17th World Conference on Nondestructive Testing, 25-28 Oct 2008, Shanghai, China

Contact defect detection in plates using guided wave and vibro-acoustic modulation

Jingpin JIAO [1], Bruce W. DRINKWATER [2], Simon A. NEILD [2], P D WILCOX [2], Bin WU[1], Cunfu HE [1]

[1] Department of Mechanical Engineering, Beijing University of Technology, Beijing, 100022, China, Email: jiaojp@bjut.edu.cn

[2] Department of Mechanical Engineering, University of Bristol, Bristol, BS8 1TR , UK, Email: B.drinkwater@bristol.ac.uk

Abstract

In this paper, guided wave health monitoring in plate structure for detection of nonlinear contact scatter is conduct using vibration modulation technique. By time-frequency analysis of modulated guided wave series, the nonlinear responses at frequency of vibration are extracted out and used for defect imaging. It is shown that the nonlinear guided wave imaging method based on vibration modulation can effectively characterize and locate the nonlinear contact defects.

Key words: guided waves, SHM, nonlinearity, vibration modulation

1. Introduction

Guided waves have been proposed by many researchers for structural health monitoring (SHM) applications due to their ability to propagate long distances in structures. A network of sparsely located sensor is efficiently used in guided wave SHM applications for detection of linear localized scatters, such as holes and bonded objects [1-3]. But it is difficult for traditional SHM method to detect the contact defects, such as closed crack, disbondings, delaminations etc. The characteristic element of these defects is a contact interface, in which surfaces are in close proximity, or even touching each other.

Recent experimental research demonstrated that a weakly or incompletely bonded interfaces exhibit highly nonlinear behavior. One of acoustic manifestations of such nonlinearity is the modulation of a high-frequency signal by low-frequency vibration. The vibration varies the contact area modulating the phase and amplitude of high-frequency signal passing through the interface. In frequency domain, the result of this modulation manifests itself as side-band spectral components with respect to the low-frequency vibration.

Zaitsev[4] used cross-modulation method for crack detection, the method allows to effectively use the sample resonances to achieve the necessary level of pump excitation. Duffor [5] investigated the level of sideband on a set of mild steel beams with cracks of different size and shape. Donskov [6-7] used vibration modulation technique for fatigue and stress-corrosion crack detection in metal, plastics, composites and concrete structures. Kim [8] studied the low-frequency parametric modulation of a pulsed surface wave in sample with a partially closed fatigue crack. Kazakov [9-10] extracted nonlinear response from a series of repetitive high-frequency tone burst modulated by low-frequency vibration, and developed an imaging method for locating isolated nonlinear scatter. In this paper, guided wave health monitoring in plate structure for detection of nonlinear scatter is conduct using similar low-frequency and high-frequency signals.

2. Methodology of time-frequency analysis on modulated guided waves

Suppose $u(t)$ is the guided wave signal received by transducer in plate, and its waveform is shown in Fig.1. If a low-frequency vibration $g(t)=e^{i\omega_0 t}$ (ω_0=20 Hz) is applied to the plate, and causes the flexural vibration of plate. According to the theory of contact acoustic nonlinearity, if there is any contact scatter in the plate, the high-frequency guided wave and low-frequency vibration will interact. As a result, the guided wave is modulated by low-frequency vibration. At a series position of low-frequency cycle $\tau=\frac{T_0}{40}n$ ($T_0=\frac{2\pi}{\omega_0}$, $n=1,2,.....,512$), the series of modulated guided wave signals are represented as

