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Detection on Fatigue Crack of Aluminum Alloy Plate Based on Modulation Nonlinear Lamb Waves and Time Reversal Method

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Abstract

Novel modulation nonlinear Lamb waves (MNLW)and time reversal method for fatigue crack detection are carried out in this paper. MNLW focus on the application of harmonics and sum and difference frequency frequency to discern damages in plates. In combination, we are applying the focusing properties of TRA and the modulation nonlinear properties of cracks to detect damages in the plates. The experiments on 2024 aluminum alloy plates, one with a fatigue crack and the other intact, are comparatively experimented. And this experiment system consists of two piezoelectric transducers, arbitrary waveform generator, power amplifier, laser vibrometer, digital oscilloscope and computer. The experimental results show that there are only two fundamental frequencies and no harmonics and sidebands occur in the intact sample. In the cracked sample, there is an abundance of the harmonics and sidebands. So, these new modulation components can be used to indicate the presence of a crack or damage.

Keywords: Fatigue crack; Modualtion; Nonlinear Lamb wave; Time reversal; Aluminum alloy

1. Introduction

Aluminum alloy plates have been increasingly applied in aircraft skins and space structures due to their superior mechanical properties[1,2]. Airworthiness regulations require the use of a damage tolerant design philosophy for the design of most structural parts of aircraft[3]. Usually, aircraft skins must comply with airworthiness regulations. However, aircraft skins inflate and deflate with each cycle of pressurization and depressurization. The resulting stress causes several kinds of damage, primarily radial fatigue cracks around rivets. If those fatigue cracks were unchecked, the results would be

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catastrophic[4]. Consequently, the development of structural integrity monitoring techniques has received great progress in recent decades. The ultrasonic waves are considered as a powerful method because the characteristics of its propagation are directly related to the materials properties [5].

Conventional acoustic non-destructive testing methods are based on the linear acoustics. However, some types of qualitative behavior encountered in engineering cannot be solved by linear models. In these cases, nonlinear behavior is significant and nonlinear models are required[6]. Nonlinear Lamb wave inspection is most widely used in damage detection[7]. Although it has demonstrated great potential for structural damage detection, the practical commercial exploitation is very limited[8,9]. An alternative method is the nonlinear responses of these cracks. It is established that cracked metallic materials contain small soft features with a hard matrix producing a very large nonlinear response[8]. This response corresponds to a nonlinear effect characterized by a hysteretic behavior.

Furthermore, time reversal (TR) process is a perfect tool for focusing acoustic energy on any point within a sample. The TR provides the means to narrowly focus wave energy in time and space as well as the ability to focus acoustic energy on a scatter without knowing its location [10]. Combining the time reversal method with nonlinear Lamb wave holds great promise for isolating a nonlinear scatterer such as a crack. The focusing abilities of TR method can be used in conjunction with nonlinear Lamb wave to locate and image nonlinear scatterer in an otherwise linearly elastic medium.

In this paper, the detection of fatigue cracks in 2024 aluminum alloy plates is experimentally studied by using the combination of TR and elastic nonlinear Lamb wave response. The changes of nonlinear elastic wave behavior were documented for both two types of samples-with and without presence of fatigue cracks, and the experimental results are analyzed and compared.

2. Experiment setup

2.1. Sample Preparation

Two samples are carried out in this study. One sample plate is intact and the other type is with the presence of a fatigue crack. They have the same geometrical size, namely, the length, width and thickness are 150mm, 90mm and 2mm, respectively. The materials of the samples are 2024 aluminum alloy plates and their chemical compositions are as follows: Al: 93.63%, Si: 0.09%, Fe: 0.21%, Cu: 4.06%, Mn: 0.47%, Mg: 1.37%, Cr: 0.01%, Zn: 0.14%.

The intact samples used to be a reference are directly machined by cutting from 2024 aluminum alloy plates, and the microcracked samples are got by creating a fatigue microcrack in the intact ones. The full-length of the fatigue microcrack located at the center of the samples is about 6mm and it is crossing the whole cross-section of the samples. A part of the samples with the fatigue microcrack is shown in Fig.1. Its preparation process is the following. Firstly, at the center of the intact sample, a hole of 0.2mm in diameter is produced by the laser as a stress raiser to facilitate fatigue microcrack initiation and subsequent microcrack growth. Then, the sample is fatigued in symmetrical sinusoidal wave pull-push loading to prefabricate a microcrack. The microcrack length can be automatically observed and measured by the computer connected with a CCD camera. The fatigue tests will be stopped as soon as the length of the microcrack reaches about 6mm.

