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Detection of fatigue crack in an aluminium pipe with nonlinear guided waves

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ABSTRACT

Guided wave based inspection using nonlinear characteristics has attracted great attention for micro-scale damage in metallic structures. However, the curvature of the pipeline complicates the detection of damage in it. In this study, fatigue testing with a nonlinear signal collecting system and surface-bonded piezoelectric transducers is carried out to identify the fatigue crack in an aluminium pipe using second harmonic as nonlinear wave characteristics. Due to the co-existence of multiple wave modes in a pipe structure, an appropriate nonlinear index is used to describe the nonlinearity. The experimental results show that the breathing behaviour exists only at the early stage of the fatigue crack within 1 mm in length and it can be detected by the method based on nonlinear guided waves. This study provides an effective approach for the measurement of the fatigue crack initiation in pipe-like structures using piezoelectric transducers.

1. Introduction

Pipelines are crucial infrastructure which may suffer from various sorts of damage such as impact, corrosion and aging. Cylindrical guided waves are efficient for pipeline inspection, with the advantages of long propagation distance and high sensitivity[1]. Much research has been undertaken to detect different types of gross damage[2-5] in pipes using linear wave characteristics. However, micro-scale damage such as initiation of fatigue cracks, corrosion at early stage, and material degradation cannot be detected in some circumstances using linear wave characteristics, due to limitations of the wavelength of the excited wave mode. On the other hand, guided wave based methods using nonlinear wave characteristics are promising in these cases, where nonlinear distortion caused by the damage, such as higher harmonic generation, mixed frequency responses, and subharmonic generation, can be detected in the structure.

Applications of numerical simulation and experimental observation in terms of the material nonlinearity and contact acoustic nonlinearity (CAN) caused by damage in metallic structures have shown great progress. Among different modelling approaches for wave and microcrack interaction[6], a "breathing" crack model has been widely utilised to explain the interactions between guided waves and fatigue crack. To simulate material nonlinearity or CAN, the finite element (FE) method has generally been used to

