Experimental study on fatigue crack identification of 7075 aluminium alloy plate using combination NEWMS and TRA

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According to nonlinear elastic wave modulation spectroscopy (NEWMS) and time reversal acoustic (TRA), a system is constructed to study the fatigue crack in 7075 aluminium alloy plate. Using different frequency excitation source ($f_1=270$ kHz and $f_2=70$ kHz), two types of samples, one is with the crack and the other is without the crack, are comparatively experimented. Intermodulation components ($f_\pm = f_1 \pm f_2$, $f_\pm = f_1 - f_2$) around the fatigue crack are analyzed. The experimental results show $f_\pm$ can be used to indicate the presence of the crack. The two-dimensional contour plot of the energy from the sample surface amplitude can be used to locate the crack position.

Keywords: Fatigue crack, Identification, Intermodulation, Nonlinear elastic wave modulation spectroscopy, Time reversal acoustic, 7075 Aluminium alloy plate

Due to their superior mechanical properties such as high stiffness, strength and corrosion resistance, aluminium alloys plate structures have been increasingly applied in aerospace, ground transportation, turbines and so on1-3. Although these systems are carefully designed for fatigue loading, they are subjected to many forms cyclical loading, and if the growth of fatigue crack goes unchecked the results can be catastrophic4,5. Consequently, to avoid failure caused by damages especially early fatigue cracks and ensure the safety of the structures during their lifetime, it is imperative to develop structural integrity monitoring techniques6-8.

In an isotropic solid plate, it responds with atomic nonlinearity or deformation at the atomic/molecular scale9. However, in the same materials when damaged, the nonlinear response and the manifestations of nonlinearity are very large. Nonlinear elastic wave modulation spectroscopy (NEWMS) techniques have been developed to probe the existence of damage induced nonlinearity and this method exhibits a powerful tool to detect damaged zones in a sample10. Time reversal acoustic (TRA) method provides a means to focus acoustic energy to any point in a solid11. In TRA method, an input signal at an excitation point can be reconstructed if a response signal measured at another point is re-emitted to the original excitation point after being reversal in a time domain. Only when the non-linear components of the received signal are time reversed, the combination of these methods with TR process can be used to either increase the stress on the focusing position or to focusing elastic wave on the crack12. So NEWMS-TRA can be defined by sending back only the nonlinear components which are preliminary time reversed.

The aim of this paper is to study the indication and identification of the fatigue cracks in 7075 aluminium alloy samples based on the combination NEWMS and TR methods. The intact samples and the cracked samples are experimented respectively using two frequency excitation source.

Experiment Procedure

In this study, two types of samples are examined. One type is intact and the other type is with the presence of the fatigue crack. These two samples have the same geometrical size, namely, the length, width and thickness are 150 mm, 60 mm and 2 mm, respectively. The intact samples are directly machined by cutting from 7075 aluminium alloy plate, and the cracked samples are got by creating a fatigue crack in the intact ones. The full length of the fatigue crack located at the sample center is 8 mm and it is crossing
the whole cross-section of the sample. Its preparation process was the following. Firstly, at the center of the intact sample, a hole of 0.2 mm diameter is produced by the laser as a stress raiser to facilitate fatigue crack initiation and subsequent crack growth. Then, the sample is fatigued in push-pull cyclic bending to prefabricate a crack. The crack length can be automatically observed and measured by the computer.

The experimental system used to study the fatigue crack is schematically shown in Fig. 1. Two thin PZT transducers are used to be excitation source and their sizes are 10 mm in diameter and 1 mm in thickness. The transducers are fixed on the surface of samples by using the polymer adhesive and are driven by two excitation signals generated by an arbitrary waveform generator FLUK294. One is high-frequency signal \( f_1 \) with central frequency 270 kHz, the other is low-frequency signal \( f_2 \) with central frequency 70 kHz. The excitation signals are 6-cycle sinusoidal tone-bursts and their voltages are 20 V. The laser vibrometer V1002 acted as a receiver is used to measure real-time vibration velocity of the sample surface, and the acquired signal is stored in digital oscilloscope DPO4054 connected to the laser vibrometer. Then, computer through GPIB interface to the digital oscilloscope can get data from digital oscilloscope and the data are processed by MATLAB.

