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Development of nonlinear spectral correlation between ultrasonic modulation components

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ABSTRACT

When a damaged structure is exposed to ultrasonic waves at two distinct frequencies, nonlinear wave modulation resulted from a damage such as a fatigue crack can be observed in the corresponding response, offering an opportunity for early damage detection. This study attempted to improve nonlinear wave modulation-based damage detection by applying statistically weak-linked inputs over two distinct frequencies to the target structure and then conducting a cyclostationarity analysis of the corresponding structural response. The cyclostationary nature of the structural response produces a statistical variation over time, allowing the structural response to be processed using a spectral correlation function. The spectral correlation can thus be used to transform the structural response into two dimensions characterized by their cyclic and spectral frequencies. Then, the damage-induced nonlinear modulation can be detected by studying the spectral correlation values for the specific cyclic and spectral frequencies defined by the modulation frequencies. This premise forms the basis for nonlinear spectral correlation, which is a new damage feature that is superior in terms of its sensitivity for nonlinear damage and improved robustness against noise compared to a conventional spectral density function. The performance of the proposed technique was validated by conducting an experiment with aluminum plates containing real fatigue cracks. The results of this experiment showed that the proposed technique could detect damage even under severely noisy conditions.

1. Introduction

Structural damage detection is essential for the inspection and maintenance of structures in a wide range of civil, mechanical, and aerospace applications. Furthermore, early damage detection has become an important issue to prevent catastrophic failures [1]. Indeed, most damage evolves in a nonlinear manner, causing an intact structure with predominantly linear properties to exhibit nonlinear properties. A growing number of non-destructive testing (NDT) and structural health monitoring (SHM) techniques have been developed to take advantage of damage-induced nonlinearity using nonlinear vibrations [2–5] and nonlinear ultrasonics [6–10]. For example, incipient damage has been detected in an early stage through the generation of ultrasound harmonics [11,12] and the modulation of two input frequencies [13].

However, technical hurdles still need to be overcome before these nonlinear techniques can make transitions to practical NDT/SHM applications. One big issue is that the amplitudes of the nonlinear components are at least one or two orders of magnitude smaller than those of the linear components. Thus, it is difficult to extract the nonlinear components using a conventional spectral density function (power spectrum) in a noisy field, especially when the noise overlaps the nonlinear components in the frequency domain. A bispectrum is used to address this issue, which results in a frequency-frequency-amplitude relationship showing the coupling between signals at different frequencies [14]. The generation of non-zero bispectrum peaks due to the harmonics induced by nonlinear damage was numerically and experimentally demonstrated in the presence of white noise interference [15], and the bispectrum was also used to detect the modulation created by a fatigue crack in a metal specimen [16].

The drawback of using these power spectrum and bispectrum analyses is that they are mainly defined for stationary signals and cannot handle the non-stationary properties of a structural response. More specifically, numerous physical and manmade processes are cyclostationary or pseudo-cyclostationary processes, in which certain statistics vary periodically over time [17], and cyclostationarity has been encountered in various fields such as the diagnosis of gear faults in moving mechanical systems [18–22] and channel-sensing and spectrum allocation in wireless communication [23–25]. These studies have shown that the periodic

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features present in cyclostationary signals can be exploited to produce algorithms with a substantial improvement in performance relative to the case where processed signals are considered to be stationary.

This paper presents a new damage detection technique to improve the performance of nonlinear ultrasonic-based damage detection by using statistically weak-linked ultrasonic inputs and conducting a cyclostationarity analysis of the non-stationary ultrasonic responses. The proposed technique offers the following advantages. (1) The nonlinear spectral correlation is extracted as a new feature, and its superior sensitivity to nonlinear damage is demonstrated. (2) Statistically weak-linked ultrasonic inputs are used to enhance the contrast of the nonlinear spectral correlations between damage and intact conditions relative to a classical nonlinear coefficient. (3) The proposed nonlinear spectral correlation is insensitive to noise interference, and (4) can be successfully applied to fatigue crack detection.

This paper is organized as follows. Section 2 introduces the working principle of the nonlinear wave modulation and cyclostationarity analysis, and the nonlinear spectral correlation is defined as a new damage feature. Section 3 describes the experimental test conducted on aluminum plates with real fatigue cracks to validate the proposed technique. Finally, the conclusion is provided in section 4.