$$y_n(t)=A_0 e^{i\omega_0\frac{nT_0}{40}}u(t) \tag{1}$$

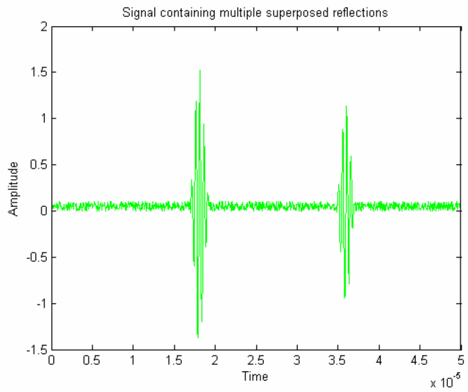


Fig.1 Simulated signal received at position R

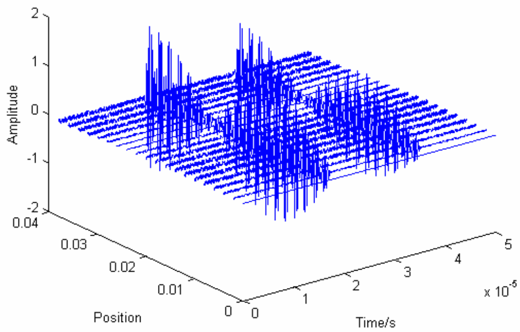


Fig.2 Waveforms of modulated guided waves series

The waveforms of modulated guided wave series are shown in Fig.2. The two dimension time series $y_n(t)$ are processed with a synchronous demodulation. At each sampling interval $t=t_m$, a Fourier Transfer is expressed as follows:

$$A_{nm}(f_n, t_m) = \sum_{n=1}^{N} y_n(t_m).e^{-i2\pi f_n \tau} \quad (2)$$

Where m is sample number of each recording. The 2D plot of $A_{nm}(f_n, t_m)$ can be regard as a time-frequency distribution of the series of modulated guided wave signals (shown in Fig.3). It can be seen that there is obvious component at frequency (20Hz) of vibration in the plot of time-frequency distribution.

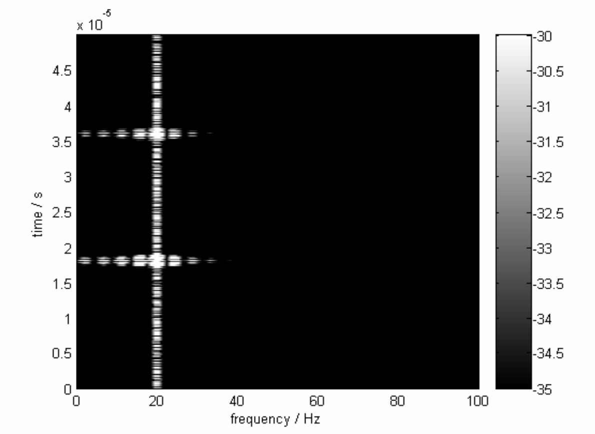


Fig.3 Time-frequency distribution of series of modulated guided wave signals

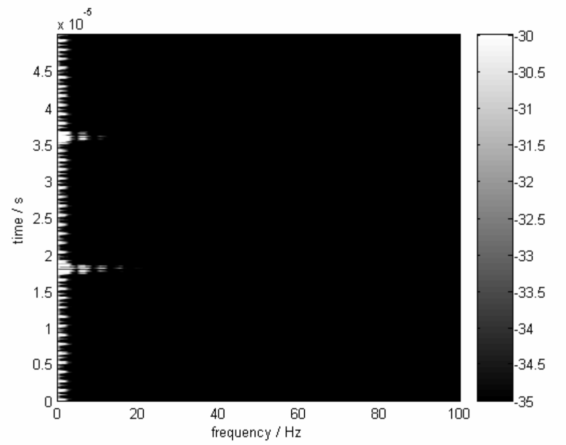


Fig.4 Waveforms extracted from the superposition of guided wave and low-frequency vibration

If there is no any nonlinear scatter in the plate, the high-frequency guided wave and low-frequency vibration will have no interact, and the resultant field is the superposition of the fields obtained by applying the two excitations separately. The superposition of guided wave signals and vibration is processed using the time-frequency analysis method (Equation (2)), the result is shown in Fig.4. It can be seen that there is only DC component and no component at the frequency of vibration.

3. Experiment

All experimental work in this paper is conducted on a 750mm × 550mm aluminum plate with a thickness of 3mm. A copper cylinder (12mm diameter, 12mm height) is introduced into plate as defect. When the cylinder is bonded to the plate with cynoacrylate adhesive, it acts as a linear scatter; when it is unbonded but loaded to the plate, it behaves as a nonlinear contact scatter.

The experiments involve the transmitting and receiving of high-frequency guided waves in presence of low-frequency flexural vibration. The experimental configuration is represented in Fig.5. A 20 Hz low-frequency continuous wave is applied to the plate by a mechanical shaker to excite the plate in flexural vibration. The transmitting and receiving of guided waves is performed using three 3-mm-thick, 3-mm-diameter piezoelectric discs. The transmitted signal is a 5 cycles tone burst windowed, and its centre frequency is 200 kHz. The guided wave is transmitted repeatedly at a repetition frequency of 200Hz ($T_0 = 0.005$ s). Considered the response time and delay of system, the series of guided wave signals are actually recorded at a period of $\tau_0 = 10T_0 + \frac{T_0}{40} n$.

