Numerical simulation of nonlinear ultrasonic guided waves for micro-cracking detection in pipelines

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ABSTRACT: In this study, the interaction between nonlinear ultrasonic guided waves and micro-cracking in pipelines was simulated using finite element method (FEM). The numerical results indicate that after interacting with a micro-crack, the second or higher order harmonics were caused by nonlinear acoustic effects at the micro-crack. The dynamic responses of the pipe with and without a crack were studied in the time domain and frequency domain, respectively. A series of crack sizes were simulated to investigate the sensitivity of the proposed method. In addition, besides the ultrasonic guided waves, low-frequency vibration was simultaneously applied on the pipe with a micro-crack, the simulation results show that the low-frequency vibration could strengthen the higher harmonics, and that its function with respect to cracking identification was highlighted. The numerical results will provide a valuable guide for the application of nonlinear ultrasonic techniques for micro-damage detection in pipelines.

1 INTRODUCTION

Water, gas or oil infrastructures have become critical focuses where existing pipelines are ageing and therefore vulnerable to a diversity of damage, which will cause significant direct or indirect economic and social costs. Pipeline failure is likely to occur when environmental and operational stresses act upon ageing water pipes, whose structural integrity has been compromised by cracking and corrosion due to adverse condition, inadequate installation and manufacturing defects [Rizzo (2010)].

Many techniques have been implemented in the monitoring and maintenance of these pipelines with some success. Current technologies for assessing pipeline conditions are generally electromagnetic-, mechanical- or visual-based, according to the physical phenomenon being exploited, inspecting the pipeline system internally or externally [Rizzo (2010); Taghvaei et al (2007)]. In particular, ultrasonic guided waves have been widely applied to the long-range inspection and online monitoring of pipes. On the other hand, increasing attention has been focused in recent years on the application of nonlinear methods to detect the presence of defects, in particular the micro ones. Nonlinear ultrasonic behaviours include nonlinear resonance, mixed frequency response, sub-harmonics generation, and higher harmonics generation. The nonlinear technologies have been investigated to overcome the limitations of linear technologies [Abeelel et al. (2006), Ulrich et al. (2008), Jhang (2000)]. Higher harmonics generation from a micro-crack in a plate was investigated [Wan et al (2014)]. The basic physical mechanism is contact acoustic nonlinearity (CAN) [Kim et al (2006)], and it is recently attracting increasing attention regarding the characterization of closed defects or imperfect bond interfaces [Jhang (2009)]. Experimental studies on nonlinear ultrasonic techniques have been used successfully to evaluate the damage in beams or plates [Wei et al (2013), Klepka et al (2011), Pieczonka et al (2013), Su et al (2014)]. However, nonlinear ultrasonic techniques have seldom been applied yet on pipe structures for damage identification [Guo et al. (2012), Liu et al. (2013)].

In this study, FEM was adopted to simulate the interaction between nonlinear ultrasonic guided waves and a surface-breathing crack in a pipe. In addition, the pipe was simultaneously excited using a low-frequency vibration and high-frequency excitations to analyse the breathing of the crack. Dynamic responses were acquired and the Fourier analysis was applied to obtain power spectra to reveal possible mechanisms associated with crack-induced nonlinearities. This paper is organized as follows: Section 2 introduces the basic theoretical principles of higher harmonics generation through CAN. In section 3, a finite element model of the interaction between nonlinear ultrasonic guided waves and a crack is described in detail. FE simulation results are presented and discussed, and conclusions are drawn in Section 4.

2 BASIC THEORETICAL BACKGROUND

When an ultrasonic wave with large amplitude is incident to imperfect interfaces, higher harmonic waves are generated. This phenomenon is so-called as CAN, and has attracted increasing attention regarding the characterization of closed cracking or imperfect bond interfaces [Jhang (2009)].