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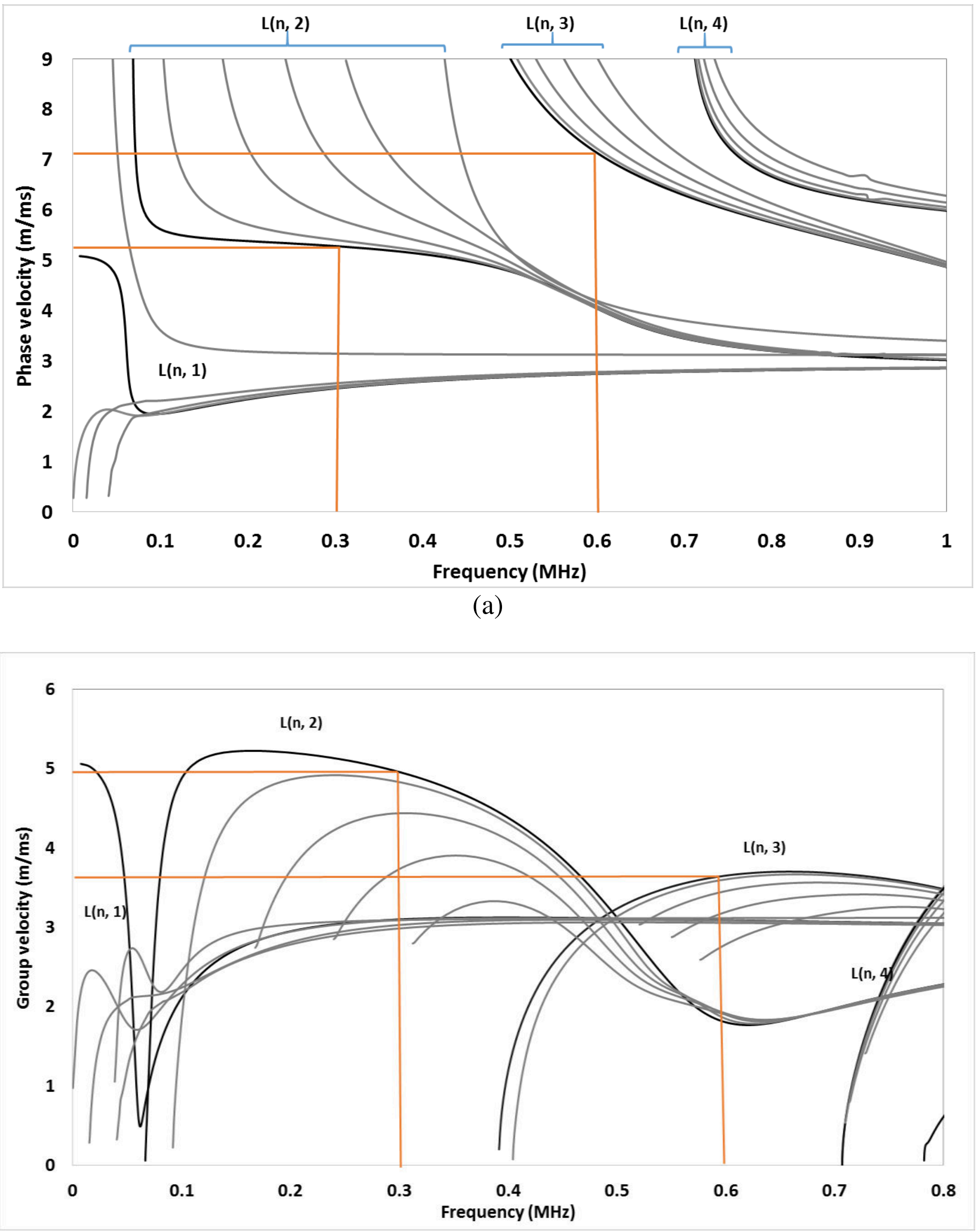
Email: *ye.lu@monash.edu* (Dr Ye LU) Fax: +61-3-9905-4944 analyse the relation between nonlinear parameters and microcrack length[7] as well as to locate microcracks[8] in plate structures. So far, however, studies conducted in pipes have been most focused on material nonlinearity. Theoretical and numerical analyses of higher harmonic generation, from nonlinear waveguides with arbitrary cross-section[9] to weakly nonlinear cylinders[10-12], have been investigated comprehensively. Simulation results have illustrated the observation of cumulative second harmonic generation with longitudinal, torsional or flexural mode excitation in pipe structures when two conditions, i.e. synchronism and non-zero power flux, were satisfied. Through experimental studies, an aluminium pipe under thermal fatigue damage was detected by the second harmonic generation method and the cumulative second harmonic was also observed with the increase in propagation distance[13]. Furthermore, studies using torsional waves to detect cubic material nonlinearity in a pipe have shown linearly increasing cumulative harmonic as the wave propagation distance increased[14]. Apart from using waves that propagate axially in cylinders, experiments with nonlinear circumferential guided waves have also been carried out to validate the severity assessment of accumulated damage in tubes using the second harmonic generation method[15].

However, limited studies using CAN have been undertaken for pipe-like structures, while the relation between the severity of microcracks and the nonlinear parameter is not yet well established. In particular, the existence of flexural wave modes as a group in pipe-like structures further complicates the interaction between breathing crack and waves, in comparison with plate-like structures[16]. The objective of this paper is therefore to experimentally quantify the relations between the nonlinear parameter and crack length in pipe structures.

2. Selection of excitation wave

In this study, a notation from Rose[17] was adopted, where L(n, m) was defined as a longitudinal mode group including axisymmetric modes L(0, m) and non-axisymmetric modes F(n, m). The integer *n* stands for the circumferential order of a mode and the integer *m* is the group order of a mode.

The wave mode selected for the second harmonic generation was based on the dispersion curve of an aluminium pipe with 30 mm outer diameter and 4 mm wall thickness, as shown in Figure 1. Wave mode L(0, 2) was selected as the fundamental wave due to its fastest group velocity and non-dispersive properties within a wide frequency range. The excitation frequency was 300 kHz, such that the L(0, 2) mode would convert to the L(0, 3) mode at the double frequency 600 kHz. Since the velocities of these two wave modes were different, the cumulative effect induced by material nonlinearity could be minimised and the second harmonic generated by a fatigue crack could be highlighted. It could be observed from the dispersion curve that a group of flexural wave modes F(n, 2) had group velocities close to that of the longitudinal wave mode L(0, 2). Therefore, more than one wave mode would be generated at the fundamental frequency when a single surface-bonded actuator was excited. As a result, the waves at fundamental frequency for the pipe under investigation were a group of wave modes L(n, 2) which would then be converted by a fatigue crack to L(n, 3) modes at the second harmonic.



