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Damage detection using sideband peak count in spectral correlation domain

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Nonlinear ultrasonic techniques have been proven to be more sensitive to the presence of an early-stage damage than linear techniques. Among various nonlinear techniques, laser nonlinear wave modulation spectroscopy (LNWMS) utilizes a pulse laser to exert a broadband input and a damage on the target structure exhibits nonlinear wave modulation among various input frequency components. A sideband peak count (SPC) technique in the spectral frequency domain was proposed to estimate the damage-induced nonlinearity. In this study, the SPC operation is conducted in the spectral correlation domain so that noise has less influence on damage detection performance and a higher sensitivity to damage can be achieved. In addition, through spatial comparison of SPC over an inspection area, damage can be detected without relying on the baseline data obtained from a pristine condition. The performance of the proposed technique is validated using a numerical simulation performed on an aluminum plate with a simulated crack, and experiments performed on an aluminum plate with a fatigue crack and a carbon fiber reinforced polymer plate with delamination.

1. Introduction

Damage evolution in a structure is often a nonlinear process that causes a linear structure to exhibit nonlinear properties. Examples of such damages include fatigue cracks, fiber debonding and delamination, etc [1,2]. Among various ultrasonic techniques, it has been shown that the sensitivity of nonlinear ultrasonic techniques to an early-stage damage is much higher than what can be achieved by linear ultrasonic techniques [3–6]. Specifically, the linear ultrasonic techniques detect the presence and location of a damage by measuring variations of amplitude, phase and mode conversion of ultrasonic waves that are either transmitted or reflected from the damage [7–9]. However, these linear features are not sensitive to early-stage damages whose dimensions are comparable to the ultrasonic wavelength. Furthermore, the interpretation of linear features becomes complex in plate-like structures due to dispersion and multimode characteristics [10], and even more challenging in inhomogeneous materials like composites [11,12].

On the other hand, nonlinear ultrasonic techniques detect a damage by investigating accompanying harmonics, modulations (sidebands) of different frequencies, or changing resonance frequencies as the amplitude of the driving input changes. These nonlinear features are observed in the course of structural degradation processes much sooner than any changes of linear features can be detected, making the nonlinear ultrasonic features more attractive for early-stage damage detection.

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For nonlinear wave modulation spectroscopy (NWMS) which is one of the nonlinear ultrasonic techniques, a low-frequency pumping input and a high-frequency probing input are simultaneously applied on a damaged structure to create modulation [13]. For the generation of nonlinear modulation using NWMS, there are certain binding conditions should be satisfied in addition to the existence of a damage [14,15]: (1) The strain (displacement) at the damage location should be oscillated by both inputs; and (2) The motion induced by one of the two inputs should modulate the other input at the damage location. That is, the generation of nonlinear modulation also depends on the choice of input frequencies and can be easily affected by the configuration of the damage as well as by variations in the environmental and operational conditions (e.g., temperature and loading) of the target structure [16].

To ensure that the binding conditions be satisfied and damage be detected, frequency-swept probing signals and a frequency-fixed pumping signal were used to find input frequency combinations that could amplify the amplitude of damage-induced modulation [17]. Similarly, fatigue cracks in aircraft fitting-lug mock-up specimens were detected by sweeping both low-frequency pumping and high-frequency probing inputs [18]. In another study, instead of using two distinct frequency inputs, a pulse signal was designed as an input to reveal reduction of the nonlinear modulation behavior in glass fiber reinforced cement material with aging [19]. A laser nonlinear wave modulation spectroscopy (LNWMS) utilized a pulse laser signal to excite multiple frequency components simultaneously into a target structure [20,21]. The basic premise is that nonlinear wave modulation can occur among frequency components excited by the pulse input at the existence of a damage, as illustrated in Fig. 1. The broadband nature of the pulse laser input guarantees that the binding conditions can be satisfied among a subset of frequency combinations within the excited frequency band. The pulse excitation also can reduce the data collection time compared to the sweeping of input frequencies within the same frequency band. Note that, because the nonlinear modulation (sideband) and the linear response components overlap in the spectral frequency domain, a sideband peak count (SPC) was developed to detect the spectral peaks created by a damage [20,21]. LNWMS experiments were conducted on simple aluminum plates and aircraft fitting-lugs with a complete noncontact laser ultrasonic system, and the test results demonstrated that an increased number of weak spectral peaks appeared when fatigue cracks were formed [22].

This study develops a new SPC technique by conducting the SPC operation in a spectral correlation domain for damage detection rather than the conventional spectral frequency domain. The proposed technique offers the following advantages: (1) The new SPC technique is robust against noise interferences; (2) The new SPC technique has a higher sensitivity to damage than the conventional SPC technique conducted in the spectral frequency domain; (3) The new SPC technique is realized in a fully noncontact manner; and (4) By spatial comparison through laser scanning, damage can be detected without relying on baseline data obtained from the pristine condition of a target structure.

This paper is organized as follows. Section 2 briefly reviews the working principle of the SPC technique. Then, Section 2 presents the new spectral correlation based SPC technique and its advantages over the conventional SPC technique. In addition, a baseline-free damage detection strategy is proposed by spatial comparison through laser scanning. In Section 3, the proposed technique is numerically validated by detecting a simulated crack in an aluminum plate model. In Sections 4 and 5, the performance of the proposed technique is examined by detecting a fatigue crack in an aluminum plate, and delamination in a carbon fiber reinforced polymer (CFRP) plate. Finally, a conclusion is provided in Section 6.

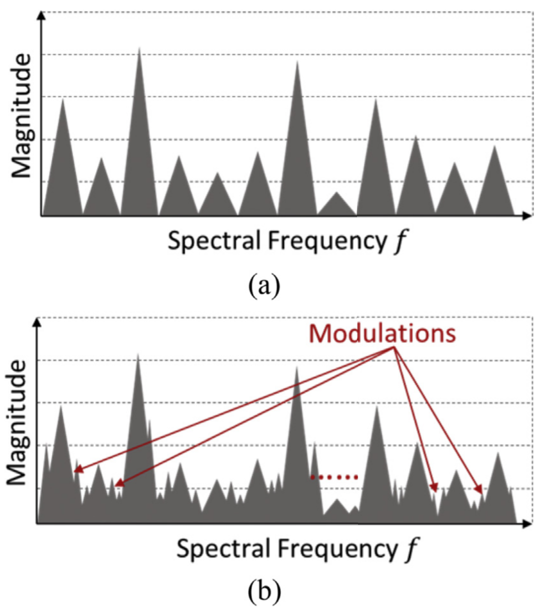

Fig. 1. Illustration of laser nonlinear wave modulation spectroscopy in the spectral frequency domain: (a) intact case, (b) damage case.