

Nonlinear Time Reversal Focusing and Detection of Fatigue Crack

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Abstract This paper presents an experimental study on the detection and location of nonlinear scattering source due to the presence of fatigue crack in a laboratory specimen. The proposed technique is based on a combination of nonlinear elastic wave spectroscopy(NEWS) and time reversal(TR) focusing approach. In order to focus on the nonlinear scattering position due to the fatigue crack, we employed only one transmitting transducer and one receiving transducer, taking advantage of long duration of reception signal that includes multiple linear scattering such as mode conversion and boundary reflections. NEWS technique was then used as a pre-treatment of TR for spatial focusing of reemitted second harmonic signal. The robustness of this approach was demonstrated on a cracked specimen and the nonlinear TR focusing behavior is observed on the crack interface from which the second harmonic signal was originated.

Keywords: Fatigue Crack, Nonlinear Scatterer, Nonlinear Elastic Wave Spectroscopy(NEWS), Time Reversal(TR), Harmonic Generation, Crack Localization

1. Introduction

One of the important roles of ultrasonic nondestructive evaluation (NDE) is to detect and characterize crack-like flaws in critical components and structures. Both linear and nonlinear ultrasonic techniques can be applied for these purposes. When cracks are open, linear methods based on the time-of-flight diffraction (TOFD) or a pulse-echo reflection can be a useful tool. However, when cracks are closed or partially closed, it will be more challenging to detect them because the diffracted or reflected signal is too weak. An alternative technique to overcome this limitation is nonlinear ultrasonics. Ultrasonic nonlinearity is manifested as harmonic generations (sub or super) in the power spectrum of the received signal when an intense ultrasonic wave is incident into imperfect interfaces. This effect is known as the contact acoustic

nonlinearity (CAN), and it has been the topic of much research work concerning the characterization of closed cracks or imperfect bond interfaces [1]. Earlier theoretical investigations [2-4] predicted that a weak or incompletely bonded interface will generate high second harmonics when subjected to sufficiently intense acoustic energy, and previous experiments have indicated that acoustic harmonic generation occurs on various types of interface, such as unbounded interfaces [5] microstructural changes [6-9], cracks [10-12] and adhesive joints [13,14].

In more recent years, nonlinear elastic wave spectroscopy (NEWS) methods have been introduced to assess nonlinear elastic effects of damaged materials [15-18]. NEWS is a set of techniques to determine the existence and degree of nonlinearity in elastic systems. Nonlinear elastic waves can be generated in a material from a variety of reasons. They can be

distributed throughout the material or be highly localized. In this work, we are more concerned with detection and location of localized nonlinear elastic features such as cracks.

In the last few years, NEWS methods have been combined with focusing techniques of time reversal acoustics (TRA) in order to enhance the detection and localization capabilities of NEWS [19,20]. As in the linear case, the nonlinear TRA is based on the principle of time reversal invariance and spatial reciprocity of the wave equation in a lossless medium, and it is usually composed of two steps. In the forward propagation step, the cracks must be stimulated with an external excitation in order to actively generate the nonlinear frequencies, thus becoming an active nonlinear source. The elastic waves scattering from the nonlinear source are recorded by a set of transducers [time reversal mirror (TRM)]. The nonlinear frequency components are then extracted from the signals acquired by the TRM elements. In the backward propagation step, the nonlinear waveform extracted from each TRM sensor is time reversed and reemitted into the medium in order to be focused back onto their original nonlinear source, the crack. Therefore, measuring this focused signal around the nonlinear scattering source (for instance, crack) will highlight the presence of crack.

TRM of finite bandwidth and aperture can limit the focusing quality. Nevertheless, it was demonstrated that the presence of a reverberant wave field (multiple scattering, mode conversion, and boundary reflections) enhances the spatial focusing of the reemitted signals. The effect is to create a virtual enlargement of the transducers angular aperture, thus to permit the reduction of the number of sensors needed to backpropagate the acquired waveforms, even to only one single element [21-24].

