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Nonlinear spectral correlation for fatigue crack detection under noisy environments

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ABSTRACT

When ultrasonic waves at two distinct frequencies are applied to a structure with a fatigue crack, crack-induced nonlinearity creates nonlinear ultrasonic modulations at the sum and difference of the two input frequencies. The amplitude of the nonlinear modulation components is typically one or two orders of magnitude smaller than that of the primary linear components. Therefore, the modulation components can be easily buried under noise levels and it becomes difficult to extract the nonlinear modulation components under noisy environments using a conventional spectral density function. In this study, nonlinear spectral correlation, which calculates the spectral correlation between nonlinear modulation components, is proposed to isolate the nonlinear modulation components from noisy environments and used for fatigue crack detection. The proposed nonlinear spectral correlation offers the following benefits: (1) Stationary noises have little effect on nonlinear spectral correlation; (2) By using a wideband high-frequency input and a single low-frequency input, the contrast of nonlinear spectral correlation between damage and intact conditions can be enhanced; and (3) The test efficiency can be also improved via reducing the data collection time. Validation tests are performed on aluminum plates and scaled steel shafts with real fatigue cracks. The experimental results demonstrate that the proposed nonlinear spectral correlation owns a higher sensitivity to fatigue crack than the classical nonlinear coefficient estimated from the spectral density function, and the usage of nonlinear spectral correlation allows the detection of fatigue crack even using noncontact air-coupled transducers with a low signal-to-noise ratio.

1. Introduction

A fatigue crack is a major cause for the failure of metallic structures [1]. Typically, a fatigue crack becomes conspicuous only after the crack reaches about 80% of the total fatigue life of a structure [2]. Among various non-destructive evaluation (NDE) and structural health monitoring (SHM) techniques such as ultrasonic, acoustic emission, thermography, eddy current, magnetic particle inspection, X-ray and etc [3–6]., the ultrasonic technique is one of the most promising approaches for fatigue crack detection and has proven its effectiveness in achieving a reasonable compromise between resolution, practicality and detectability. Conventional linear ultrasonic techniques measure variations of the amplitude, phase, and mode conversion of linear ultrasonic waves either transmitted or reflected from a crack [7–10]. However, it is difficult to detect a fatigue crack at its early stage using the conventional linear ultrasonic techniques, because the changes of these linear

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features only become prominent when the damage is severe. Recent studies have shown that a fatigue crack and its precursor often serve as a source for generating nonlinear waves, and the sensitivity of the nonlinear ultrasonic techniques to a fatigue crack is much higher than what can be achieved by the conventional linear techniques [11–21].

More specifically, nonlinear ultrasonic techniques detect a fatigue crack by investigating accompanying harmonics, modulations of different frequencies, or changing resonance frequencies as the amplitude of the driving input changes. For nonlinear ultrasonic modulation, normally, a low-frequency input and a high-frequency input are simultaneously applied on a damaged structure to create modulation [12]. For example, a fatigue crack in an aluminum plate was detected by using a piezoelectric stack actuator for generation of a low-frequency input and a surface-mounted piezoelectric transducer for creation of a high-frequency input [13]. Nonlinear ultrasonic modulation has also been used for detecting fatigue cracks in welded pipe joints and concrete beams [14,15].

A few technical hurdles still, however, need to be overcome before these nonlinear ultrasonic techniques can make transitions to real field applications. One issue is that the generation of nonlinear modulation is heavily dependent on the choice of the input frequencies and can be easily affected by the configuration of the fatigue crack as well as variations of the environmental and operational conditions (e.g., temperature and loading) of the target structure [16,17]. Correspondingly, fixed low-frequency and swept high-frequency inputs were used to find an optimal combination of the low-frequency and high-frequency inputs that could amplify the amplitude of crack-induced modulation [18]. Fatigue cracks in aircraft fitting-lug mock-up specimens were detected by sweeping both low-frequency and high-frequency inputs [19]. But sweeping input signals over wide frequency ranges takes a long data collection time and can be impractical for field applications. In another study, a pulse laser input was used instead of two individual input frequencies for fatigue crack detection [20]. But since the linear and nonlinear components overlapped each other in the frequency domain, cracks can only be detected by statistically counting the spectral peaks (or energy redistribution) produced by modulations among the broadband input frequencies.

Another issue is that the amplitude of nonlinear components is at least one or two orders of magnitude smaller than that of the linear components, so it is difficult to extract the nonlinear components using a conventional spectral density function (power spectrum) under noisy environments, especially when the noise overlaps the nonlinear components in the frequency domain. The bispectrum was used to address this issue, which results in a frequency-frequency-amplitude relationship showing the coupling between signals at different frequencies [21]. The generation of non-zero bispectrum peaks due to damage-induced harmonics was numerically and experimentally demonstrated in the presence of white noise interference [22], and the bispectrum was also used to detect the modulation created by a fatigue crack in a metal specimen [23]. Furthermore, the non-stationary nature of the structural response was considered, and a baseline-free technique based on spectral correlation between nonlinear modulation components was developed for fatigue crack detection [24]. Here, the spectral correlation method has more advantages than the bispectrum in terms of computation time and flexibility of use [25].

This paper proposes a new nonlinear damage feature named nonlinear spectral correlation, and the combination of a wideband high-frequency input and a single low-frequency input is used to enhance the performance of nonlinear spectral correlation for fatigue crack detection. The proposed technique offers the following advantages: (1) A new damage feature coined nonlinear spectral correlation between two nonlinear modulation components is defined; (2) The nonlinear spectral correlation is insensitive to noise interference; (3) The contrast between damage and intact conditions is enhanced by using nonlinear spectral correlation instead of classical nonlinear coefficient; (4) The possibility of satisfying the binding conditions, which are necessary for the generation of modulation, is increased using a wideband high-frequency input and a single low-frequency input; and (5) The employment of a wideband high-frequency input and a single low-frequency input also reduces the data collection time significantly.

This paper is organized as follows. Section 2 introduces the proposed nonlinear spectral correlation and its enhanced sensitivity to damage by using a wideband high-frequency input and a single low-frequency input. Section 3 demonstrates the effectiveness of the nonlinear spectral correlation by detecting real fatigue cracks in aluminum plates. In Section 4, the effectiveness is further validated by detecting fatigue cracks in scaled steel shafts using noncontact air-coupled transducers with a low signal-to-noise ratio. Finally, a conclusion is provided in Section 5.

2. Development of nonlinear spectral correlation

2.1. Nonlinear wave modulation

When two inputs with distinct frequencies f_a and f_b $\left(f_a > f_b\right)$ are applied to an intact (linear) structure, the structural response contains the frequency components corresponding only to the input frequencies. Once the structure behaves nonlinearly (e.g., due to fatigue crack), the structural response will contain not only the input frequency components but also their harmonics (multiples of input frequencies, i.e., $2f_a$, $2f_b$, etc.) and modulations (linear combinations of two input frequencies, i.e., $f_a \pm f_b$, $f_a \pm 2f_b$, $2f_a \pm f_b$, etc.), as illustrated in Fig. 1. This phenomenon is referred to as nonlinear ultrasonic modulation or nonlinear wave modulation [12,26]. Because this phenomenon occurs only if nonlinear sources exist, it can be considered a signature of the presence of nonlinearity and thus the existence of a crack, assuming that the inherent material nonlinearity is weak. Considering only the first-order nonlinear modulations at $f_a + f_b$ and $f_a - f_b$, their amplitudes