(a)

(b)

Figure 1 Dispersion curve of aluminium pipe with 20 mm diameter and 4 mm wall thickness. (a) Phase velocity; (b) Group velocity

3. Experimental analysis

3.1 Experimental procedure

Experimental testing was performed on an aluminium pipe with the material properties listed in Table 1. A through thickness notch was drilled in the middle of the pipe for the fatigue crack initiation. 5 mm × 10 mm rectangular and 5 mm × 5 mm square surface-bonded piezoelectric transducers were used as actuator and receivers in the experiment, with the locations as in Figure 2. A system for generating and collecting signals was adopted, which included a Ritec RAM-5000 SNAP and an Agilent digital oscilloscope. A high-power low-pass filter was connected to the system, which could suppress harmonics higher than the fundamental frequency from the source before the signal was input to the transducer.

Table 1 Material properties for experimental test

Material properties	
Density (kg/m^3)	2700
Young's modulus (GPa)	68.9
Poisson's ratio	0.33

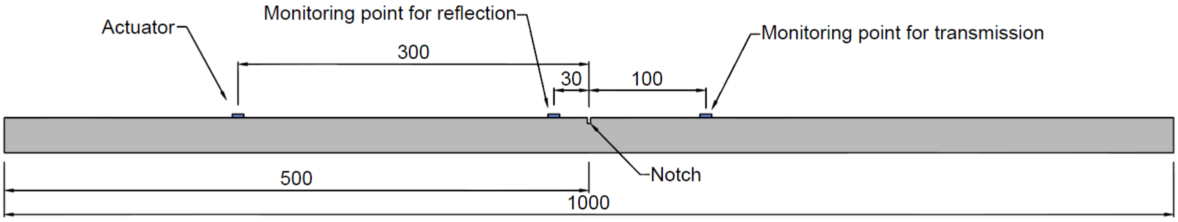


Figure 2 Arrangement of actuator and sensors (unit: mm)

When a 6-cycle tone-burst signal at a central frequency of 300 kHz was generated, the reflected and transmitted signals were recorded before the fatigue test as benchmark signals. A steel frame combined with a fatigue machine was used to generate fatigue crack in the pipe. The pipe was then under three-point bending on the fatigue machine with a cyclic load in the middle, as shown in Figure 3. The cyclic load from the fatigue machine ranged from 0.2 kN to 2 kN, with the equivalent highest stress on the cross section at about 50% of the yield stress of the pipe, and the loading frequency was at 2 Hz. During fatigue testing, the transmitted and reflected signals were continuously collected every 2000 cycles until 22000 cycles, after which the collection interval was changed to 4000 cycles. Fatigue testing was stopped at 42000 cycles when the nonlinearity in the received signals dropped to noise level. Signals were averaged 1024 times with a sampling frequency of 200 MHz before recording. It should be noted that during each moment of signal collection the load from the fatigue machine was removed to avoid any adverse effect of the external loads on the "breathing" behaviour of the fatigue crack.

