to the size and location of kissing bond. Consequently, in an experimental damage identification procedure, NDIFs can be used as an indicator of kissing bond type damages in adhesive joints.

1. Introduction

Joining structures through elastic adhesives have advantages such as uniformly distributed stresses along the bond line, sealing, shock-absorbing, noise and vibration damping and insulating properties over the traditional joining methods like welding, bolting or riveting. These advantages result in continually growing application of elastic bonding in various industries, most notably in the wind turbines and air, road and rail vehicles.

On the other hand, different type of damages can occur in the adhesive joints during manufacturing and/or due to in service accidents which will reduce the strength and stiffness of the joints. Voids, debonds, kissing bonds, poor cure and porosity are examples of possible damages that can occur in elastic adhesive joints.

The kissing bond or zero volume debond is mentioned for the situation where two surfaces are only partially bonded or are debonded but touching or in very close proximity. This may occur due to poor adhesion, service loading or impact damage. The kissing bond may not be visible externally and because of intimate contact of the surfaces may be more difficult to detect using common Non-Destructive Examination (NDE) methods than a conventional debond in which there is a gap between two surfaces [1,2].

Amongst NDE methods, vibration-based techniques are effective in detection of damages such as cracks in structures, specifically in situations where the existence of damage brings about significant changes in linear or nonlinear dynamic properties of the structure. In many cases such as those considered in this study, damage causes a structure that initially behaves in a predominantly linear manner to exhibit nonlinear behaviors.

In some of the vibration-based damage identification processes, changes in modal properties of the structure are monitored as damage signatures. Natural frequencies, mode shapes, modal damping and modal strain energy are examples of these characteristics. Comprehensive reviews of these types of vibration-based damage detection methods can be found in literature, for instance [3–9]. The main drawback of these vibration-based damage detection methods is the fact that, in the cases of damages with small sizes, modal properties may show a low sensitivity to defects. For example, Bovsunovskii [10] showed that in a beam with breathing crack which covers 20% of the undamaged cross-sectional area, the first natural frequency only is reduced by 1%.

Response of a linear structure to a harmonic excitation is a harmonic signal with the frequency which is expected to be the same as the input signal but with different amplitude and phase angle. In contrast, in case of nonlinear structures, the sub- and super-harmonic components may become visible in the output. These circumstances are referred to as harmonic distortion or energy transfer in frequency domain and are known as one of the nonlinear dynamic

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behaviors. Nonlinear dynamic behaviors can be used as an indicator of the presence and extent of damage in structures. This fact forms the basis of another category of vibration-based Damage identification methods. A brief review of some damage-sensitive features extracted based on nonlinear system response can be found in [11].

When a crack exists in a structure, dynamic loading of the structure may results in nonlinear oscillations due to opening and closing in cracked region. This nonlinear behavior can be explained by different stiffness and damping of the structure in open and close conditions of the crack, leading to piecewise linear behavior. This type of cracks with opening and closing behavior is referred to as breathing or closing crack. For instance, dynamic of a linear beam with breathing crack near its first mode of vibration can be simulated with bilinear oscillator that shows special nonlinear characteristics. Nonlinear behavior of the beams with breathing crack is investigated in numerous studies and various damage identification methods have been developed in this field [12–26].

Rivola and White [12] simulated the nonlinear behavior of a beam in bending with a closing crack through bilinear oscillator model and used normalized version of the bispectrum, namely the bicoherence, to analyze the system response. They found that the bicoherence shows high sensitivity to the bilinear nature of the crack and applied this method as a tool for experimental detection of a fatigue crack in a straight beam. Hillis et al. [13] studied the applicability of the bispectrum analysis to detect cracks in bars. They used a waveform consisting of two sinusoidal waves to excite an experimental steel bar with fatigue cracks, and then using bispectrum they showed that the response contains mixing frequencies at the sum and difference of the input frequencies and the amplitude of the bispectrum at mixing frequencies increases in line with the crack size. Sinha [14] applied both bicoherence and tricoherence methods on the acceleration response of a cracked beam in numerically simulated experiments to detect the crack. The study showed that the computation of only few components of the bicoherence and tricoherence are sufficient for the crack detection, even for small fatigue cracks and the noisy responses. Andreaus et al. [15] studied the non-linear response of a cantilever cracked beam to harmonic loading, using a two-dimensional (2D) finite element model with frictionless contact model, to simulate the behavior of breathing crack. The effect of driving frequency was investigated and showed that when the excitation frequency is approximately $1/n$ or n of the first natural frequency of the cracked beam, the amplitude of the $(1/n)$th or nth harmonic becomes large and detectable. Using these results with the same procedure, Andreaus and Baragatti [16] observed that even for a small crack, if the excitation frequency was about one- third, one-half, and two times of the first natural frequency of the system, the relative amplitude of the third, second, and one-half harmonics became notably large and hence detectable. These nonlinear dynamic behaviors were quantized by the definition of Nonlinear Damage Indicators (NDIs). They developed an identification procedure to detect the crack presence, position and depth by the method of Damage Indicators Interpolation (DII) and constructing surfaces that related the crack position and depth to each one of the NDI value. In addition, they applied this method on an experimental case of a cracked cantilever beam [17]. Also, Giannini et al. [18] exploited similar approach and introduced concept of modal-effective damage. They considered more than one mode of vibration and showed that in comparison to single mode techniques, their method is more effective for identification of the size and position especially for cracks with small size. Dubey and Kapila [19] considered a FE model of a beam excited by a chaotic force input to detect and characterize a crack. They showed that a trend in wave fractal dimension can be used to predict crack location and size. They validated the simulation results experimentally.