Physically, the phenomenon of higher harmonic generation is related to nonlinearity in the elastic behavior of material, as illustrated in Fig.1. The relationship between stress σ and strain ε is nonlinear, which is called the nonlinear version of Hooke's law as shown in Eq.1 [Sutin (1996)]

$$\sigma = E\varepsilon(1+\beta\varepsilon+\gamma\varepsilon^2+\cdots) \quad (1)$$

where E is Young's modulus, and β and γ are second and third order nonlinear elastic coefficients respectively. Here, we consider a nonlinear dynamic system of the form:

$$y = Cu(1+\beta u+\gamma u+\cdots) \quad (2)$$

where u and y are the general input and output, respectively, and C is a scale factor. Consider a harmonic input:

$$u(\omega) = \bar{u}e^{j\omega t} \quad (3)$$

By substituting Eq. (3) into (2), the output takes the following form [Wan et al (2014)]:

$$y = Cu(\omega) + C\beta\bar{u}\cdot u(2\omega) + C\gamma\bar{u}^2\cdot u(3\omega) + \cdots \quad (4)$$

Eq. (4) indicates that the output of the nonlinear system contains not only the fundamental frequency ω but also higher order harmonics 2ω, 3ω… This distinctive feature makes it possible to evaluate the material degradation, assess fatigue, or detect micro-cracking that introduce nonlinearity to the specimen.

When ultrasonic waves traverse the interface between two surfaces of a micro-crack, the "breathing" motion pattern of the crack under cyclic loading closes the gap during wave compression, in which the compressional part of the waves can be transmitted. That is to say, only the compressional part of ultrasonic wave can penetrate the interface of the crack, and their tensile part cannot penetrate the interface, as shown in Fig. 2. Thus, after penetrating the interface, the waves exhibit about half-wave rectification, which means that they have obvious nonlinearity. This nonlinearity can be detected by higher harmonics.

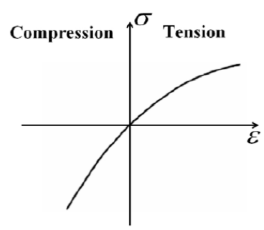

Fig.1 The nonlinear relationship between stress σ and strain ε [Jhang (2009)].

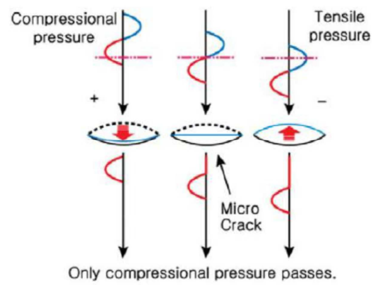

Fig. 2 Schematic diagram illustrating the concept of CAN at a micro-crack [Jhang (2009)].

3 FINITE ELEMENT MODEL

Wave propagation properties in pipes are more complicated than those in plates. The modes include a family of axially symmetric longitudinal, flexural and torsional motion of the pipe wall. The mode which was chosen for excitation in this study is the axially symmetric L(0,2) mode. This mode also gives good signal strength and demonstrates less dispersion over a long propagation distance. A tone burst of 10 cycles at a central frequency of 100 kHz in a Hanning window was adopted, as shown in Fig. 3.

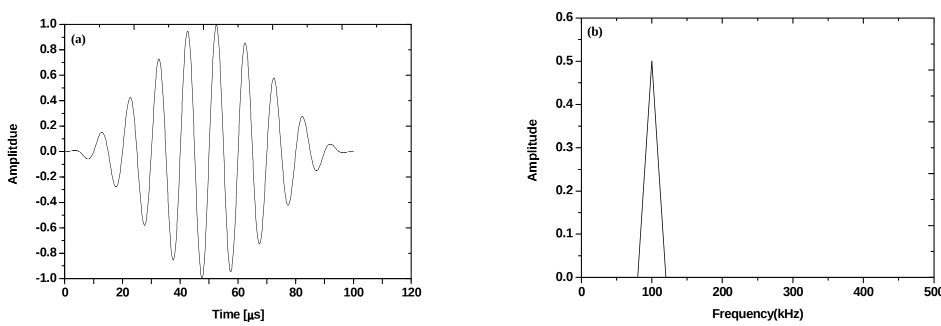

Fig. 3 Narrow band signal consisting of 10 cycles modulated by a Hanning window: (a) time domain; (b) frequency domain.

Three-dimensional FEM models were developed and dynamic simulations were performed using ABAQUS software package. The model of the pipe is shown in Fig. 4. Both ends of the tube are fixed. The dimensions of the pipe are 194 mm in outer diameter, 10 mm in wall thickness and 2000 mm in length. The pipe material is steel (density 7800 kg/m^3; Young's modulus 206 GPa, Poisson's ratio 0.28).

