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Quantitative evaluation of micro-cracks using nonlinear ultrasonic modulation method

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ABSTRACT

Nonlinear acoustic coefficients have a close relationship with structural cracks. A nonlinear ultrasonic modulation method for micro-crack quantitative evaluation is developed. The influence of phase threshold on the crack evaluation is discussed. Ultrasonic modulation using a unilateral incentive model is applied to the quantitative evaluation of micro-cracks for different specimens. The experimental results indicate that the method can be beneficially applied for micro-cracks detection. A proper phase threshold can improve the reliability of the method based on nonlinear ultrasonic modulation. The presented modulation factor can be used to quantitatively evaluate the structural cracks, and it is suitable for small-crack quantitative evaluation.

1. Introduction

Ultrasound detection techniques are available to detect and characterize damage in materials and structures. The conventional ultrasonic techniques are base on the phenomenon of reflection or transmission, and are therefore sensitive to gross defects and open cracks [1]. However, for the detection of smaller cracks or structural 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 [2–4]. The research on nonlinear acoustic modulation techniques first appeared in the 1990s, and focused primarily on the vibro-acoustic modulation method [5–8]. There is a close relationship between the structure micro-damage and nonlinear ultrasonic factors. Some techniques using modulation method are proposed for quantitative characterization of micro-damage, such as side lobe amplitude method [9], modulation index method [10], damage index method, bispectrum analysis method [10–12], etc. Straka et al. illustrated influence of the number of the fatigue cycles on signal magnitude of the inter-modulation products. The experimental results indicate a large monotonic increase in the magnitude of the inter-modulation products with increasing number of fatigue cycles. Therefore, the method could be used for investigation of fatigue damage [13]. Parsons et al. set the ratio of the frequency bandwidth to the carrier frequency as a damage index, and the experimental results indicate that the modulation effects due to fatigue cracking can be observed in the monitored specimen and used for damage detection via nonlinear acoustics with low-profile pizoceramic excitation [14]. Donskoy et al. developed vibro-modulation and impact-modulation methods for nondestructive inspection and evaluation of fatigued materials. The developed nonlinear technique is much better than the conventional linear acoustic technique [15, 16]. According to a review of the literature, most of the micro-crack quantitative characterization methods are based on a modulation technique, especially on vibro-acoustic modulation technique [9,17–19]. Since development of the ultrasonic modulation technique as another potential method, it has become more and more popular in the micro-crack quantitative characterization field. Van Den Abeele et al. presented a nonlinear elastic wave spectroscopy (NEWS) techniques to discern material damage, and the experimental results indicate that the method to discern material damage is far greater than that of linear acoustic methods [20,21]. Michele et al. applied two different nonlinear elastic wave spectroscopy methods to detect delamination damage due to low velocity impact on various composite plates [22]. Based on the NEWS technique, a new method called TR-NEWS (the nonlinear elastic wave spectroscopy method with a time reversal process) was proposed by Goursolle et al., which also had been proved the feasibility and value of the TR-NEWS methodology for microdamage imaging [23]. Collison and Stratoudaki et al tried to use a dual frequency mixing technique to measure velocity changes caused by material nonlinearity, the final experiments showed that the technique has potential to be applied to life-time predictions of engineered components [24,25]. Matar and Vila et al. used the phase modulation method to measure "in situ" the

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nonlinearity parameter of solids, without any fluid coupling medium [26,27]. Hillis [11] and Courtney et al. [10,28] developed a bispectrum method for ultrasonic signal modulation analysis. The bispectrum at the position of difference frequency is set as the quantitative characterization parameter of the micro-damage, and the experimental results prove that the method is effective and feasible. Jacob et al. used the collinear mixing of eleastic waves to measure the acoustic nonlinearity parameter in solids. The method is based on the detection of the phase modulation resulting from the parametric interaction between a high frequency acoustic wave and a lower frequency acoustic pulse. The measurement uncertainty is small and the measurement can be performed on samples with a thickness smaller than 5 mm [29]. Croxford et al. proposed a non-collinear mixing technique to the ultrasonic measurement of material nonlinearity to assess plasticity and fatigue damage [30,31]. Santos et al. presented a new method consisted of symmetry analysis of excitations (ESAM) to complete full analysis of the 3rd order nonlinear systems. They pointed out that the method can be easily extended to higher order analysis, and the method could be used to evaluate non-linearity of the system [32]. Liu et al. focused on assessing the effects of damping, excitation type and signal processing window on the harmonic measurement, a theoretical model of the generation of nonlinearity was derived by using perturbation and multiple scales techniques [33]. Many ultrasonic modulation based indexes are proposed to quantitatively characterize the micro-damage of different structures, and the problems of localization of cracks in complex medium are also concerned. Guo et al. proposed a three-dimensional (3D) fatigue-crack imaging technique combining nonlinear guided waves with time reversal to locate the micro-cracks in pipelines [34]. Quan et al. applied nonlinear acoustic method to locate multiple cracks in a one-dimensional bar. The amplitude and the phase of the harmonics were analyzed to complete the multiple cracks locating. To sum up, finding a more proper damage characterization factor is very important and necessary.

