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Micro-crack detection using a collinear wave mixing technique

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ABSTRACT

A collinear wave mixing technique was developed to detect micro-cracks in samples by measuring the mixing of two ultrasonic sinusoidal waves. The bispectrum was used to process the nonlinear response. Experiments were conducted to investigate the influence of excitation parameters, such as driving frequency and time delay, on intermodulation among ultrasonic waves and defects. Mixing components were tracked for varying frequency or time delay, and the nonlinear response was measured at fixed frequencies and time delay. The driving frequency was found to strongly affect micro-crack detection; the optimal driving frequency corresponded to maximum amplitudes of sum and difference frequency sidebands. The time-delay dependence of the amplitude of mixing components allowed the location of defects throughout a sample.

1. Introduction

The use of ultrasound is one of the most powerful techniques available to detect and characterize defects in materials and structures. The conventional ultrasonic technique is based on the phenomenon of reflection or transmission and is therefore sensitive to gross defects and open cracks. However, for the detection of micro-cracks or degradation, the conventional ultrasonic technique has quite low sensitivity. The use of nonlinear ultrasonic techniques has been found to be promising in overcoming this problem [1,2].

The most common methods of measuring the nonlinearity in solids are those based on the acoustoelastic effect [3,4], harmonic generation [5–7] and wave mixing [8,9]. The acoustoelastic method measures acoustic velocity variations induced by damage to structures. However, the approach is limited by the difficulty of measuring the small changes in acoustic velocity in practice. The most classical phenomenon employed in measuring nonlinearity is harmonic generation, where the waveform of an incident wave is distorted by the nonlinear elastic response of the medium to finite-amplitude waves. However, practical implementation of the harmonic method requires much effort to minimize nonlinear distortions in transmitting/receiving devices.

The wave mixing method is based on the fact that a resonant wave might be generated by two incident waves if certain conditions are satisfied. The generated resonant wave is related to the nonlinearity of materials/structures. Therefore, by measuring the generated resonant wave, the nonlinearity might be obtained. The wave mixing technique has two important advantages over the conventional nonlinear ultrasonic harmonic generation technique: it is less sensitive to nonlinearities in the measurement system and it allows for great flexibility in selecting the wave modes, frequencies, and propagating directions [10,11].

According to the incident directions of two ultrasonic waves, a wave mixing method can be classified as collinear wave mixing and non-collinear wave mixing. Recent research suggests that these methods have promise as nondestructive testing techniques. Croxford et al. reported the application of a non-collinear mixing technique to the ultrasonic measurement of material nonlinearity to assess plasticity and fatigue damage [12,13]. The linear ultrasonic measurement technique and the non-collinear ultrasonic wave mixing technique have been used to detect the physical ageing of polyvinyl chloride [14]. It was demonstrated experimentally that linear ultrasonic parameters, such as velocity dispersion and attenuation, were insensitive to the physical ageing state of polyvinyl chloride. However, the non-collinear ultrasonic wave mixing process does lead to significant sensitivity to the physical ageing of polyvinyl chloride, which has been verified experimentally in the laboratory and field. Jacob [15] applied the collinear mixing technique to measure the nonlinearity parameter for various solids. Since the determination of the nonlinearity parameter is based on the measurement of the phase modulation, the measurement was absolute and the uncertainty was small. Liu [16] introduced a new acoustic nonlinearity parameter associated with the interaction between a longitudinal wave and a shear wave in isotropic elastic solids. Experimental measurements were conducted to demonstrate that the collinear wave mixing technique is capable of measuring plastic deformation in Al-6061 alloys. These

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results indicate that collinear wave mixing is a promising method for nondestructive assessment of plastic deformation, and possibly, fatigue damage in metallic materials. Hills [17,18] and Courtney [19] developed a special collinear wave mixing technique for global crack detection in structures. The main difference in their technique was that the two sinusoidal signals were applied to the same transmitter. To isolate the sideband at the sum or difference frequency, the received signal was processed employing bispectral analysis. The bispectrum was shown to be particularly useful in extracting the nonlinearity related to phase coupling. Courtney [20] thoroughly discussed how the sensitivity of the technique depends on the frequencies and amplitudes of the applied signals, the positions of the transducers and the support conditions. In this work, the collinear waves mixing technique is used to detect fatigue cracks in metal, and the nonlinear response of the samples to continuous excitations at two frequencies is processed using the well-known bispectrum method. The research focuses on the experimental effects of excitation parameters, such as the driving frequency and time delay, on the intermodulation of ultrasonic waves and defects.

2. Bispectrum analysis for nonlinearity characterization in wave mixing

As a nonlinear element, a defect can transform part of the incident acoustic energy into nonlinear acoustic waves with different frequencies (harmonics and combination frequencies), effectively becoming a source of nonlinear acoustic waves. Therefore, an elastic structure with a defect can be considered as a quadratic system described by [19]

$$y(t)=\alpha x(t)+\beta x^2(t), \tag{1}$$

where $x(t)$ is the input, $y(t)$ is the response, and α,β are constants. Suppose the input contains two sinusoids:

$$x(t)=A_1 \sin(2\pi f_1 t+\phi_1)+A_2 \sin(2\pi f_2 t+\phi_2), \tag{2}$$

where A_1, A_2, f_1 f_2 ϕ_1, and ϕ_2 are respectively the amplitudes, frequencies and initial phases of the two sinusoids. The corresponding response is

$$\begin{aligned}y(t)=&\alpha A_1 \sin(2\pi f_1 t+\phi_1)+\alpha A_2 \sin(2\pi f_2 t+\phi_2)\\&-\beta\frac{A_1^2}{2}\cos[2\pi(2f_1)t+2\phi_1]\\&-\beta\frac{A_2^2}{2}\cos[2\pi(2f_2)t+2\phi_2]+\beta A_1A_2\cos[2\pi(f_2-f_1)t\\&+(\phi_2-\phi_1)]-\beta A_1A_2\cos[2\pi(f_2+f_1)t+(\phi_2+\phi_1)].\end{aligned} \tag{3}$$

