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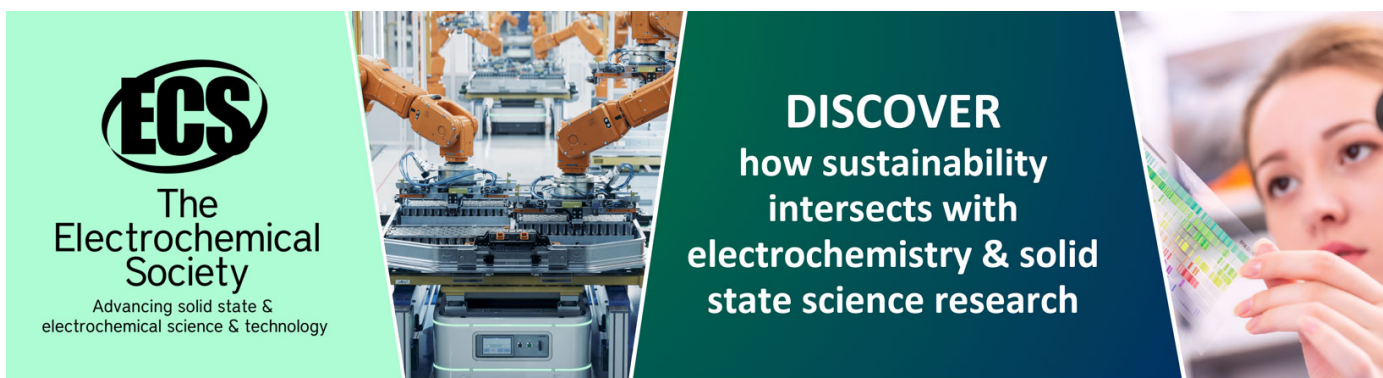
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Study of micro-crack localization based on vibro-acoustic modulation

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Abstract. As a prevalent nonlinear acoustic method, vibro-acoustic modulation (VAM) is more sensitive to micro-crack than the traditional linear acoustic. Nevertheless, recent theoretical and experimental studies have demonstrated that VAM cannot quantitatively ascertain the location of micro-crack. To overcome this limitation, VAM is combined with time reversal (TR) in this paper. The finite element (FE) software was used to simulate the process of VAM detecting micro-crack and the VAM experimental system was established by using an aluminum plate with presupposed micro-crack. The TR method was used to reverse the first-order nonlinear signals from VAM simulated signals in time domain, then the pre-processed signals were reloaded into aluminum plate model and the TR simulation was implemented. The results showed that the first-order side-lobe signals were able to focus around original crack location. It is proved that TR method can be used to combine with VAM and realize micro-crack localization.

1. Introduction

VAM is based on the modulation effect of a low-frequency (LF) vibration on a high-frequency (HF) ultrasonic wave, which is more sensitive to micro-crack than the traditional linear acoustic, and is less affected by the nonlinearity of system. However, the researches of VAM are limited to the influential factors of modulation signals [1], and the quantitative characterization of damage [2] at present, which are rarely involved in localization [3]. Kim et al [4] studied the modulation mechanism of the high frequency (HF) ultrasonic wave and low frequency (LF) vibration, then analysed how the crack length and opening-closing states affected the modulation effect. Jia et al [5] used impact excitation of LF vibration which were modulated by HF ultrasonic wave to detect the structure with crack, and the amplitude modulation phenomenon was found.

The TR method [6] which can realize adaptive focusing of acoustic energy is used for the micro-crack localization. According to Huygens principle, the micro-crack can be regarded as the source of the nonlinear signals. Therefore, the TR method can be used to make the nonlinear signals in the VAM detection signals focus on the micro-crack. Sutni et al [7] studied the location of vitreous body by combining nonlinear ultrasound with TR method and found that the high-order harmonic of TR signals could be focused on the crack. Dos et al [8] used nonlinear TR method to detect and image the teeth, successfully distinguished the enamel interface and internal cracks in the teeth.

The surface of the specimen is generally scanned by the laser vibrometer in the above literatures, and the distribution of the acoustic energy is observed to determine the location of micro-crack. However, the high cost and complex operation of the laser vibrometer limits its universality. In this paper, the FE software was used to simulate the process of VAM detecting micro-crack and the VAM



experimental system was established by using an aluminum plate with presupposed micro-crack. The nonlinear signals from VAM simulation signals which were reversed in the time domain and were reloaded on the aluminum plate model, then the TR simulation was carried out. The size and location of micro-crack could be determined according to the cloud image and particle displacement information of the simulated results. Finally, the detection and localization of micro-crack were realized.