The NEWMS-TR experiments are performed according to the following steps: (1) two excitation signals \( f_1 \) and \( f_2 \) are simultaneously emitted by two separate channels of arbitrary waveform generator and are applied to the PZTs, respectively; (2) the vibration signals are acquired by the laser vibrometer V1002 and Fourier analysis is made by MATLAB program; (3) in order to only rebroadcast the nonlinear signature \( (f_1 = f_1 + f_2, f_1 = f_1 - f_2) \) in the cracked sample, the received signals are processed by harmonics filtering, and then only nonlinear frequency components \( f_k \) are reversed in time domain, respectively; (4) 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.

**Result and Discussion**

Figure 2 shows the frequency spectrum analysis results of the received signals in step (2). It can be seen from Fig. 2a that in the intact samples the spectrum contains two fundamental frequencies, namely \( f_1 = 270 \) kHz and \( f_2 = 70 \) kHz. However, in the cracked samples, besides these two fundamental
frequencies, the intermodulation (harmonics and sidebands) $f_+ = 340$ kHz and $f_- = 200$ kHz will occur, which can be seen from Fig. 2b.

In the intact samples, the output spectrum is affected by the linear processes of wave dissipation and scattering, and by very small atomic non-linearities. On the contrary, in the cracked samples, the presence of the fatigue crack will introduce a local flexibility that affects its dynamic response. During vibrations, the crack will open and close over time depending on the loading conditions and vibration amplitudes. The opening and closing of the fatigue cracks will produce a nonlinear response. Therefore, in the cracked samples, harmonics and sidebands are mainly created by the non-linearity of the medium in addition to the linear effects. In other words, the presence of the harmonics and sidebands can be used to indicate the crack or damage.

In order to locate the crack position, after the received signals are filtered and reversed, the intermodulation at the focused signals in time is then analyzed in terms of the sum- and difference- components ($f_+$ and $f_-$). This procedure mentioned earlier is repeated point-by-point along a line crossing the fatigue crack position and scanned by the laser vibrometer.

For an intact position there is no intermodulation. However, for a crack zone the intermodulation will be quite high. The non-linearity signatures contained in the sum- and difference- frequency are shown in Fig. 3 as a function of the distance to the crack. At the position of the crack, the intermodulation signature is evidently much larger than elsewhere. We can see a clear indication of the crack position. Doing so, the imaging of the crack can be performed by evaluating the focused energy after the signals are reversed and rebroadcast sum- and difference- frequency. The rebroadcast signals are detected by the laser vibrometer in the vicinity of the crack. Two-dimensional contour plot of the energy from the surface amplitude of $f_+$ and $f_-$ results in image is shown in Fig. 4. For rebroadcast at $f_+ = 340$ kHz and $f_- = 200$ kHz there is energy focusing near the crack, which can be seen from Figs 4a and 4b. In contrast to using a time reversed signal filtered about
f_+ = 340 kHz in the intact sample, Fig. 4c shows no evidence of such focusing. So, the crack position in 7075 aluminium alloy plate may be located according to the two-dimensional contour plot of the energy.

Different characteristics can be seen in the f_+ = 340 kHz and f_- = 200 kHz images. For example, the result of using f_+ appears to focus the energy at the crack tip while the use of f_- indicates that some elastic energy is focused at the crack opening (the end of the crack exposed to the holed free boundary) with most the energy focused at the crack tip as before. The main reason may be that the crack tip is known to be areas of the high stress concentration, which may play a role in the source of non-linear elastic.

Conclusions
From this study, the following conclusions can be drawn:
(i) According to the combination of the nonlinear elastic wave modulation spectroscopy and time reversal acoustic, using piezoelectric transducers, arbitrary waveform generator, laser vibrometer, digital oscilloscope and computer, we have constructed a system to study the fatigue cracks in 7075 aluminium alloy plate.
(ii) The comparative experiments using two different frequency excitation source shows harmonics and sideband in the cracked samples is extremely large in comparison with the intact samples. The intermodulation frequency f_± = f_1 ± f_2 can be used to indicate the presence of the crack. According to the two-dimensional contour plot of the energy from the samples surface amplitude, the crack position of 7075 aluminium alloy plate can be located.

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