Mechanical Systems and Signal Processing 100 (2018) 384–397

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Location identification of closed crack based on Duffing oscillator transient transition

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ARTICLE INFO

Article history:
Received 27 April 2017
Received in revised form 2 July 2017
Accepted 22 July 2017

Keywords:
Duffing oscillator
Transient transition
Location identification of closed micro-crack
Nonlinear Lamb harmonic

ABSTRACT

The existence of a closed micro-crack in plates can be detected by using the nonlinear harmonic characteristics of the Lamb wave. However, its location identification is difficult. By considering the transient nonlinear Lamb under the noise interference, we proposed a location identification method for the closed crack based on the quantitative measurement of Duffing oscillator transient transfer in the phase space. The sliding short-time window was used to create a window truncation of to-be-detected signal. And then, the periodic extension processing for transient nonlinear Lamb wave was performed to ensure that the Duffing oscillator has adequate response time to reach a steady state. The transient autocorrelation method was used to reduce the occurrence of missed harmonic detection due to the random variable phase of nonlinear Lamb wave. Moreover, to overcome the deficiency in the quantitative analysis of Duffing system state by phase trajectory diagram and eliminate the misjudgment caused by harmonic frequency component contained in broadband noise, logic operation method of oscillator state transition function based on circular zone partition was adopted to establish the mapping relation between the oscillator transition state and the nonlinear harmonic time domain information. Final state transition discriminant function of Duffing oscillator was used as basis for identifying the reflected and transmitted harmonics from the crack. Chirplet time-frequency analysis was conducted to identify the mode of generated harmonics and determine the propagation speed. Through these steps, accurate position identification of the closed crack was achieved.

1. Introduction

Compared with traditional linear Lamb waves based technology, nonlinear Lamb waves based technology has higher sensitivity to the microstructure characteristics of material, leading to a special advantage in the evaluation and detection of early degradation of material properties and early damage in plate structure [1,2]. The traditional methods for locating defect in plate structures based on linear Lamb waves include direct method [3–5], possibility evaluation method [6,7], tomography [8–10], phase array method [11,12], and artificial intelligence method [13,14]. These methods for locating structural defect are no longer suitable for closed micro-cracks when using nonlinear Lamb waves. Owing to the strong sonolucency of crack

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http://dx.doi.org/10.1016/j.ymssp.2017.07.048
0888-3270/

closure, the nonlinear harmonic energy generated is extremely weak. Furthermore, being limited by a multiplex mode of nonlinear harmonic, noise sensitivity, and envelope fluctuation, identifying and extracting nonlinear harmonics become very difficult. At present, nonlinear ultrasonic detection technologies that have been widely studied, e.g., high-order harmonic technique [15,16], subharmonic and mixing response technique [17,18], nonlinear ultrasonic resonance technique [19,20], etc. Most of these techniques are limited to the qualitative study of damage. The nonlinear harmonics generated from cracks decay extremely easily because of diffraction and scattering and are disturbed by noise and other mode waves. Such fragility will pose significant difficulties in the crack location identification. At present, literatures on locating micro-cracks using nonlinear Lamb harmonics are extremely scarce. Based on the Gabor wavelet transform of nonlinear Lamb waves, Soleimanpour et al. conducted the location identification on a delamination of composites using a sensor network [21]. Hong et al. carried out the crack location identification on aluminum plate based on the reference signal in a healthy state and the transient signal characteristics of nonlinear Lamb waves [22,23]. Yelve et al. located a delamination of composite using the Lamb wave signal spectrum and the corresponding transient response information [24]. Notably, selecting a reference signal is affected by the environment and operational conditions, and the difference between the signal of a structure with micro-cracks and healthy signal may be insignificant. Such problems may lead to erroneous judgment of cracks. The precondition of using the transient signal characteristic methods [21–24] is: the nonlinear harmonic generated from a defect is identifiable in the time-frequency domain. In practical applications, it is generally difficult to identify weak nonlinear harmonic generated from closed micro-cracks in the time-frequency domain because of the noise interference. Therefore, for a signal containing strong noise, if without a reference signal the correct extraction of transient characteristics of nonlinear Lamb wave is crucial.