2. Theory

The principle of VAM is that the HF ultrasonic wave (f_h) and the LF vibration (f_l) are loaded on the material respectively. If the material is intact, the detection signals are represented by a linear superposition of two fundamental frequency signals. Whereas the frequency domain produces the nonlinear side-lobe signals ($f_h \pm f_l$). TR method is that the received signals are reversed in time domain, then are retransmitted by corresponding receiving sensors and focus on space and time [9].

The schematic of combining VAM with TR methods is shown in figure 1. The acoustic wave with nonlinear components will arrive at the receiving sensors through different paths, which will cause the different in time domain. The nonlinear signals are extracted and reversed in time domain, which are retransmitted by corresponding receiving sensors and reach the sound source with same phase at same time. Finally, the focusing of nonlinear signals is realized in micro-crack.

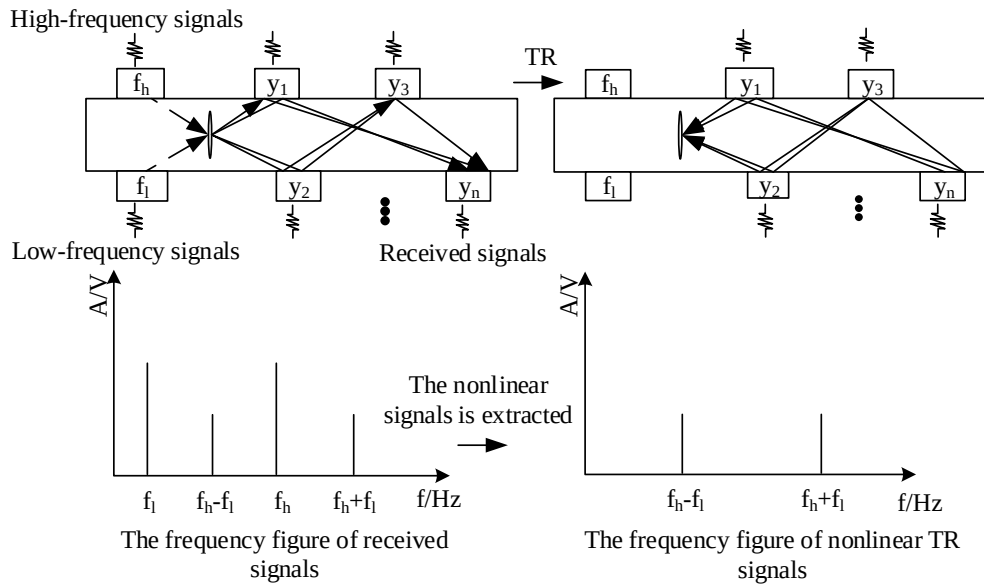


Figure 1. The schematic of combining VAM with TR method.

In order to describe the TR method in more details, the following theoretical formula is derived to explain the focusing process of the signals. The total signals received by the sensor array are denoted as [10]:

$$s_i(t) = \sum_{j=1}^{\infty} A_j \varphi(t - t_j) \quad (1)$$

where i and j are the serial number of the sensors and the propagation paths, respectively. A_j is the corresponding acoustic amplitude for different paths, t_j is the time delay for different paths.

The signals received by the sensors array and reversed in time domain, and since the reversed time is subtractive, it is impossible to realize in practice. Therefore, the reference time T is added to the subtractive time variable (where $T > t$), then the TR signals are determined by the formula:

$$s_i(T-t) = \sum_{j=1}^{\infty} A_j \varphi(T-t-t_j) \quad (2)$$

The amplitude of the TR signals are normalized and reloaded onto the corresponding receiving sensors, which are represented by symbol $\varphi_i(t)_{TR}$

$$\varphi_i(t)_{TR} = \frac{1}{A_j^{\max}} s_i(T-t) = \frac{A_j}{A_j^{\max}} \sum_j^{\infty} \varphi(T-t-t_j) \quad (3)$$

where $A_j^{\max}$ is greatest amplitude of equation (2).

According to the foregoing, the sound field generated by the sensors in the sound source is determined as:

$$s_i(t)_{TR} = \sum_{J=1}^{\infty} A_J \varphi_i(t-t_J)_{TR} = \frac{A_J A_J}{A_j^{\max}} \sum_{J=1}^{\infty} \sum_{j=1}^{\infty} \varphi(T-(t-t_J)-t_j) = \frac{A_J A_J}{A_j^{\max}} \left[\sum_{J=1}^{\infty} \sum_{j=1}^{\infty} \varphi(T-t-t_J-t_j) + \sum_{J=1}^{\infty} \sum_{j=1}^{\infty} \varphi(T-t+t_J-t_j) \right] \quad (4)$$

where J indicated the serial number of propagation paths from the sensors to the sound source when the TR signals are reloaded.