In the frequency domain, the above equation can be written as

$$\begin{aligned}Y(f)=&-i\frac{\alpha A_1}{2}\delta(f_1-f)e^{i\phi_1}-i\frac{\alpha A_2}{2}\delta(f_2-f)e^{i\phi_2}-i\frac{\beta A_1^2}{4}\delta(2f_1-f)e^{i\phi_1}\\&-i\frac{\beta A_2^2}{4}\delta(2f_2-f)e^{i\phi_2}+i\frac{\beta A_1A_2}{2}\delta(f_2-f_1-f)e^{i(\phi_2-\phi_1)}\\&-i\frac{\beta A_1A_2}{2}\delta(f_2+f_1-f)e^{i(\phi_2+\phi_1)}.\end{aligned} \tag{4}$$

As expected, the nonlinearity induces the interaction of ultrasonic waves, and generates harmonic waves at $2f_1$, $2f_2$ and sidebands at the sum and difference frequency f_1+f_2 and f_2-f_1. Note that the new spectral components (i.e., $f_3=f_1+f_2$) resulting from nonlinearity are phased coupled with the permanent interacting frequencies (i.e., f_1, f_2), which means that the sum of the phases at f_1 and f_2 is the phase at frequency f_3. This is known as quadratic phase coupling and can be considered an indication of second-order nonlinearities in the system.

The traditional linear power spectrum is the Fourier transform of the second-order cumulant, and carries no phase information. As a type of higher-order spectral density, the bispectrum is the Fourier transform of the third-order cumulant-generating function. Compared with linear power spectral analysis, the advantage of bispectral analysis is that it has the ability to characterize the quadratic phase coupling in monitored systems, and it has been applied successfully to evaluate the quadratic phase coupling types of nonlinear effects in mechanical systems [20].

For a stationary, random signal $x(t)$, the bispectral spectrum is given by

$$B(f_1,f_2)=E[X(f_1)X(f_2)X^*(f_1+f_2)], \tag{5}$$

where $X(f)$ is the Fourier transform of $x(t)$, $E[\,]$ indicates the expectation value and $*$ denotes the complex conjugate.

In practice, the expectation values in Eq. (5) need to be estimated from a finite quantity of available data. The estimated bispectrum of M separate databases is given by

$$\hat{B}(f_1,f_2)=\frac{1}{M}\sum_{i=1}^{M}X_i(f_1)X_i(f_2)X_i^*(f_1+f_2). \tag{6}$$

To more clearly describe the validity of the bispectrum for the characterization of quadratic phase coupling, we conduct bispectrum analysis on a signal similar to that described by Eq. (3), substituting ϕ_3 for $\phi_1+\phi_2$:

$$\begin{aligned}y(t)=&\alpha A_1 \sin(2\pi f_1 t+\phi_1)+\alpha A_2 \sin(2\pi f_2 t+\phi_2)\\&-\beta\frac{A_1^2}{2}\cos[2\pi(2f_1)t+2\phi_1]\\&-\beta\frac{A_2^2}{2}\cos[2\pi(2f_2)t+2\phi_2]+\beta A_1A_2\cos(2\pi(f_2-f_1)t\\&+(\phi_2-\phi_1))-\beta A_1A_2\cos(2\pi(f_2+f_1)t+\phi_3).\end{aligned} \tag{7}$$

The bispectrum estimate of the above signal is then

$$\begin{aligned}\hat{B}(f_1,f_2)&=\frac{1}{M}\sum_{i=1}^{M}Y_i(f_1)Y_i(f_2)Y_i^*(f_1+f_2)\\&=\frac{\alpha^2\beta}{8M}A_1{}^2A_2{}^2\sum_{i=1}^{M}e^{i(\phi_1+\phi_2-\phi_3)}.\end{aligned} \tag{8}$$

If the phase ϕ_3 is randomly distributed with respect to ϕ_1 and ϕ_2, then the summation in Eq. (8) sums components randomly distributed in phase and so tends to zero as $M\to\infty$. However, in the case that $\phi_3=\phi_1+\phi_2$, i.e. the three components are quadratically phase coupled, the resulting bispectrum is real-valued and nonzero, then the estimated bispectrum becomes

$$\hat{B}(f_1,f_2)=\frac{\alpha^2\beta}{8M}A_1{}^2A_2{}^2. \tag{9}$$

This allows detection of quadratically phase-coupled responses, and the bispectrum can be used to detect nonlinearity in systems (such as that induced by a defect). Therefore, the occurrence of sidebands at the sum or difference frequency in bispectral analysis can be taken as an indication of the presence of damage in the specimen and can be used as the basis of a nondestructive technique for damage detection.

3. Experiments and results

Micro-crack detection experiments were conducted using the collinear wave mixing technique. The Ritec Advanced Measurement SNAP 5000 system (RITEC Inc.) was used to conduct two types of experiments: measurements of the amplitudes of the mixing components at different frequencies or at different time delays, and measurements of the intermodulated waves at fixed frequencies and time delays.