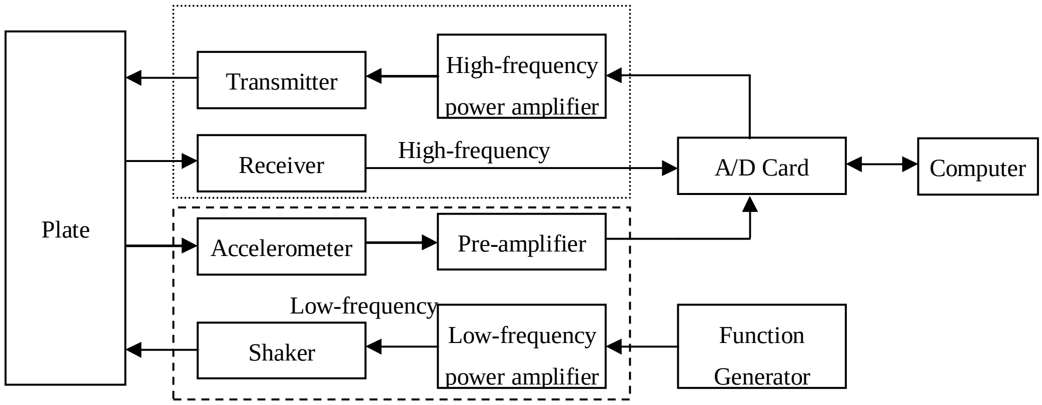


Fig.5 Configuration of experimental setup

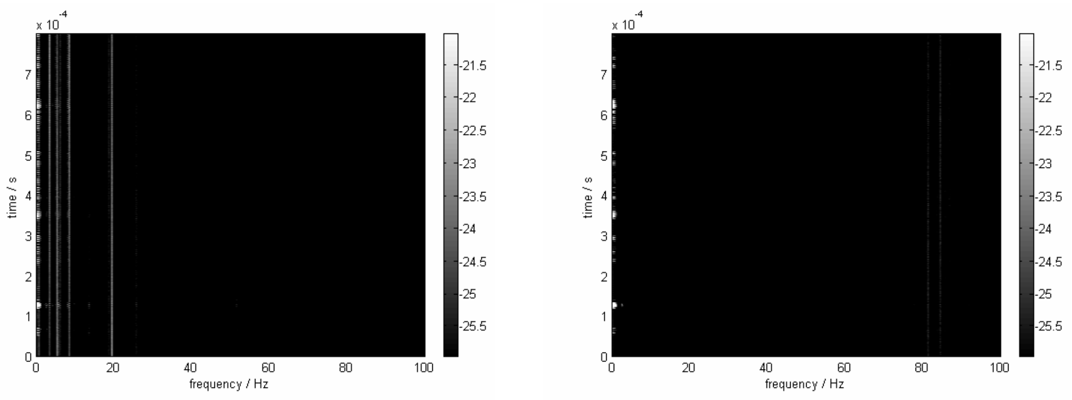
Firstly, guide wave SHM experiments are conducted in defect-free plate. When the low-frequency vibration is applied to the plate, guide wave SHM experiments are conducted respectively for detection of linear and nonlinear scatters.

4. Imaging of nonlinear guided waves

4.1 Time-frequency analysis of modulated guided waves

The received series of guided wave signals are performed a Fourier transform at fixed phase by Equation (2), and the results are shown in Fig.6. For the case of contact scatter (unbonded cylinder) shown in Fig. 6(a), it can be seen that there is component at frequency (20 Hz) of vibration, which shows the existing of contact defect and modulation of guided waves by vibration. But there is no component at frequency of vibration appears in the result of linear scatter (bonded cylinder) shown in Fig.6 (b).

Meanwhile in Fig.6 (a) there are other frequencies components emerge themselves out beside the component of vibration, which can be possibly explained by the complexity of vibration. The flexural vibration of plate is actually not a simple harmonic wave, and includes other frequency components. The time record at frequency of 20 Hz is extracted out and used to image the position of scatters.