Let each sensor simultaneously stimulate the corresponding TR signals, and the sound field of the sound source can be presented in the form:

$$s(t)_{TR} = \sum_{i=1}^b s_j(t)_{TR} = \sum_{i=1}^b \sum_{J=1}^{\infty} A_J \varphi_i(t-t_J)_{TR} = \frac{A_J A_J}{A_j^{\max}} \sum_{i=1}^b \left[\sum_{J=1}^{\infty} \varphi(T-t) + \sum_{J=1}^{\infty} \sum_{j=1}^{\infty} \varphi(T-t+t_J+t_j) \right] \quad (5)$$

where the first item on the right side of equation (5) is the collection of the nonlinear side-lobe signals, which are detected by different sensors with different paths and same phase at the same time. In contrast to the second is the collection of the nonlinear side-lobe signals, which are detected by different sensors with different paths and different phases at the different time.

3. The simulation of VAM

In this paper, the FE software is used to simulate the process that VAM detects micro-crack. The size of the aluminum plate model is 500mm×250mm×2mm. The length of micro-crack is 18.4mm and the distance from the right of the aluminium plate is 249.7mm. The density is 2700 kg / m³, Young's modulus is 72 GPa, Poisson coefficient is 0.35. The contact surface property of the micro-crack is set to the hard contact. The model is divided by using sweep mesh dividing, the element shape is hex, and the element type is C3D8R. The constructed aluminum plate model is shown in figure 2. The LF (10 kHz) and HF (50 kHz) are loaded at arrow's location of model.

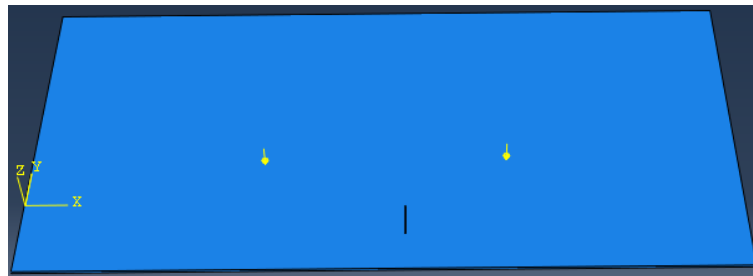


Figure 2. The schematic of aluminum plate model.

Figure 3 shows the time and frequency domain of VAM signals which are obtained by the simulation of aluminum plate. The nonlinear signals can be observed in the frequency domain, A (40kHz) and B (60kHz) are the first-order difference frequency and sum frequency.

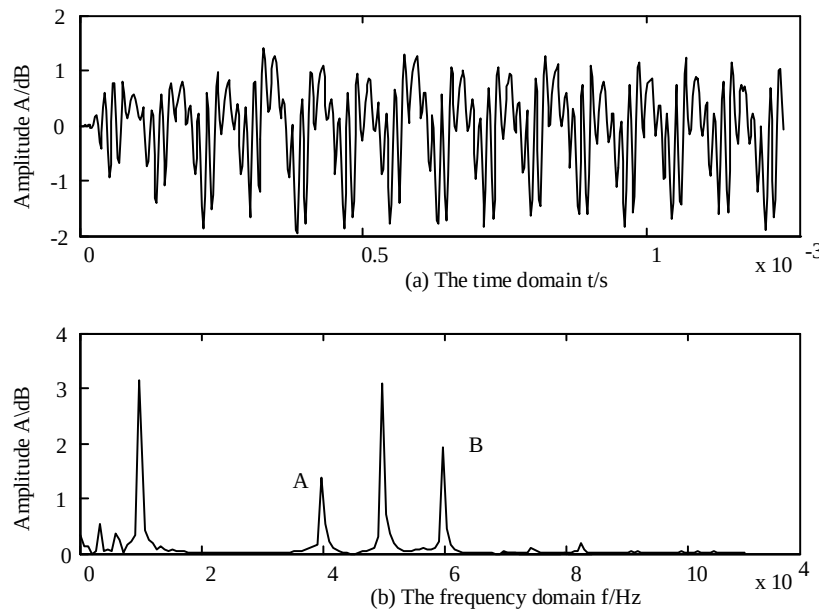


Figure 3. The VAM signals of aluminum plate simulation (a) The figure of time domain (b) The figure of frequency domain.

It is obvious that the fundamental frequency and the first-order sidelobe nonlinear signals which are produced by interaction of micro-crack and acoustic are found from the frequency domain of VAM signals. The focusing signals at the micro-crack location are submerged by the fundamental frequency focusing signals if TR focusing simulation is directly implemented. To ensure the focusing effect, the first-order sidelobe signals with the highest signal to noise ratio are selected to reverse. Then the VAM signals are processed by the bandpass and bandstop filter, the bandpass width [30kHz, 70kHz], the bandstop width [40kHz, 60kHz].