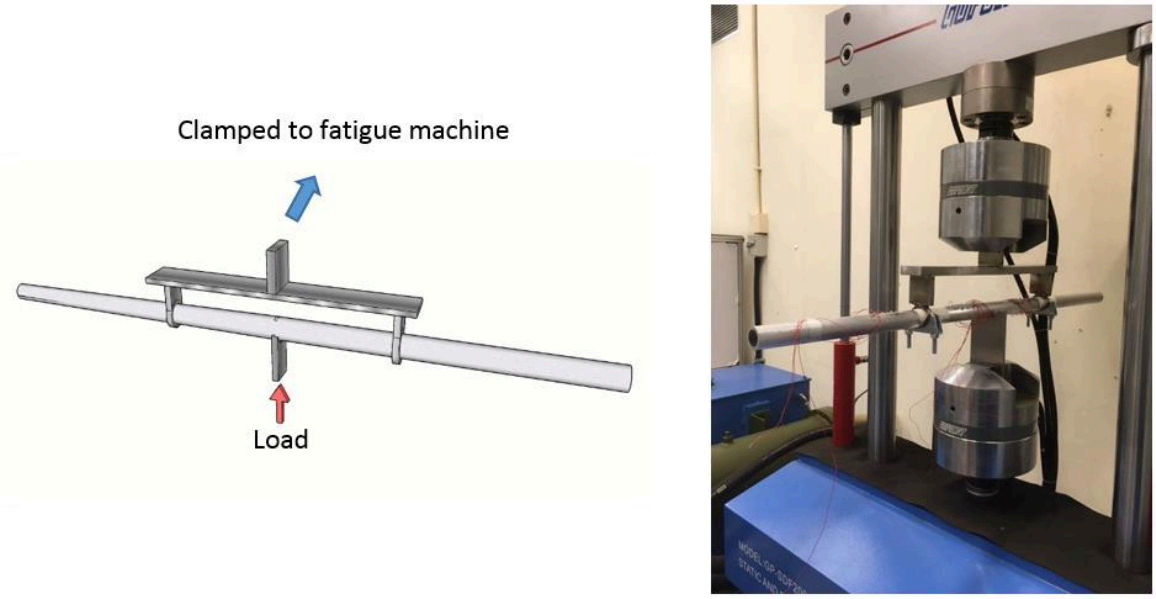


Figure 3 Steel frame combined with fatigue machine for three-point bending fatigue test

3.2 Results of transmission and reflection characteristics

The transmitted signal after signal processing is shown in Figure 4. For the signal at fundamental frequency, the first wave packet is recognised as multiple L(n, 2) modes within the time period from 86 μs to 126 μs before the arrival of L(0, 1).

As compared in Figure 4(a) for the benchmark signal before the fatigue test and the signals after 12000 and 22000 fatigue cycles, signals for the damage cases show no obvious difference from the benchmark at fundamental frequency. In the comparison between those two damage cases at double frequency in Figure 4(b), the average amplitude level of the second harmonic wave after 22000 cycles is more than 2% of the wave at the fundamental frequency, higher than the case after 12000 cycles as well; more importantly, both damage cases show greater nonlinearity than that in the benchmark. On the other hand, the average amplitude of the second harmonic wave of the benchmark, which is about 0.8% of that at fundamental frequency, is noticeable. This nonlinearity can be attributed to unavoidable nonlinearities from equipment and environment, as well as to the material nonlinearity of the pipe which was not ideally homogeneous. Furthermore, it can be seen in Figure 4(b) that the second harmonic wave from both damage cases arrives later than the benchmark signal and more than one wave packet is generated. The reflected signals also have similar results in Figure 5, whereas the multi-mode second harmonic waves are not as obvious as in the transmitted signals, because the different wave modes with close velocities are not completely separated within the shorter distance from the sensor to the microcrack.

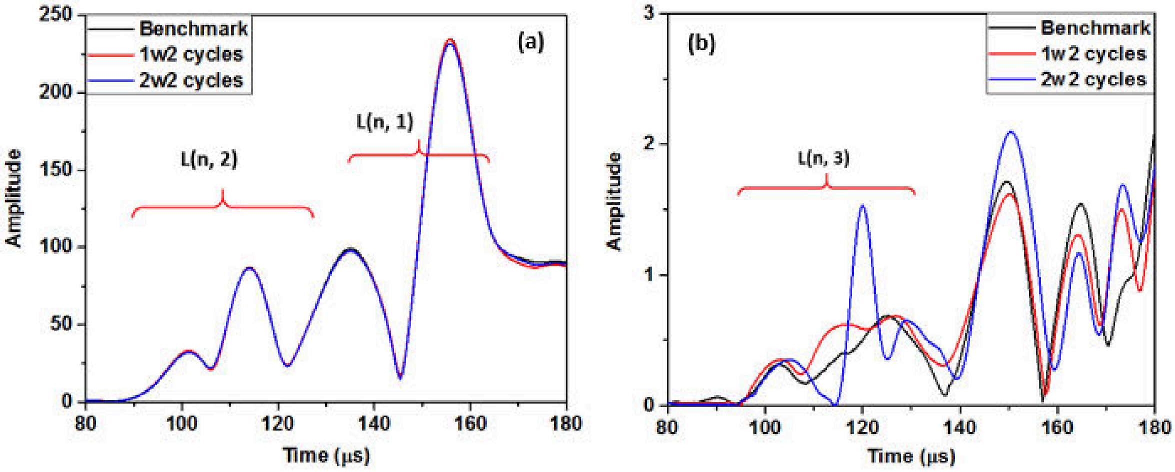


Figure 4 Transmitted signal from experiment at different fatigue cycles compared with benchmark signal (a) at fundamental frequency; (b) at double frequency

