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Assessing the severity of fatigue crack using acoustics modulated by hysteretic vibration for a cantilever beam

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ABSTRACT

This paper investigates fatigue crack severity assessment using acoustics modulated by hysteretic vibration for a cantilever beam. In this study, a nonlinear oscillator system is constructed to induce the hysteretic frequency response of the cantilever beam in dynamics, and the hysteretic vibration is then used to modulate the acoustic waves to generate the vibro-acoustic modulation (VAM) effect. Through modulation of hysteretic vibration, the hysteretic response of the VAM can be achieved. The experimental results further validated that the VAM hysteresis phenomenon can be enhanced with the increase of crack severity owing to the change of beam's effective stiffness. Simulations in the proposed physical model explained the reason of enhancement of hysteresis phenomenon. Combined with nonlinear bistable structural model, a fatigue crack severity assessment approach was proposed by evaluating the hysteretic region (e.g., bandwidth or jumping frequency) in the vibration frequency response of the VAM effect. The reported study is valuable in building a monotonic relationship to assess the severity of fatigue crack by a nonlinear acoustics approach.

1. Introduction

Ultrasonic inspection is an important non-destructive evaluation (NDE) approach which has been an area of intensive study. Most conventional ultrasonic techniques are based on linear theory, and can detect gross defects or open cracks in a solid through linear scattering, reflection, and transmission of ultrasonic waves. However when the cracks are contact-type cracks (close cracks, fatigue cracks, graincontacts, delaminations, etc.), there will be no significant changes in these linear parameters. Consequently, linear theory-based ultrasonic NDE methods are unable to detect fatigue cracks, a kind of contact-type cracks.

Nonlinear ultrasonic techniques have been investigated as an effective approach to overcome the limitations of linear ultrasonic techniques. Donskoy et al. found that even a rather weak crack can also lead to an anomalously high level of nonlinearity, and the ultrasound waves propagating inside will introduce nonlinear acoustic response [1]. Contact acoustic nonlinearity (CAN) [2] and hysteretic nonlinearity [3] are two typical models considered in nonlinear ultrasonic techniques for material inspection and damage detection in complex structures [4–7].

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As one of typical nonlinear ultrasonic techniques for detection of nonlinear cracks, vibro-acoustic modulation (VAM) [1,8] is attributed to contact nonlinearities [2,4], specifically the clapping (opening and closing) mechanism of the CAN. The principle of the VAM phenomenon can be described as follows [9–12]: if an undamaged specimen or a specimen with linear cracks (e.g., gross defects or open cracks) is subjected to both a low-frequency vibration and a high-frequency ultrasonic wave, the result shows a linear superposition of two waves; however if the system is nonlinearly damaged (e.g., close cracks or some debonding), the two waves interact so that the ultrasonic wave is modulated in amplitude and/or phase by the low frequency oscillation. Therefore, the occurrence of modulation phenomenon can be taken as an indication of the presence of nonlinear damage in the specimen and could be used as the basis of a NDE technique for fatigue damage detection [12].

While previous studies have proven that using VAM can successfully detect contact-type cracks in complex media, it is not yet mature on the aspect of damage severity assessment. One important reason is that, in previous researches, there still have some different opinions about the internal mechanism of VAM technique (e.g., the coupling mechanism between the two excitations, and the relationship between damage severity and modulation intensity). Duffour et al. [13] believed the modulation between low-frequency vibration excitation and high-frequency acoustic waves belongs to the amplitude modulation (AM), and they had validated the relationship between the modulation index and crack length is non-monotonic. However, Donskoy et al. [10] suggested that there exist both phase modulation (PM) and amplitude modulation (AM) between two waves. The other reason is that in most researches, the modulation phenomenon was usually studied in the frequency domain where the modulating effect is manifested by the presence of sidebands around the main peak at the ultrasonic frequency. Current studies usually regard the ratio of the sidebands and the main peak as a damage index to indicate the presence of cracks. Hu et al. [14] found that the damage index calculated in the spectral domain may lead to false indications about the damage severity owing to the complex modulation processes. Donskoy et al. [10] and Duffour et al. [12] addressed on averaging the amplitude of the sidebands over a wide ultrasonic frequency range to eliminate the dependence of the sensitivity of VAM on the ultrasonic frequencies, which however still showed nonideal correlation between the crack size and the strength of modulation. Therefore, the modulation intensity-based VAM technology may not effectively estimate structural damage severity.

Hysteresis in elastic behavior of materials is a well-known physical phenomenon. The hysteretic phenomena generally occur in dynamic structures or nonlinear vibration systems. Accordingly, hysteretic nonlinearities could be classified into two categories. One is that, under the cyclic load, the loading and unloading do not follow the same stress–strain curve resulting in formation of hysteretic loop. In accordance with this theory, Moussatov et al. [15] observed a self-induced hysteresis phenomenon in the case of high-amplitude surface acoustic pulse interaction with surface-breaking cracks. Kober et al. [16] proposed an algorithm mainly for building a hysteretic loop and extracted a nonlinear parameter estimator (e.g., the dependence of spectral amplitudes on driving amplitudes) by Nonlinear Wave Modulation Spectroscopy (NWMS) method for depicting crack growth. The other kind of hysteresis means that a different behavior can be obtained for increasing or decreasing frequency in nonlinear vibration systems (e.g., oscillators), which usually gives an indication of the distortion from linear resonance [17]. Mann and Sims [18] revealed that engaging the nonlinear response of system can result in relatively large oscillations over a wider range of frequencies. That is to say, in nonlinear systems, the resonance

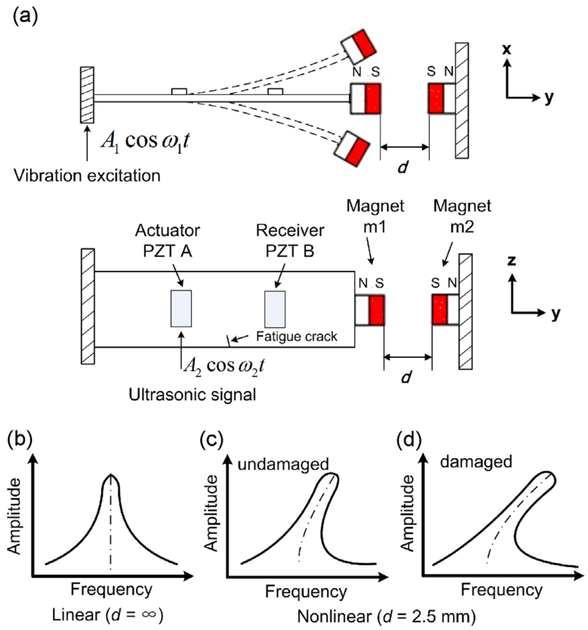

Fig. 1. (a) Schematic of the proposed physical model for fatigue crack severity assessment via VAM; illustration of amplitude–frequency response curve in (b) linear system, (c) nonlinear system with undamaged beam, and (d) nonlinear system with damaged beam.