In this paper, a compact tension specimen with fatigue crack is used to apply the proposed

NEWS TR technique. The harmonic generation measurement is first conducted in a through transmission mode using a 10 MHz transmitter and a 20 MHz receiver. A high power amplifier is employed to generate harmonics from the crack interface. The second harmonic signal of $2f=20$ MHz is filtered out of the received signal for long duration, time reversed and reemitted from the 20 MHz receiving transducer. Another 20 MHz contact transducer was used to measure the point-by-point surface displacement during the reemission process. The nonlinear TR focusing behavior is observed on the crack interface from which the second harmonic signal is originated.

2. Experiments

2.1 Harmonic Generation

A compact tension (CT) specimen of Al 6061-T6 is used in this work. This cracked specimen was fabricated by applying a high cycle fatigue loading on a chevron notch. Fig. 1 shows the schematic configuration of the cracked CT specimen. The crack length was measured to be about 40 mm from the notch center.

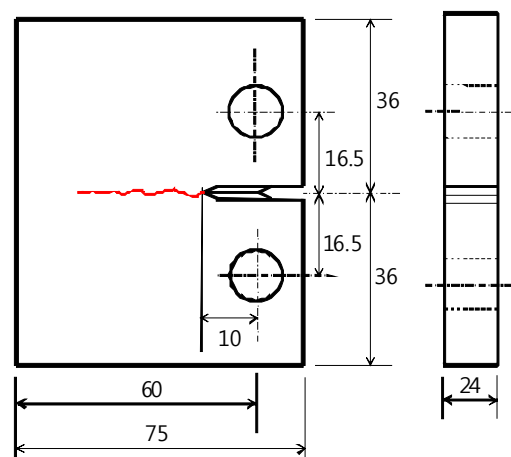


Fig. 1 Configuration of CT specimen with fatigue crack (unit: mm)

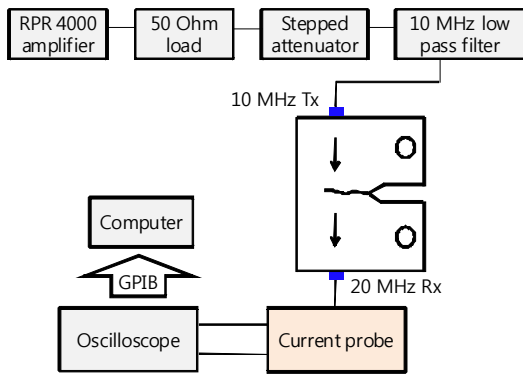
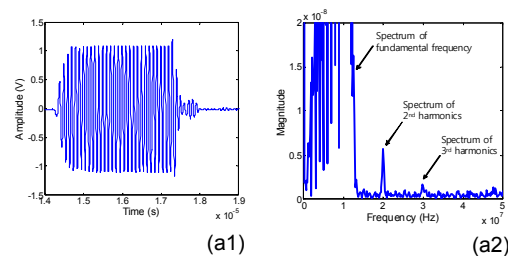


Fig. 2 Schematic diagram for harmonic generation measurement

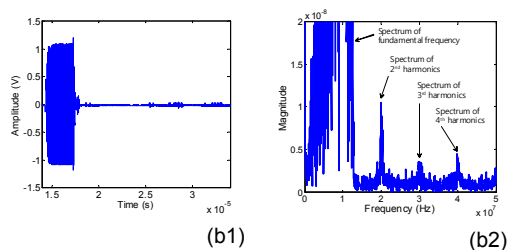
Harmonic generation measurements are made in the through transmission mode as shown in Fig. 2. Fig. 2 shows a schematic representation of the harmonic generation measurement. The transmitting transducer is coupled to the sample for the transmission measurement. A monochromatic toneburst at the fundamental frequency is injected into the sample, propagates through the cracked interface of the sample and is received by the receiving transducer.