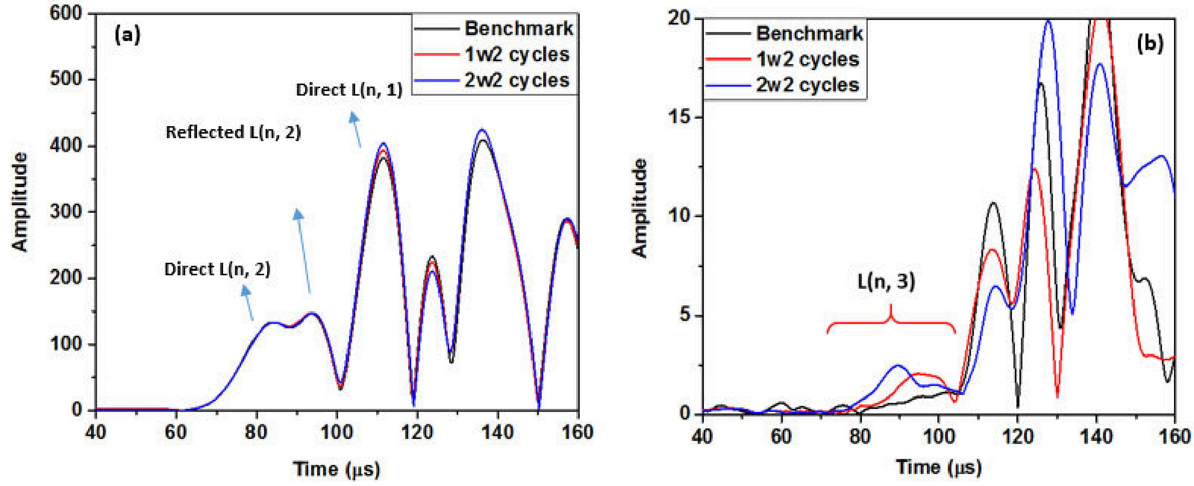


Figure 5 Reflected signal from experiment at different fatigue cycles compared with benchmark signal (a) at fundamental frequency; (b) at double frequency

4. Nonlinear index with fatigue crack growth

From the analysis of signals received in experiment, it could be observed that the nonlinearity changed with fatigue cycle. Generally, a relative nonlinear parameter $\beta'=A_2/A_1^2$ is used to measure the nonlinearity in a system, where A_1 and A_2 are the amplitudes of fundamental wave and second harmonic wave respectively [20, 21]. However, due to the multiple wave mode generation at fundamental and double frequencies and the nonlinearity is mainly from the crack breathing behaviour, the conventional relative nonlinear parameter is not suitable to evaluate the CAN in pipe structures. A proper parameter in the time domain was proposed in a previous study[16] to include all the wave packets induced by damage in order to evaluate quantitatively the nonlinearity caused by the breathing crack in the pipe. In this study, the nonlinear parameter for both transmitted and reflected signals were defined as the integral of the amplitude profile of L(n, 3) until the arrival time of L(0, 1) extracted at double frequency divided by the integral of the amplitude profile of L(n, 2) before the arrival time of L(0, 1) at the fundamental frequency.

Such a nonlinear index was calculated for all received signals in experiment under different fatigue cycles and was used as a measurement of the nonlinearity in the pipe so as to quantify the severity of the fatigue crack.

As shown in Figure 6, where the nonlinear index is curve-fitted using a fifth order polynomial function, the nonlinear index increases gradually with the fatigue cycle until about 26000 cycles and then decreases to the same level as in the benchmark. It is understood that the initiation of fatigue crack includes the accumulation of material dislocation around the notch tips and the formation of microcracks, which contribute to the increase in wave nonlinearity. It should be mentioned that at the end of the fatigue test, the crack length observed in the experiment was about 1 mm only. However, the nonlinear index in the experiment began to drop at such an early stage, indicating the breathing behaviour in practice existed only at the early stage of a fatigue crack, which would become an open crack immediately upon growing to a macro scale.