It is well known that the high sensitivity of non-equilibrium phase transition of chaotic oscillator to system parameters and its immunity capacity to contaminated noise can be utilized to successfully detect weak signals in a strong noise background. To date, some works have adopted the Duffing systems to analyze the linear guided waves. Zhang et al. [25] emphasized the potential of Duffing system in the ultrasonic guided wave detection. Zhang et al. [26] discussed the system parameter setting of a given guided wave signal and revealed the effectiveness of nondestructive inspection using the Duffing system. Zhou et al. [27] attempted to detect an experimental guided wave signal of a steel strand using the phase trajectory of Duffing system. Wu et al. studied the chaotic oscillator detection of guided waves in the inclined cracks [28]. Yang et al. evaluated and located the pipe defect using the Lyapunov exponent [29].

Although some achievements have been obtained in the location identification of *macro defects* by combining the Duffing chaotic oscillator with linear Lamb waves, there is no work for locating *closed micro-cracks* using nonlinear Lamb wave. The reasons may be: (1) the signal detection window for a single Duffing oscillator cannot cover 2π range and cannot detect any initial phase signals. However, the phase of nonlinear harmonic generated from closed micro-cracks is random and may prevent the Duffing oscillator system from making an effective state transition under harmonic excitation; (2) nonlinear harmonic has a short-time transient state, and its time length is insufficient to cause a stable change in the state of the Duffing system; (3) nonlinear harmonic is extremely weak, thereby adding difficulty in distinguishing the state transition caused by noise and by harmonic; and (4) the mapping relationship between defect wave package and oscillator state transition based on the qualitative change of phase trajectory diagram is significantly affected by the oscillator parameter setting, and the identification result has high uncertainty. Hence, with a good robustness to noise and parameter selection, a self-adaptive identification method for locating closed micro-cracks is extremely urgent. In this work, we proposed a novel method of locating closed micro-cracks based on the transient transition of Duffing oscillator being capable of identifying and positioning nonlinear harmonic with noise interference, and innovatively distinguishing the nonlinear harmonic mode with Chirplet time-frequency decomposition.

2. Detection of weak signal using Duffing oscillator

The principle of weak signal detection by Duffing oscillator is stated as follows: when the oscillator is in a chaotic critical state, as long as a weak signal exists with internal driving force in the same frequency, the system will jump into a large-scale periodic motion. Improving the sensitivity of oscillator to weak harmonic detection and the working stability requires the removal of the linear part x in restoring force in the original Duffing oscillator with nonlinear part x^5 introduced, which is conversed into the Duffing-Holmes oscillator equation [30]:

$$\ddot{x}(t) + k\dot{x}(t) - x^3(t) + x^5(t) = \gamma\cos(t) + \text{input} \tag{1}$$

In Eq. (1), k refers to damping ratio; $-x^3(t) + x^5(t)$ refers to nonlinear restoring force; $\gamma\cos(t)$ refers to internal driving force; "input" is composed of the frequency component to be detected and zero mean white Gaussian noise $n(t)$, namely, "input" = $s(t)$+$n(t)$, where $s(t) = a\cos(\omega t + \theta)$. Taking $t = \tau\omega$, Eq. (1) is changed to

$$\frac{1}{\omega^2}\ddot{x}(\tau) + \frac{k}{\omega}\dot{x}(\tau) - x^3(\tau) + x^5(\tau) = \gamma\cos(\omega\tau) + \text{input} \tag{2}$$

In Eq. (2), $\omega = 2\pi f$, f refers to to-be-detected frequency. $x(\tau)$ represents $x(t)$ in another time scale. Compared with Eq. (1), the dynamic property and critical value in Eq. (2) are unchanged. The set of internal driving force $\gamma = \gamma_d$, makes the Duffing oscillator be in the critical chaotic-periodic state. The signal is fed into the oscillator system for detection. If the system is