4. The VAM experimental

Figure 4 shows that the VAM experimental system was established around an aluminium plate. The main instruments include power amplifier, signal generator, oscilloscope, aluminum plate and cushioning pad etc. The LF vibration is used by VAM experiment is 53kHz and HF ultrasonic wave is 263kHz in this paper.



Figure 4. The VAM experimental system.

Figure 5 shows the raw VAM signals from a piezoelectric ceramic on the aluminum plate. A(53kHz) and B(263kHz) are the fundamental frequency signals. It is obvious that the nonlinear features cannot be clearly manifested from frequency domain, and the results verify the simulation is better than actual experiment.

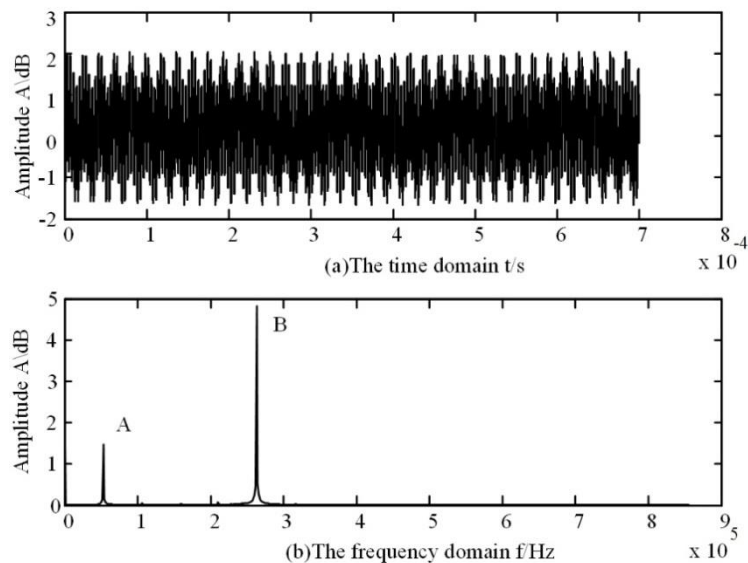


Figure 5. The VAM experimental signals (a) The figure of time domain (b) The figure of frequency domain.

5. The focusing simulation of TR signals

In this paper, the focusing process of TR signals is simulated by FE software. The first-order nonlinear signals from VAM simulated signals are reversed in time domain, and are loaded on the corresponding location of aluminum model. In order to the accurate simulate result, the increment of analysis step is 1×10^{-8} s, the boundary grid property of the model is set to CIN3D8 infinite type. The total length of the simulation is 0.4ms. The output of the history variable is set to 20 increment steps to output a sampling value. The animation of the open database (OBD) is 0.001ms/frame. The cloud image and local particle displacement information of the aluminum plate model are observed in the visual module of FE software after the simulation is completed.

The cloud image of aluminum plate is examined, and the obvious focusing location of the TR signals is found, as shown in figure 6. It is observed that the nonlinear TR signals have been focused on near the actual location of micro-crack. The length of the focusing image in the aluminum plate cloud image is 29.8mm, and the distance from the right boundary is 245.4mm which are obtained by using the query tool of distance in FE software. The relative errors are 62% and 1.7%, respectively.

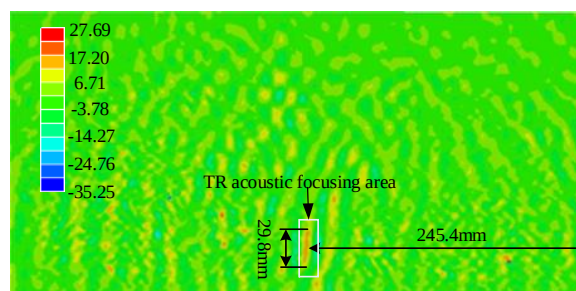


Figure 6. Cloud image of the TR signals.

6. Conclusions

In this paper, the FE software was used to simulate the process of VAM detecting micro-crack and the VAM experimental system was established by using an aluminum plate with presupposed micro-crack. The TR method was used to reverse the first-order sidelobe nonlinear signals from VAM simulated signals in time domain, then the pre-processed signals were loaded into aluminum plate model and the

TR simulation was implemented. The focusing location can be determined according to the cloud image of the aluminum plate.

In addition, the VAM detection signals are obtained by simulation is better than the experiment in this paper. The actual experimental data contain all kinds of interference information. How to obtain the high signal to noise ratio signals for TR simulation is still further studied.

Acknowledgements

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