Applicability of non-linear time reversal acoustics system for detection of fatigue cracks

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Abstract

A system arranged from piezoelectric transducer, arbitrary waveform generator, laser vibrometer, digital oscilloscope and computer is used to study the fatigue crack in 2024 aluminium alloy plate. Based on the method combining the non-linear response and time reversal acoustic, two types of samples made of 2024 aluminium alloy plate, one with the presence of a fatigue crack and the other intact, are comparatively experimented, and the experimental results are analysed in the time domain, the frequency domain and the time-frequency domain, respectively. The results lead to the following conclusions. After the signals are reversed and refocused, the non-linear response in samples with a fatigue crack is extremely remarkable. By contrast, the non-linear response is very weak in the intact samples. The experiments show that the third harmonic can be used for the indication of the presence of fatigue cracks and for the location of their position.

Key words: fatigue crack detection, 2024 aluminium alloy, non-linear time reversal acoustics, acoustic methods

1. Introduction

In recent years, aluminium alloys are being used to replace traditional cast irons and forged steel components in the automotive and aerospace industries due to its potential weight reduction and consequent improvement in fuel economy of vehicles [1]. However, the relatively low fatigue resistance of these alloys is known to be an obstacle in terms of cost-effective design and safety. In some cases, fatigue cracks are a potential source of catastrophic structural failure. Therefore, to avoid failure caused mainly by fatigue cracks, many researchers have performed extensive investigations to develop structural integrity monitoring technique [2].

The vibration characteristics of cracked structures can be useful for an on-line detection of cracks without actually dismantling the structure [3–5]. Therefore, the development of structural integrity monitoring techniques has received great progress in recent decades. Among those techniques, ultrasonic wave is considered a powerful method because the characteristics of its propagation are directly related to the properties of materials.

Conventional acoustic methods of non-destructive testing (NDT) are based on the principles of linear acoustics. However, some types of qualitative behaviour encountered in engineering, such as the generation of harmonics and intermodulation, cannot be solved by linear models because of their inherently low sensitivity to defects. In these cases, non-linear behaviour is significant and the effect is dominant. Thus, non-linear models are required for their description [6–8].

Due to material nonlinearity, a wave can distort, creating accompanying harmonics and multiplication of waves with different frequencies. The localized damage portion of materials acts as a multiplier and non-linear mixer of the excitation frequencies. Consequently, the monitoring of these phenomena will be an effective method for detecting fatigue cracks because of their high sensitivity to the structural change. However, the studies on non-linear elastic wave spectrum do not give any inform-

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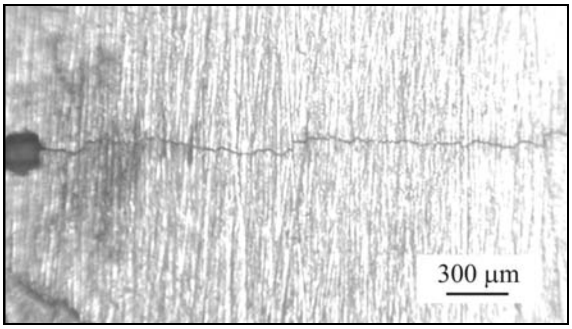

Fig. 1. The shape of part of the fatigue crack.

ation of damage location. Fortunately, time reversal acoustic (TRA) allows the focusing of acoustic energy to any point, and the non-linear response in the focused signals may be used for damage location.

This work is concentrated on experimental study and detection of fatigue cracks in 2024 aluminium alloy plate using the method combining the non-linear response and TRA. The changes of non-linear elastic wave behaviour were documented for two types of samples – with and without presence of fatigue cracks and the experimental results are analysed and compared.

2. Sample preparation

Two types of samples are examined in this study. One type 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 150 mm, 60 mm and 2 mm, respectively.

The intact samples are directly machined by cutting from 2024 aluminium alloy plate, and the cracked samples are obtained by creating a fatigue crack in the intact ones. The full length of the fatigue crack located at the sample centre is 5 mm and it is crossing the whole cross-section of the sample. A part of the sample with the fatigue crack is shown in Fig. 1; its preparation process is the following. Firstly, at the centre of the intact sample, a hole of 0.2 mm in 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 symmetrical sinusoidal wave pull-push loading to prefabricate a crack. The crack length can be automatically observed and measured by the computer connected with a CCD camera. The fatigue tests were stopped as soon as the surface crack length reached about 5 mm.