Fig. 2 also shows an equipment block diagram of the harmonic generation measurement system. A high power amplifier (RITEC RPR 4000) tuned to the fundamental frequency (10 MHz for these measurements) provides the high power monochromatic toneburst for the harmonic generation. The two transducers are made of LiNbO₃ wafers (longitudinal polarization) and coupled to the sample with a light oil. The size of the transducer is 12.7 mm in diameter. The transmitter has a center frequency of 10 MHz, while the receiver has a broad bandwidth with a center frequency of 20 MHz. (Both transducers are the product of CTS Valpey Corporation, Hopkinton, MA, USA). The two transducers are aligned with each other by being placed in a test fixture that can provide a constant pressure during the entire measurement.

The received signals with two different record lengths are shown in Fig. 3 together with their corresponding Fourier spectra. The input signal used is the monochromatic toneburst of the center frequency $f = 10$ MHz. The received signal in Fig. 3(a1) was recorded up to 19 μ s, while the received signal in Fig. 3(b1) was recorded up to 34 μ s. In addition to the fundamental component at $f = 10$ MHz, both the second harmonic and the third harmonic components are clearly seen at $2f = 20$ MHz and $3f = 30$ MHz. The longer is the record length, the higher are the magnitudes of harmonic components. It is also known that the longer is the record length, the better is the TR focusing effect. However, there was a limitation in record length because of the memory size of the oscilloscope used. We will use the longer received signal in the time reversal process of the second harmonic component and reemission.



(a) Received signal from the through transmission measurement and its Fourier spectrum (record length = 19 μ s)



(b) Received signal from the through transmission measurement and its Fourier spectrum (record length = 34 μ s)

Fig. 3 Received signals and their Fourier spectra for two different record lengths

2.2 Time Reversal and Remission of Second Harmonic Signal

To extract the 2nd harmonic component ($2f = 20$ MHz), a Hanning window of Fig. 4 was designed and multiplied on the Fourier spectrum of the received signal [Fig. 3(b2)]. The second harmonic signal in time domain, shown in Fig. 5(a), was then found from the inverse Fourier transform of the second harmonic spectrum. The extracted second harmonic signal was time-reversed and normalized as shown in Fig. 5(b) to be fed into the arbitrary waveform generator and then to be amplified by the ENI 2100L linear amplifier before it was used as an input source to excite the 20 MHz transducer used as the receiver in the harmonic generation measurement.

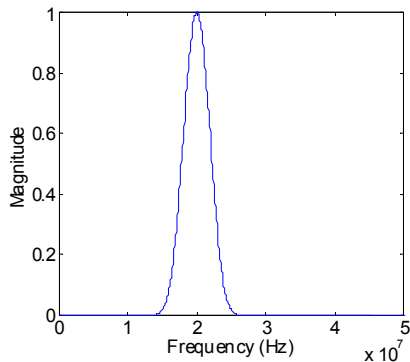


Fig. 4 A hanning window used to filter the 2nd harmonic components of $2f = 20$ MHz

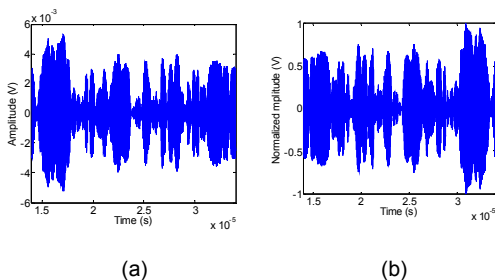


Fig. 5 (a) Recovered time domain signal of the 2nd harmonic component, and (b) Time reversed and normalized 2nd harmonic signal used for reemission and TR focusing

3. Results and Discussion

The experimental setup for reemission of the time-reversed second harmonic signal is shown in Fig. 6 below. The receiving transducer in the harmonic generation measurement is now used as a transmitting transducer. Another 20 MHz contact transducer (Panametrics V116, diameter = 0.125 inch (3.18 mm)) was used to measure the surface displacement while the time reversed harmonic signal is reemitted, as shown in Fig. 7. A total of 9 measurements were made in Fig. 7.