Also, there are studies based on Volterra series. Chatterjee [20,21] analyzed the nonlinear response of a cracked beam using Volterra series. The bilinear restoring force was approximated by a second-order polynomial series and the first and second-order frequency response functions are developed. He showed the crack size can be estimated through measurement of the first and second harmonic amplitudes. Surace et al. [22] and Ruotolo et al. [23] proposed the use of Higher-order Frequency Response Functions (HFRFs) derived from the Volterra series to detect nonlinear behavior which can be attributed to the presence of damage in a cracked cantilever beam. The principal diagonals of HFRFs were estimated via stepped-sine simulated test on a FE model and provided a useful indicator of the presence and extent of damage. The new concept of the Nonlinear Output Frequency Response Functions (NOFRF) has been applied by Peng et al. [24] for crack detection in a beam. Their experimental studies indicate that the NOFRFs are sensitive indicators of the existence and the size of cracks.

In addition, some advanced signal processing methods such as Hilbert–Huang transform (HHT) have also been adopted. For example, Douka and Hadjileontiadis [25] investigated nonlinear free vibration response of a cracked cantilever beam both theoretically and experimentally. By applying Empirical Mode Decomposition (EMD) and Hilbert Transform (HT) to obtain the Instantaneous Frequency (IF) of the Intrinsic Modes (IMs), they found that the IF exhibits a temporal behavior oscillating between the frequencies corresponding to the open and closed states and mean variation of the IF increases with crack depth. Loutridis et al. [26] extended this study for the case of nonlinear forced vibration of a cracked cantilever beam.

Similar to bilinear oscillators and beams with breathing crack, If a kissing bond region exists in adhesive joints of a structure, dynamic loading of the structure in appropriate direction and position can results in opening and closing of kissing bond region. Consequently, the nonlinear dynamic characteristics of the structure can be used as an indicator of the existence and size of kissing bond. Based on this idea, the aim of the present paper is the introduction of Nonlinear Damage Indicator Functions (NDIFs) based on higher-order harmonic responses for the purpose of kissing bond detection in adhesive joints. Nonlinear vibration analysis of a simple structure with adhesive joint using the finite element model was performed and the results serve to demonstrate that NDIFs are sensitive indicators of the size and position of kissing bond.

The paper is organized as follows. The NDIFs are introduced in Section 2. The specifications of the finite element model are presented in Section 3. In Section 4, the numerical results are presented and finally, conclusions are given in Section 5.

2. Nonlinear Damage Indicator Functions (NDIFs)

The adhesive joint with kissing bond that is considered in this study, exhibits bilinear stiffness and damping characteristics depending on whether the kissing bond is open or closed. Nonlinear forced harmonic vibration of simple bilinear oscillators was studied by Wong et al. [27] using the harmonic balance method. Also, Chatterjee [28] and Peng et al. [29] have shown that a bilinear oscillator can be well approximated with a polynomial type nonlinear system and studied this problem via Volterra series.

Higher-order harmonic responses of a nonlinear system in a given frequency range can be measured by a stepped-sine test through experiment or simulation. Applying a sinusoidal excitation with constant amplitude, the time response of the system is recorded. To determine the higher-order harmonic response by simulation (or measurement), it is necessary to attain the steady-state response. Once the transient dynamic dies out, the response is considered for Fast Fourier Transform (FFT) analysis to calculate the spectrum of the response. The values of the Fourier transform