3. Experimental set-up and procedure

The experimental set-up of an acoustic detection

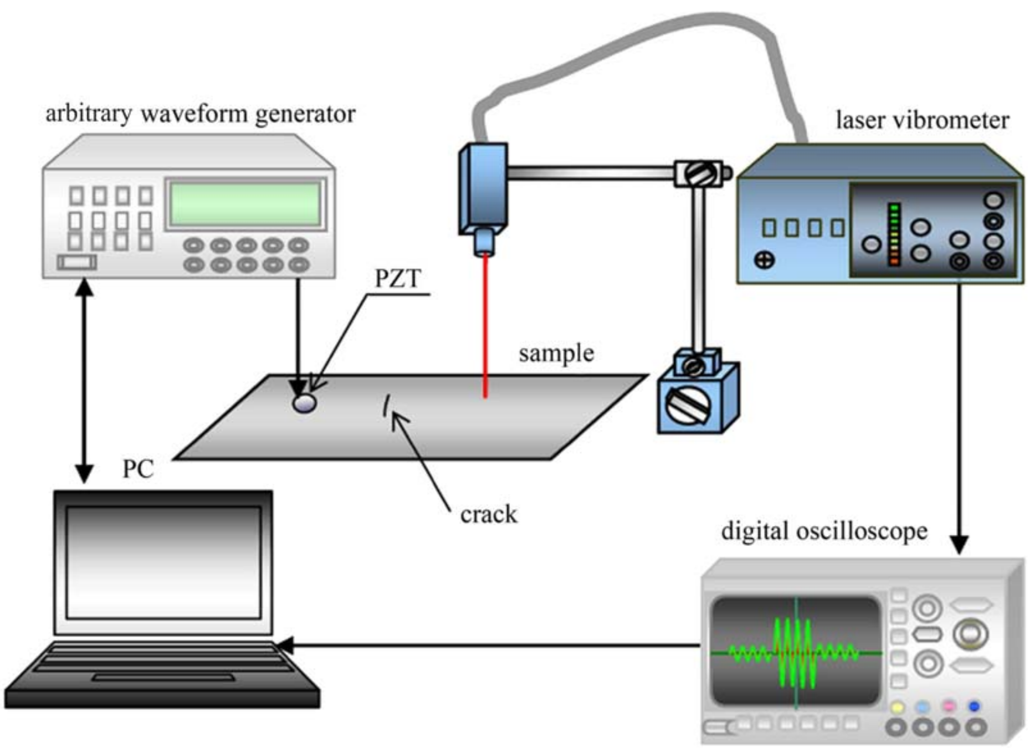

Fig. 2. The experimental setup for measurement of the samples.