Position v3 (and h3) is the measurement point where the surface displacement is highest around the crack. Other measuring points v1,

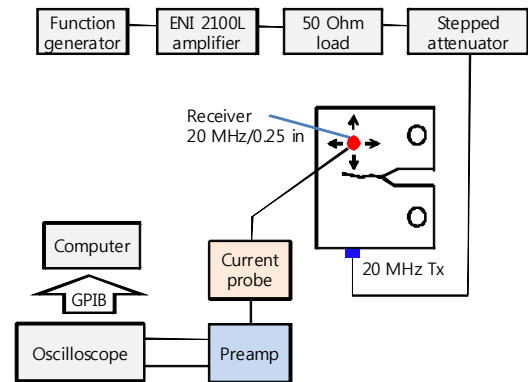


Fig. 6 Schematic diagram for time reversal and reemission of the 2nd harmonic signal

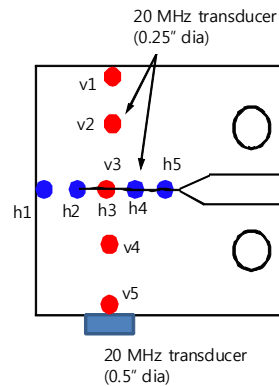


Fig. 7 Schematic illustration for measuring the surface displacement during the reemission process

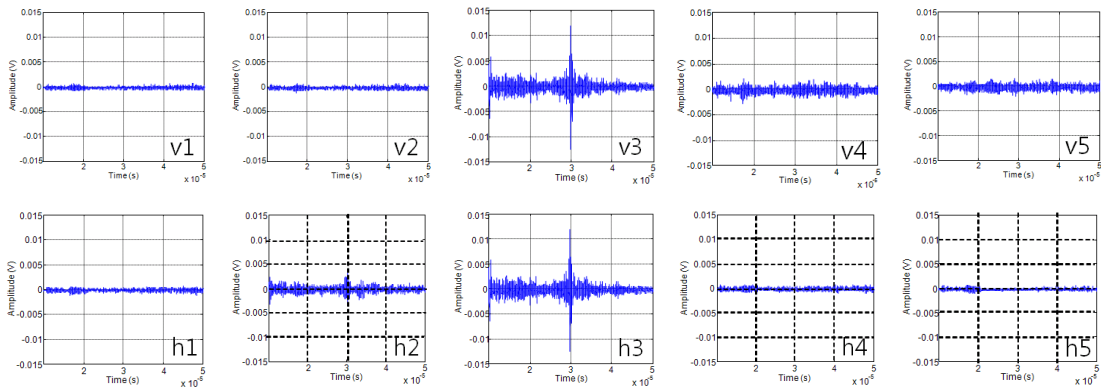


Fig. 8 Measured surface displacement at different positions of the fatigue-cracked CT specimen during the reemission of the time reversed second harmonic wave

v2, v4, and v5 represent positions along the vertical direction at equal spaces with respect to the position v3. Positions h1, h2, h4, and h5 represent the measuring points along the horizontal direction at equal spaces with respect to the position h3. Measurement results are shown in Fig. 8. First of all, we notice a strong amplitude waveform at position v3 and h3, where the reemitted time reversed second harmonic signal is focused at the position of the original nonlinear source, the crack. The surface displacement amplitudes at other positions around the focused point are very weak. We also repeated the experiments on a CT specimen of the same configuration without the fatigue crack, using the same procedure described before. As expected, no surface displacements were observed over and around the crack position.

Although a NEWS TR approach here was tested on the known fatigue crack, the technique can be applied to localize and image unknown nonlinear sources at unknown locations. Nonlinear features on or near the surface can be more easily located, however, it is theoretically possible to use TR with nonlinear signals to localize buried features through the use of numerical models.

4. Conclusions

Nonlinear elastic wave spectroscopy and time reversal technique (NEWS TR) were applied to detection and location of the fatigue crack in a compact tension specimen. Nonlinear waves were produced from the crack by insonifying a high power energy. The second harmonic signal was filtered out of the received signal, time reversed and reemitted for transmission focusing on the original nonlinear source position. It was shown that the presence and location of the crack could be highlighted by measuring surface displacements through scanning the specimen surface with a contact transducer of second harmonic frequency. Imaging of the crack localization should also be possible, for example, with the scanning laser vibrometer or the pulsed thermography.

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