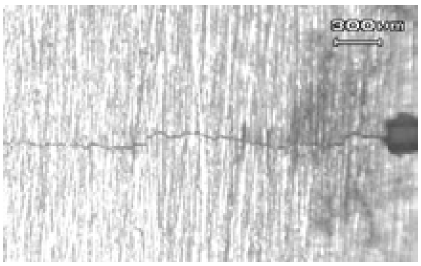

Fig.1 The shape of part of the fatigue crack

2.2. Experiment system

The experimental setup is schematically shown in Fig.2. Two piezoceramic transducers (PZTs) as actuators are used for Lamb wave generation and fixed on the sample surface. Two actuators are excited by a tone burst signals comprising a 11-cycle sine wave, respectively. The peak-to-peak amplitude of the excitation is 20V. The excitation signals are simultaneously generated by the arbitrary waveform generator FLUK294 under the control of computer. The central frequencies of excitation are f1=270kHz and f2=100kHz, respectively. Lamb wave responses are sensed by the non-contact laser vibrometer V1002, and the acquired signals are directed into the digital oscilloscope DPO4054. Then, computer connected to the digital oscilloscope through GPIB acquires data and the data are processed by MATLAB.

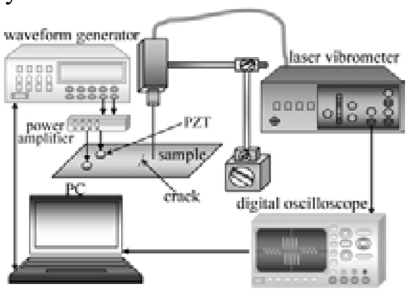

Fig.2 The experimental setup for measuring the samples

2.3. Experiment procedure

The experiments based on nonlinear Lamb wave and time reversal method are performed according to the following steps: (1) two excitation signals f1 and f2 are simultaneously emitted by two separate channels of arbitrary waveform generator and are applied to the PZTs, respectively; (2) the first response signals are acquired by the laser vibrometer V1002 and numerically time reversed; (3) the time reversal signals are stored in the arbitrary waveform generator and simultaneously re-emitted to the original PZTs; (4) the focused signals after time reversal are acquired by the laser vibrometer V1002 and their nonlinearities are analyzed.

3. Result and Discussion

The time domain signals of two samples are shown in Fig.3. It can be seen From Fig.3(a) and Fig.(d) that the distortion and overlapping each other of the waveform packets in cracked sample are much heavier than the intact samples. This can be explained as follows. When a fatigue crack is presented in the sample it will induce multiple reflection and refraction during the propagation of an ultrasonic wave and thus the amplitude energy content will be greatly increased. The magnitudes of the wave peak and the side lobe in the cracked sample become much larger in comparison with the intact sample. Secondly, a waveform deformation in the cracked sample is generated more easily in comparison with the intact one since the nonlinear response and the manifestation of nonlinearity are very large. As a result, it will induce high order harmonics and has the tendency to generate shock wave. Consequently, the large deformation in an elastic wave is induced on the surface of the cracked sample. In Fig.3(b) and Fig.(e), the focused TR signals are nicely reconstructed. The peak amplitude and the ratio between the peak and the side lobe are extremely increased by contrast to the pre-focused ones. The results presented above indicate clearly the potential of the time reversal acoustic method. In the cracked sample, multiple reflections or scattering in wave transmission will decrease the diffraction limit below half of wavelength, and thus improve the focusing. Therefore, it is necessary to further analyze the relevant information of nonlinearities.

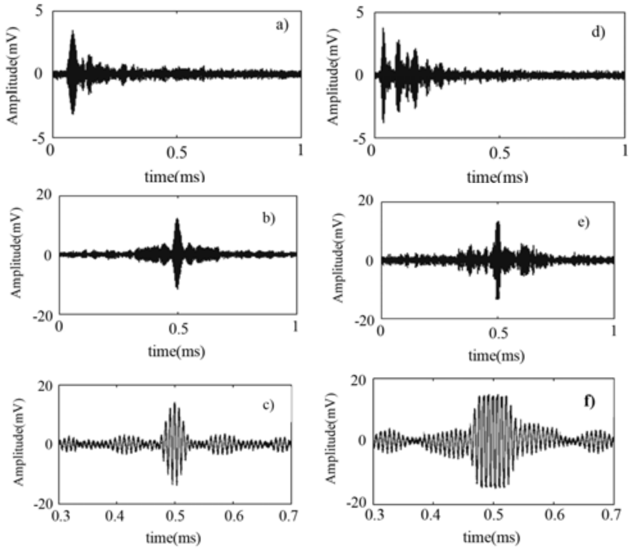

Fig.3. The waveform from the time domain signals: left (a)–(c) are the signals of the intact sample surface (a) first detected signal by laser vibrometer; (b) focused TR signal; (c) focused TR signal zoom; right (d)–(f) are the same signals of the sample surface with fatigue crack.