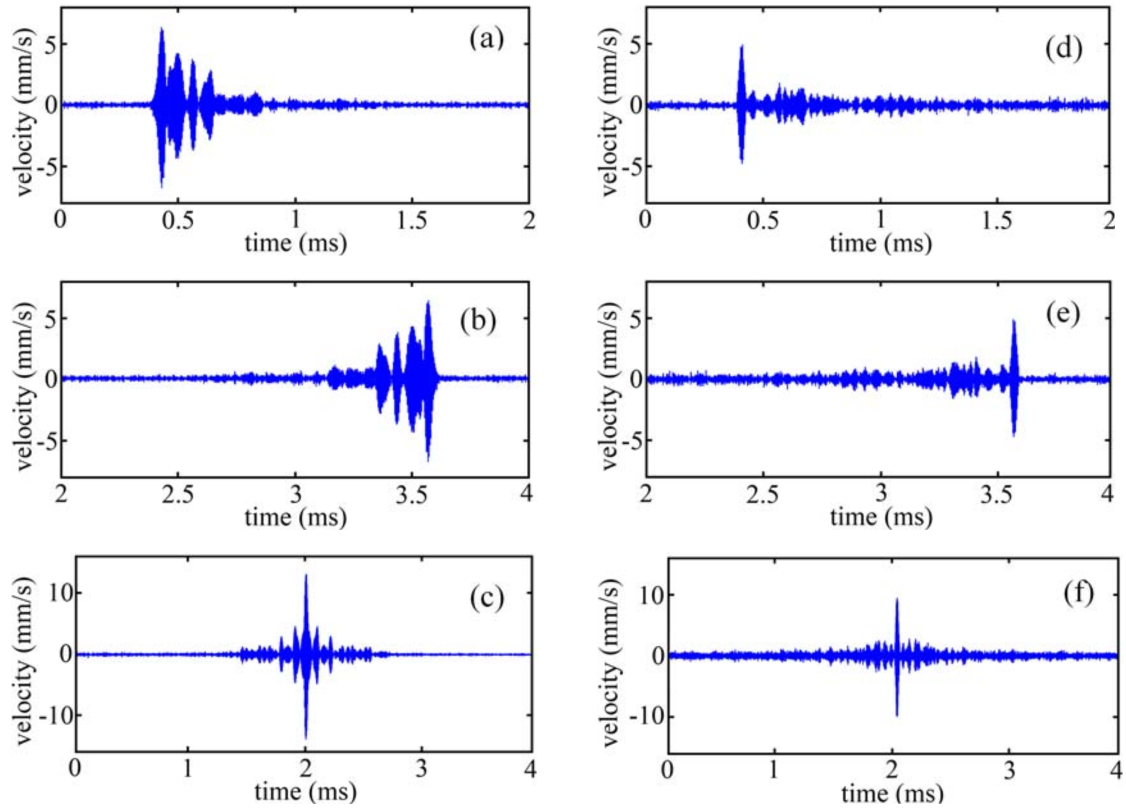

Fig. 3. The waveform from the TR experiment: *left* (a)–(c) are the signals of the sample surface with fatigue crack: (a) first detected signal by laser vibrometer, (b) radiated TR signal, (c) focused TR signal; *right* (d)–(f) are the same signals of the intact sample surface.

system is schematically shown in Fig. 2. A thin piezoelectric transducer (PZT) is used to be an emitter and its size is 10 mm in diameter and 1 mm in thickness. The PZT is fixed on the surface of samples by using polymer adhesive and is driven by an excitation signal. The excitation signal generated by an arbitrary waveform generator FLUK294 is an 11-cycle sinusoidal tone-burst with central frequency 270 kHz and its voltage is 20 V. The laser vibrometer V1002 acting as a receiver is used to measure real-time vibration velocity of sample surface, and the acquired signal is stored in digital oscilloscope DPO4054. Then, computer through GPIB interface to the digital oscilloscope and arbitrary waveform generator is used to process the signal by Matlab.

The time reversal non-linear elastic wave experiments are performed according to the following steps: (1) An 11-cycle tone-burst with central frequency 270 kHz is emitted by arbitrary waveform generator and is applied to the PZT; (2) at the distance 80 mm from the PZT, the vibration signal is acquired by the laser vibrometer, then numerically time reversed; (3) the TR signal is stored in the arbitrary waveform generator and re-emitted to the same PZT and (4) the TRA focused signals are collected by the laser vibrometer and their nonlinearity is analysed.

4. Results and discussion

According to the experimental procedure in section 3, Fig. 3 presents the waveform signals resulting from the process detailed above.

It can be seen from Figs. 3a and 3d that there are two remarkable differences between the cracked sample and intact sample. Firstly, the magnitudes of the wave peak and the side lobe in the cracked sample are much bigger than those of the intact sample. 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 non-linear 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 Figs. 3c and 3f, the focused TR signals are nicely reconstructed. The peak amplitude and the ra-