2. Development of nonlinear spectral correlation

2.1. Nonlinear wave modulation

When two inputs with distinct frequencies f_a and f_b $(f_a > f_b)$ are applied to an intact (linear) structure, as illustrated in Fig. 1, the structural response will contain only the frequency components corresponding to the inputs. Once the structure behaves nonlinearly, the structural response will contain not only the input frequency components but also their harmonics (multiples of input frequencies) and modulations (linear combinations of the two input frequencies). This phenomenon is referred to as nonlinear ultrasonic modulation or nonlinear wave modulation [6,26]. Because this phenomenon occurs only if nonlinear sources exist, it is considered to be an indicator of nonlinear damage, assuming that the inherent material nonlinearity is weak and negligible. Considering only the first-order nonlinear modulations at $f_a \pm f_b$, their amplitude $m_\pm$ is proportional to the amplitudes at f_a and f_b based on the classical two-fold nonlinear interaction between f_a and f_b [6]:

$$m_\pm \sim \beta^\pm_{a,b} ab \tag{1}$$

where $\beta^\pm_{a,b}$ is the classical nonlinear coefficient for $f_a + f_b$ and $f_a - f_b$, and a and b are the amplitudes of the linear responses at f_a and f_b, respectively.

Note that even for a structure that behaves nonlinearly, nonlinear wave modulation does not always occur. Previous studies have theoretically and experimentally investigated the binding conditions for nonlinear wave modulation with localized nonlinear damage [27,28], and these studies can be briefly summarized as follows. (1) The strain (displacement) at the location with nonlinear damage should be oscillated by both inputs, and (2) the motion induced by one of the two inputs should modulate the other input at the location of the nonlinear damage. In other words, the generation of nonlinear modulation and the value of the nonlinear coefficient $\beta^\pm_{a,b}$ are heavily dependent on the choice of f_a and f_b and can be easily affected by the configuration of the nonlinear damage, as well as by variations in the environmental and operational conditions (e.g., temperature and loading) of the target structure.

Frequency-swept high-frequency signals and a frequency-fixed low-frequency signal were used to determine the optimal frequency combinations for nonlinear wave modulation [29]. Similarly, a first sideband spectrogram was created by sweeping both the high-frequency and low-frequency signals over specific frequency ranges in order to increase the detectability of the nonlinear damage [30]. Another study used a broadband laser input instead of two individual input frequencies to detect damage by counting the spectral peaks produced by the modulations among the broadband input frequencies [31].

2.2. Cyclostationarity analysis

Cyclostationary signals are non-stationary signals for which the statistical characteristics vary periodically over time [32]. Cyclostationarity can be categorized into first-order cyclostationarity, for which the mean of a signal $x(t)$ is a periodical function of time, and second-order cyclostationarity, for which the hidden periodicity of a signal $x(t)$can be revealed by its autocorrelation, defined as follows:

$$R_x(t,\tau) = E\left[x\left(t+\frac{\tau}{2}\right)x^*\left(t-\frac{\tau}{2}\right)\right] \tag{2}$$

where τ is the time lag and * denotes the complex conjugate. If $R_x(t,\tau) = R_x(t+T_p,\tau)$, signal $x(t)$ is second-order cyclostationary for all t with a cyclic period T_p. The second-order cyclostationarity can also be analyzed in the frequency domain using a spectral correlation function, which is a double Fourier transform of the autocorrelation function

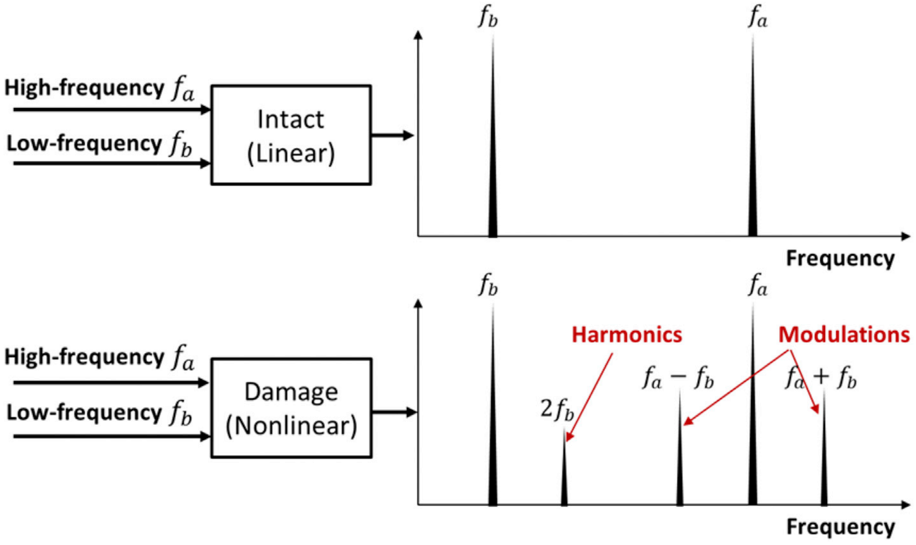

Fig. 1. Illustration of nonlinear wave modulation.