In previous work, we have done some research on the theories and applications of vibration modulation [35–37] and nonlinear ultrasonic modulation [1,38,39] techniques, respectively. We have completed the evaluation of the thermal damage based on the bispectral analysis method. However, we found that using bispectral analysis for cracks quantitative evaluation, some analytical details, such as, the impact of phase threshold selection, were not being considered.

This paper is concerned with nonlinear wave analysis and analysis of the bispectrum. We combine these two theories with the aim to developing an improved damage-characterization factor based on nonlinear ultrasonic modulation to evaluate micro-cracks in different specimens. Effects of the excitation frequency and phase threshold on micro-crack evaluation based on nonlinear ultrasonic modulation are discussed at the same time. The relationship between the open cracks and the performance of micro-crack quantitative evaluation is analyzed.

2. Definitions

2.1. Nonlinear wave theory

For plate structures, one-dimensional nonlinear elastic wave equation can be expressed as Eq. (1) [40,41]

$$\frac{\partial^2 u(x,t)}{\partial t^2} - c^2\frac{\partial^2 u(x,t)}{\partial x^2} = c^2\beta\frac{\partial^2 u(x,t)}{\partial x}\frac{\partial^2 u(x,t)}{\partial x^2} \quad (1)$$

where u is the particle displacement, c and x are the wave speed and the wave propagation distance, β is nonlinear acoustic coefficient. According to the perturbation theory [42], the solution of Eq. (1) can be assumed as Eq. (2)

$$u(x,t) = u^{(0)}(x,t) + \beta u^{(1)}(x,t) \quad (2)$$

where, $u^{(0)}$ and $u^{(1)}$ are the linear and nonlinear particle displacement respectively. We assume that $u^{(1)}$ is proportional to the wave propagation distance x, thus,

$$u^{(1)}(x,t) = xf(\tau) \quad (3)$$

where $\tau = t - x/c$, and $f(\tau)$ is the new function to be determined. Suppose two frequency ultrasound signal are input, thus

$$u^{(0)}(x,t) = A_1 \cos(f_1\tau) + A_2 \cos(f_2\tau) \quad (4)$$

where A_1, A_2 are amplitude of harmonic waves, f_1, f_2 are center frequency of harmonic waves. To determine the function $f(\tau)$, we should define that k_i is the wave number, then, $f_i = k_i c$. Eqs. (3) and (4) are substituted back into Eq. (2), and with respect to Eq. (1), function $f(\tau)$ can be derived [43].

$$f(\tau) = -\frac{A_1^2k_1^2}{8}\cos(2f_1\tau) - \frac{A_2^2k_2^2}{8}\cos(2f_2\tau) + \frac{A_1A_2k_1k_2}{4}[\cos(f_1-f_2)\tau - \cos(f_1+f_2)\tau] \quad (5)$$

Thus, $u(x, t)$ can be expressed as Eq. (6)

$$\begin{aligned} u(x,t) &= u^{(0)} + \beta u^{(1)} \\ &= A_1 \cos(f_1\tau) + A_2 \cos(f_2\tau) \\ &\quad + x\beta\left\{-\frac{A_1^2k_1^2}{8}\cos(2f_1\tau) - \frac{A_2^2k_2^2}{8}\cos(2f_2\tau)\right. \\ &\quad \left.+\frac{A_1A_2k_1k_2}{4}[\cos(f_1-f_2)\tau - \cos(f_1+f_2)\tau]\right\} \end{aligned} \quad (6)$$

2.2. Theories of bispectrum analysis

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 which can characterize the quadratic phase coupling in monitored systems.

An elastic structure with a defect can be considered as a quadratic system, and it can be described as Eq. (7) [28]

$$y(t) = ax(t) + bx^2(t) \quad (7)$$

where $x(t)$ is the input, $y(t)$ is the response, and a, b are constants.

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

$$B(f_1, f_2) = E[X(f_1)X(f_2)X^*(f_1+f_2)] \quad (8)$$

where $X(f)$ is the Fourier transform of $x(t)$, $E[\ ]$ refers to the expectation, and * denotes the complex conjugate. However, in practice, the expectation values in Eq. (8) must be estimated from a finite quantity of available data. The estimated bispectrum of M separate databases is given by

$$\hat{B}(f_1, f_2) = \frac{1}{M}\sum_{i=1}^{M} E[X(f_1)X(f_2)X^*(f_1+f_2)] \quad (9)$$

2.3. Nonlinear ultrasonic modulation factor

According to Eq. (4), based on nonlinear wave theory, we assume that the input wave signal construct of two simple harmonics with different frequencies, i.e.

$$u^{(0)}(x,t) = A_1 \cos(f_1\tau + \phi_1) + A_2 \cos(f_2\tau + \phi_2) \quad (10)$$

where ϕ_1, ϕ_2 are starting phase of two harmonics.