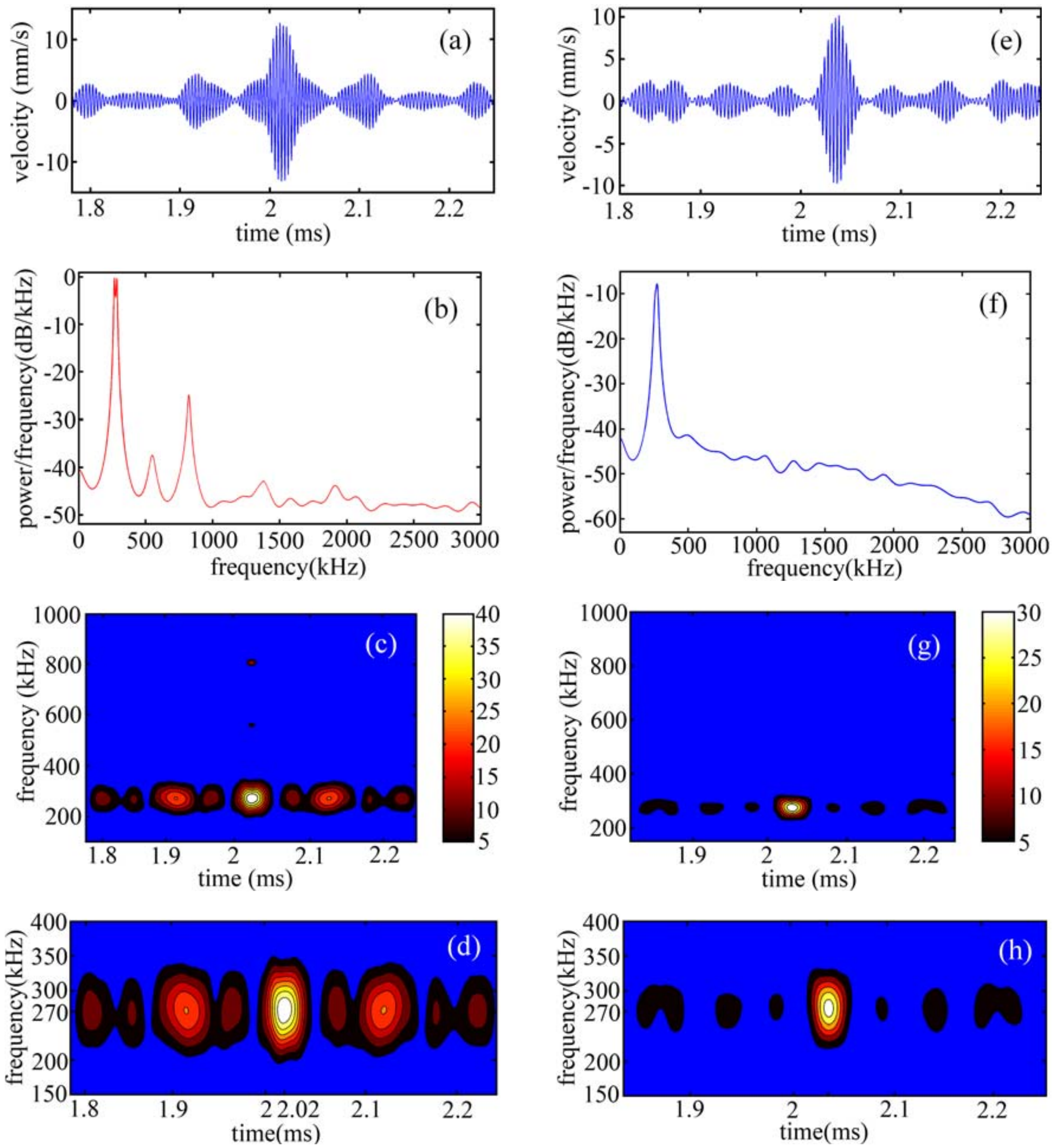

Fig. 4. Analysis of the focused TR signal: *left* (a)–(d) show the signals on the surface with the fatigue crack: (a) focused TR signal zoom, (b) power spectrum, (c) time-frequency analysis, (d) its zoom; *right* (e)–(g) show the same signals for the intact sample.

tio between the peak and the side lobe are extremely increased in contrast to the pre-focused ones.

The results presented above indicate clearly the potential of the time reversal acoustic method. On one hand, this method can narrowly focus wave energy in time and space and can efficiently focus acoustic energy to any point, regardless of the position of initial source and the heterogeneity of propagation medium [9]. 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. As a consequence, the focused acoustic energy in the cracked sample is heavily strengthened. On the other hand, the focused TR signal is ideal from the perspective of the enhancing elastic wave and non-linear response. Therefore, it is necessary to further analyse the relevant information of nonlinearities.

The further study on the focused TR signal concerned the time span $t = 1.8 \sim 2.25$ ms. Figure 4a shows that there is a superposition between the side lobe and the part of the peak packet. This is mainly because the nonlinearity in the cracked sample produces the additional frequency contents, not present in the original excitation source. These new frequencies are associated with the wave deformation and the side lobes that arise as the elastic waves encounter such localized non-linear features as cracks. In order to investigate this feature, subsequently, the power spectrum corresponding to Fig. 4a is shown in Fig. 4b. It clearly illustrates that super-harmonics such as 2*f*, 3*f*, 5*f*, etc. are abundant in the cracked sample. However, in an intact sample (see Fig. 4f) the power spectrum contains only a single frequency peak 270 kHz that corresponds to the original excitation source. This can be explained as follows. When the sample is damaged, it will show progressively enhanced features of non-linear elastic response, and this large non-linear response will entirely dominate the relatively small atomic nonlinearity [10, 11]. According to the non-linear elastic wave theory, non-linear elastic behaviour may manifest itself by the generation of harmonics and resonance frequency shift during dynamic wave propagation [12, 13]. Therefore, in the cracked sample, a wave of frequency f can transform into a wave with frequency components 2*f*, 3*f*, 5*f*, etc. Because the harmonics and the side lobes are mainly produced by the nonlinearity of the cracked sample, the appearance of the harmonics and the side lobes may be used to indicate the presence of a micro crack and/or damage.

