



Characterization of nonlinear ultrasonic effects using the dynamic wavelet fingerprint technique

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ABSTRACT

An improved dynamic wavelet fingerprint (DWFP) technique was developed to characterize nonlinear ultrasonic effects. The white area in the fingerprint was used as the nonlinear feature to quantify the degree of damage. The performance of different wavelet functions, the effect of scale factor and white subslice ratio on the nonlinear feature extraction were investigated, and the optimal wavelet function, scale factor and white subslice ratio for maximum damage sensitivity were determined. The proposed DWFP method was applied to the analysis of experimental signals obtained from nonlinear ultrasonic harmonic and wave-mixing experiments. It was demonstrated that the proposed DWFP method can be used to effectively extract nonlinear features from the experimental signals. Moreover, the proposed nonlinear fingerprint coefficient was sensitive to micro cracks and correlated well with the degree of damage.

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1. Introduction

Recent years have seen great research interest in various nondestructive testing methods based on nonlinear effects associated with ultrasonic wave propagation [1,2]. These effects include the generation of higher harmonics [3] and subharmonics [4], shifting of the resonance frequency [5], and mixed-frequency responses [6]. The primary reason for this interest is the strong nonlinearity of lattice anharmonicity of materials, microstructures of solids, defects, boundaries in crystal structure etc. Nonlinear ultrasonic methods have been used for damage evaluation in metallic structures [7] (even those with complex shapes [8]), composites [9], bones [10], soft tissues and biological media [11], concrete [12], soil and granular materials [1], and glass [2]. For all these applications of nonlinear ultrasonic, a quantity extracted from the measured response is used as a damage sensitive feature that indicates the presence of damage in a structure, which also called nonlinear ultrasonic feature.

Actually, identifying features that can accurately distinguish a damaged structure from an undamaged one is the focus of most nondestructive testing [13–15]. For nonlinear ultrasonic methods, the existence of defects or microstructural damage often results in a frequency shift of the ultrasonic signal compared with the input signal. Because of the complex nature of nonlinear ultrasonic methods, it is generally difficult or unfeasible to assess nonlinear ultrasonic features directly from the raw ultrasonic signals. To extract damage-sensitive features from the measured ultrasonic signal, three general techniques have been proposed: Fourier spectral analysis [16–18], bispectral analysis [19–21], and waveform analysis [22].

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Fourier spectral analysis is the most widely used method for nonlinear ultrasonic feature detection. From the calculated frequency spectrum, the amplitude response at any feature frequency (e.g., the fundamental harmonic, higher harmonic, subharmonic, or resonance frequency) can be obtained easily. Measurement of the well-known nonlinear parameter β in method of harmonic generation is a good example of the applications of Fourier spectral analysis [16–18].

Bispectral analysis is a third-order spectral analysis technique, which results in a frequency–frequency–amplitude relationship that reflects the coupling between signals at different frequencies. Because of its sensitivity to quadratic phase coupling, bispectral analysis is an attractive signal-analysis tool for detecting nonlinearities due to damage and has been widely used for nonlinearity measurements in various systems. Hillis et al. [19], Courtney et al. [20] and Jiao et al. [21] applied bispectrum analysis to the nonlinear response of modulated ultrasonic signals and proposed its application in crack and intergranular corrosion detection in metal structures.

Unlike the two spectral analysis methods described above, waveform analysis extracts the characteristics of defects directly using wave-packet information in time domain. For example, Croxford et al. [22] applied the noncollinear mixing technique for nonlinear ultrasonic detection of plasticity and fatigue, whereby the nonlinear interaction of two shear waves and damage was indicated by the presence of longitudinal packet-waves in the waveform. The method of waveform analysis is simple and intuitive. Unfortunately, however, in many cases it is difficult or even impossible to detect significant variation in the waveform.

The traditional techniques described above, whether in the time or frequency domain, are vulnerable to noise contamination and interference from undesired signals; hence, their effectiveness in the extraction and characterization of weak nonlinear responses is limited. The wavelet transform method is a multi-resolution analysis approach that is effective for the extraction of significant details and information in both time and frequency domains, and is widely used for processing transient and nonstationary signals [23–26]. The basic operation of wavelet transform involves dilation and translation operations, which allow multi-scale analysis of the signal. Therefore, this method can be used to effectively extract both time-domain and frequency-domain features of the inspected signal. To take advantage of the potential of the wavelet transform, a dynamic wavelet fingerprint (DWFP) technique [27–29] was developed from the wavelet transform algorithm for feature extraction from dynamic signals. In this technique, DWFPs are constructed on the spot from a projection of the continuous wavelet coefficients of the transient signal, thereby converting one-dimensional time traces into two-dimensional binary images.

Several studies have shown that the DWFP technique is effective in characterizing linear features of ultrasonic signals in nondestructive testing [30–35]. Because the waveform features of interest are too subtle to identify in the time domain, Hinders and co-workers [28,35] investigated the usefulness of the DWFP technique to render guided wave-mode information in two-dimensional binary images. The use of wavelets allows both time- and frequency-domain features from the original signals to be retained, and allows image processing to be used to automatically extract features that correspond to the arrival times of the guided wave modes. Hou et al. [32,33] applied the DWFP technique using tomographic images to estimate the arrival times of multiple Lamb wave modes. The amount of white area in the DWFP images was used as a feature to distinguish false modes caused by noise and other interference from the true modes of interest. Hinders and Hou [31] applied the DWFP technique in the ultrasonic detection of suspected scattering objects in periodontal probing. The DWFP patterns were classified and mapped onto an inclination index curve. The performance of the algorithm was evaluated by comparing the ultrasonic probing results with those of full-mouth manual probing at the same sites.

Until now, DWFP has only been used for the extraction of linear features with unequal frequency intervals/ or equal scale intervals. In the present study, an improved DWFP was applied to extract nonlinear ultrasonic features from measured signals with equal frequency intervals/ or unequal scale intervals. In Section II, a DWFP algorithm with equal frequency intervals is developed for the characterization of nonlinear effects in ultrasonic signals. In Section III, we investigate the effect of wavelet functions, the scale of the fingerprints to determine appropriate parameters in the wavelet transform, and the white subslice ratio during the slice-projection operation. The practical demonstration of the application of the algorithms to experimental ultrasonic signals is presented in Section IV.

2. DWFP technique for extraction of nonlinear ultrasonic features

To extract the nonlinear features in the measured ultrasonic signals, a DWFP technique is proposed, as outlined in the flowchart in Fig. 1. The wavelet transform of the measured signals is first conducted with an equal frequency interval. Then, the wavelet scalogram is smoothed by a median filter and normalized by the wavelet scalogram at the fundamental frequency; a slice-projection operation is applied to the normalized wavelet scalogram in the frequency range of the nonlinear response. Finally, nonlinear features are extracted from the two-dimensional fingerprint image.

2.1. Wavelet transform with an equal frequency interval

The continuous wavelet transform of a signal, $x(t)$, can be written as

$$WT_x(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t) \psi^* \left(\frac{t-b}{a} \right) dt \quad (1)$$

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