The further study on the focused TR signal concerned the time span t = 0.3~0.7ms is shown in Fig.3(c) and Fig.3(e). In order to determine the time of the corresponding harmonics and modulation frequencies, the focused signals in Fig.3 (c) and Fig.3 (e) were analyzed again in the time-frequency domain by short time Fourier frequency transform (STFT), and they are shown in Fig.4(a) and Fig.4 (b), respectively.

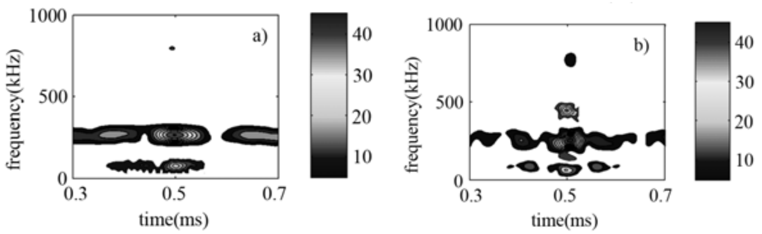

Fig.4. spectrum signals of local focused TR signals zoom: (a) in intact sample; (b) in cracked sample

As shown in Fig.4(a), the sample with nonscattering sources, the spectrum reveals two fundamental frequencies, namely f1=100kHz and f2=270kHz, and no modulation (sum- and difference-frequency) occurs, at the same time, it can be seen that there is slight amount of harmonic such as third harmonic in the intact sample, but the energy level of third harmonic are too small to be analyzed. This is primarily due to nonlinearities in the associated electronics, and a small portion is due to the inherent atomic nonlinearity of the materials. In addition, in an isotropic solid plate, it responds with atomic nonlinearity or deformation at the atomic/molecular scale. However, Fig.4(b) clearly illustrates the abundance of the harmonics and modulation frequencies (fH=f1+f2=370kHz, fL=f2-f1=170kHz) in the microcracked sample compared to the intact one. This can be explained as follows.

The presence of a fatigue microcrack in 2024 aluminum alloy plate will introduce a local flexibility that affects its dynamic response. During vibration, the microcrack does not remain always open. Contrarily, it will open and close over time depending on the loading conditions and vibration amplitudes. Consider the fatigue microcrack as a slit, an applied low frequency vibration signal fL will change the width of the slit depending on the phase of the vibration. As an example, let us consider the case where the sample is under sufficient vibration amplitude that the compression phase completely closes the microcrack, whereas the subsequent dilation opens the microcrack. If a high frequency signal fH is simultaneously applied to the microcrack, during the dilation phase of the low frequency cycle, the high frequency signal fH is partially decoupled by the open microcrack. This will reduce the amplitude of the high frequency signal fH passing through the microcrack. In the other half of the low frequency cycle, the closed microcrack does not interrupt the ultrasonic signal and the amplitude of the transmitting signal amplitude will increase.

Therefore, in the microcracked samples, the ultrasonic signal reflected from the nonlinear scatterer (microcrack) results in an amplitude modulation. Fourier transformation of this signal reveals modulation such as harmonics and sideband frequencies that are sum and difference of the frequencies of the excitation source signals. On the contrary, in the intact samples, the signal is mainly reflected by a linear scatter (plate boundary) and thus it will create no modulation. Experimental results analysis leads to the following conclusions. If there is a microcrack in the samples, some new frequency components will occur. So, these new frequency components can be used to indicate the presence of a microcrack or damge.

4. Conclusions

In summary, we constructed a system to study the nonlinear acoustic characteristics of fatigue microcracks of 2024 aluminum alloy plates. Using this system, two type of the samples, one is with a microcrack and the other is without the microcrack, are experimented, respectively. The results show that in the intact sample there are no harmonics and sidebands. On the contrary, in the microcracked sample, there is an abundance of the harmonics and sidebands. The central frequencies and the harmonic frequencies appear in the same time, and all the sidebands frequencies also occur in the other same time. Therefore, these new frequency components can be used to indicate the presence of a microcrack.

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