In addition, the third harmonic becomes dominant among the super harmonics, as shown in Fig. 4b. The main reason is that the acoustic wave impacting on the crack exhibits amplitude hysteresis and storage for parametric and non-linear acoustic effects. Also, the discrepancy between the classical theory and the present experimental results can be explained by the existence of hysteresis and discrete memory. This implies that hysteresis acts as a third order nonlinearity and the type of the nonlinearity is dominated by dynamic hysteresis in the stress-strain behaviour.

In order to determine the time of the corresponding harmonics, the focused signals in Figs. 4a and 4e were analysed again in the time-frequency domain by short time Fourier frequency transform (STFT), and they are shown in Figs. 4c and 4g, respectively. Because the high harmonics above $5f$ show lower energies in comparison with the second and third harmonics (see Fig. 4b), the analysed frequency ranged from 0 to 1000 kHz. Figure 4c shows that the central frequency f and the harmonics frequencies $2f$ and $3f$ appear in the same position on time axis, which means that all the harmonics components are contained in the peak packet. Therefore, the acoustic power of the focused peak packet in the cracked sample is larger than that in the intact one. Furthermore, Fig. 4d shows that except the peak packet the side lobes (about $t = 1.92$ ms and $t = 2.12$ ms) have a large energy level. On the contrary, in the intact sample (see Fig. 4h) there are no harmonics and the side lobes have a very modest energy level.

In summary, it can be seen from the experimental results that the cracked sample definitely indicates remarkable nonlinearity, much more than material itself,

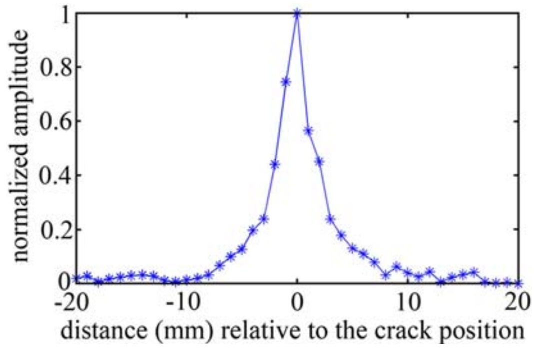

Fig. 5. The spatial distribution of the third harmonic amplitude along the sample surface: the normalized amplitude as a function of the distance to the crack.

which is in agreement with the non-linear elastic wave theory [14, 15] and the time reversal theory [16, 17]. Therefore, the high elastic nonlinearity of the focused signal can be used for the crack location. Through scanning the surface of the sample by the laser vibrometer, the TR focusing procedure and subsequent non-linear postprocessing point by point, it can be determined whether the crack exists in the scanned area or not. Here, the third harmonic is selected because it is the lowest harmonic predicted by all non-linear material models, and it has a largest energy content from higher order harmonics. In other word, the power amplitude of the third harmonic of the signals from the crack is much higher than that from the intact surface. To verify it, the procedure is conducted along a single line scan crossing the crack with a step 1 mm. Figure 5 shows the third harmonics amplitude in the dependence on the distance from fatigue crack position along the x-axis parallel to the specimen length (i.e. parallel to the stress axis). As can be seen from this figure, high level of the third harmonic is corresponding to the crack position ($x = 0$). With increasing distance of the laser from the crack position the level of the third amplitude harmonic decreases considerably. Thus, a clear indication of the crack position can be seen from Fig. 5.

5. Conclusions

(1) According to the combination of the non-linear response and time reversal acoustic, we have constructed a system to detect fatigue cracks in 2024 aluminium alloy plate.

(2) The comparative study performed on the cracked and intact 2024 aluminium alloy samples shows that the non-linear response of TR signals in the cracked sample is extremely large in comparison with that one in the intact sample. The focusing abilities of TR can be enhanced by the sensitivity of non-

-linear elastic measurements in the cracked samples. The third harmonic of focusing signals can be used for the detection of fatigue cracks and for the location of their position on the free surface.

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