(a) (b)

Fig.6 Time-frequency distribution of series of guided wave signals (a) unbonded cylinder (b) bonded cylinder

4.2 Imaging using the demodulated guided wave signals

Guided wave SHM scheme used in this paper follows similar approaches to that found in [1-3].The distribution of reflection amplitude $I(x,y)$ at each position (x,y) is represented as

$$I(x,y)=\sum_{j=1}^{3}h_j(\frac{d_j}{c_g}) \tag{3}$$

Where $h_j(t)$ is the Hilbert envelopes of received signals $x_j(t)$ of the transducer pair j ($j=1,2,3$); c_g is the group velocity of A_0 mode at centre frequency, d_j is the total path length associated with a reflector at (x,y)

$$d_j=\sqrt{(x_j^T-x)^2+(y_j^T-y)^2}+\sqrt{(x_j^R-x)^2+(y_j^R-y)^2} \tag{4}$$

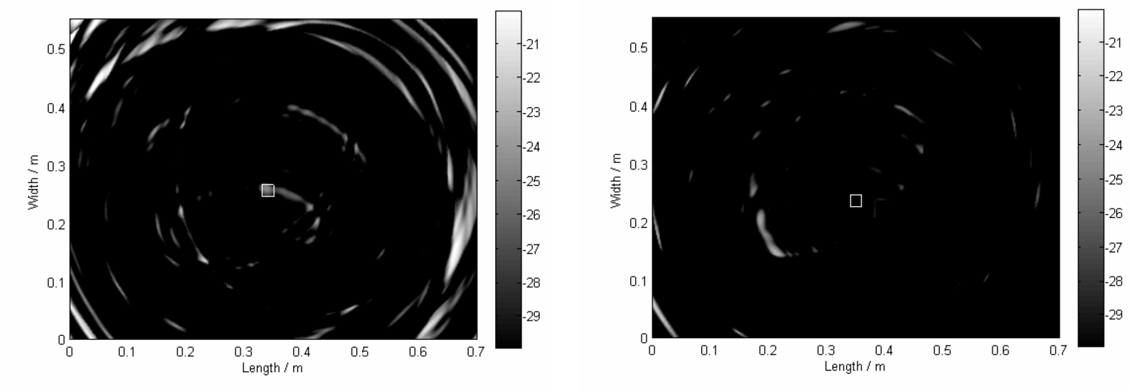
where (x_j^T, y_j^T) and (x_j^R, y_j^R) are the coordinates of transmitter and receiver.

To distinguish damage from structural features, a baseline subtraction is conducted from the defect-detection signals. It can be described as following

$$I_{Res}(x,y)=-20\log\left(\frac{\left|I_{Def}(x,y)-I_{Baseline}(x,y)\right|}{\max(I_{Baseline}(x,y)}\right) \tag{5}$$

where $I_{Baseline}(x,y)$ and $I_{Def}(x,y)$ are the reflected amplitude distribution of plate without defect and with defect.

Using the extracted guided wave signal at the frequency of vibration, a nonlinear guided waves imaging is conducted according to equation (5). Fig.7 shows the typical results for detection of linear and nonlinear scatter in plate, in which the position of scatter is labeled with a rectangle.



(a) (b)

Fig.7 Typical results using nonlinear guided wave imaging approach, a) Unbonded cylinder, b) Bonded cylinder

From Fig.7 (a), it can be seen that the unbonded cylinder (loaded with 20kN) can be detected and located using the nonlinear guided wave imaging method; however the bonded cylinder can not be obviously detected as shown in Fig.7 (b). It is shown that the nonlinear guided wave imaging method based on vibration modulation can effectively characterize and locate the contact defects.

5. Conclusions

Experimental observations on the detection of bonded and unbonded cylinders in a plate have been conducted using the techniques of guided wave imaging and vibration modulation. By time-frequency analysis of modulated guided wave series, the nonlinear responses at frequency of vibration are extracted out and used for defect imaging. Comparison with the linear scatter detection experiment indicated that the observed modulation is connected only with the presence of contact scatters.

Acknowledgments

We would like to acknowledge the support of National Natural Science Foundation of China (10772008), Beijing Municipal Science & Technology Commission (2007B012), and Beijing Municipal Commission of Education.

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