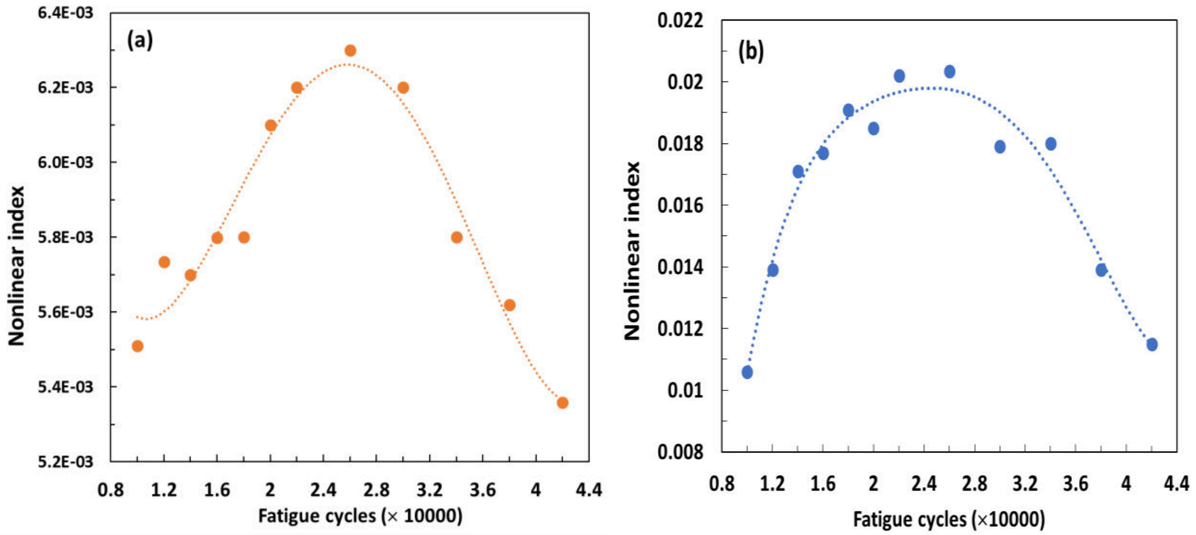


Figure 6 Nonlinear index vs fatigue cycle from experimental testing for (a) transmitted signals; (b) reflected signals

To confirm this assumption, some typical reflected signals at fundamental frequency are plotted in Figure 7, including signals at benchmark, 12000, 22000, 34000 and 42000 fatigue cycles. As evident in the figure, before 22000 fatigue cycles, there is no noticeable difference in the reflected L(0, 2). However, the reflected fundamental wave L(0, 2) clearly increases at 34000 and 42000 cycles, revealing that the crack evolves from micro to macro one and even the fundamental wave may be able to detect its existence.

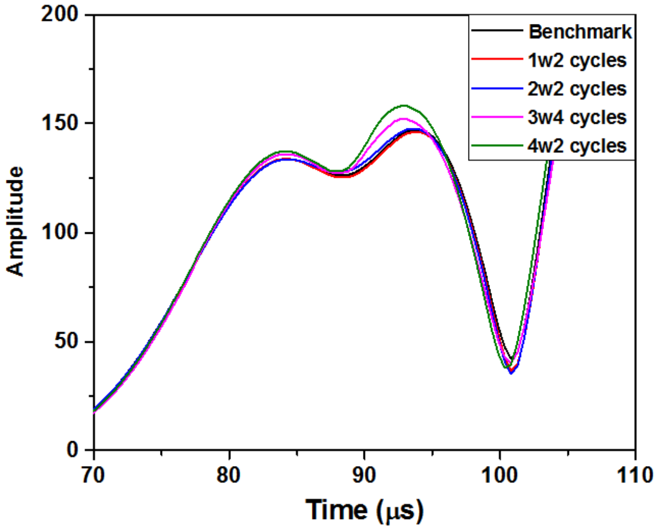


Figure 7 Reflected signals under different fatigue cycles at fundamental frequency

4. Conclusions

The relation between nonlinear guided waves and a fatigue crack in an aluminium pipe was investigated in this study with a proper nonlinear index which considers the existence of multiple modes in the pipe structure. Experimental studies were carried out with fatigue test until 42000 fatigue cycles. From the experimental results, it was found that the nonlinear index increased monotonously with crack length at the early stage because of the accumulative material dislocation around the tips of notch and increasing length of the breathing crack. The index then began to decrease at 26000 fatigue cycles with fatigue crack length shorter than 1 mm. The main reason of decrease in experiments is that the crack was involved from micro to macro scale as an open crack at early stage of fatigue. The results from this studies show that the nonlinear index can quantify the nonlinearity in a pipe structure caused by crack and it can detect the initial stage of a fatigue crack within 1 mm in practice, providing higher sensitivity than linear guided waves for microcrack detection.

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