To obtain adequate accuracy and high efficiency, the maximum element size and time step to ensure accuracy were adopted as [Diligent et al (2002)].

$$\lambda_{\min} \geq 7\Delta x \tag{5}$$

$$\Delta t = \Delta x / v_{\max} \tag{6}$$

where, $\triangle x$ is the maximum element size, $\lambda_{\min}$ is the minimum wave length. $v_{\max}$ is the maximum wave velocity. Therefore, a mesh size of 2 mm and a time step of 0.1 μs are sufficient to ensure the accuracy. The pipe was meshed into 1525000 solid C3D8R elements.

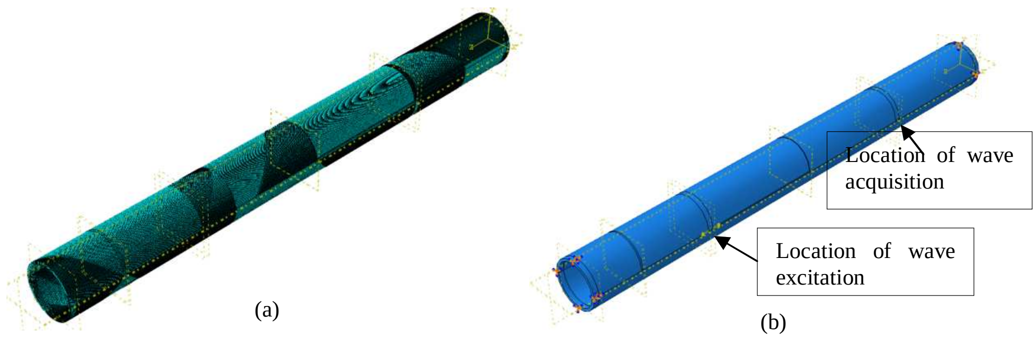

Fig. 4 The FEM model of a pipe: (a) the meshed model, (b) the boundary condition.

3.1 Results

The pipe was then excited at the location as indicated in Fig. 4 by ultrasonic guided waves at a high frequency of 100 kHz. Configuration of cracking in the pipe was shown in Fig. 5. The signals acquired at the location indicated in Fig. 4 from the pipe with and without a cracking were analysed in time domain and frequency domain, respectively. It is noteworthy that the seam or notch is not positioned in the middle of the actuator-sensor path in Fig. 5(a) whereas the 5mm long seam in Fig. 5(b) is.

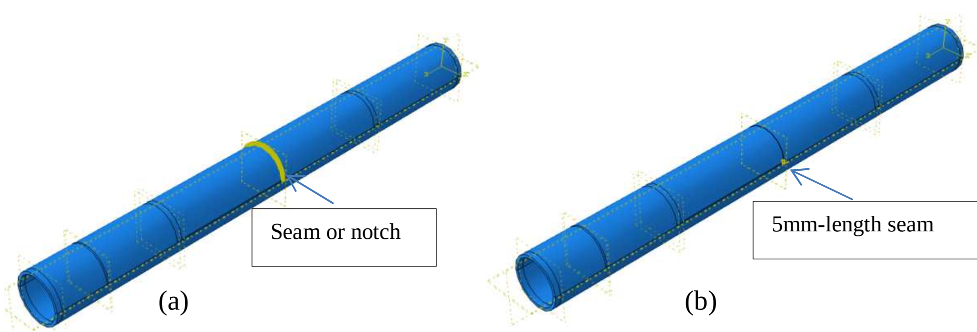

Fig.5 Configuration of a cracking in the pipe.

(1) When the crack is a through-thickness notch with 2mm in width, and its length is half of the circumference, the signals from the pipe were shown in Fig. 6. It can be seen that there are distinctive differences in the signals between the notched pipe and intact one. A method based on linear ultrasonic guided waves is easy to detect the notch. In addition, Fourier spectrum analysis revealed that there is no higher harmonic wave mode generated in the undamaged pipe and the pipe with a notch;

(2) When the crack is a through-thickness seam with zero-width, and its length is half of the circumference, the signals from the pipe were described in Fig.7. It can be shown that there are still certain difference in the signals between the damaged pipe and intact one. As indicated in Fig. 7(b), three amplitude peaks were noticed around 97.99 kHz, 194.98

kHz and 294.97 kHz for the damaged pipe. Because the excitation frequency was centred at 100 kHz, the peak at 97.99 kHz corresponded to the amplitude of the fundamental frequency component, while the other peaks are corresponding to the amplitudes of the second and the third harmonic components.

(3) When the crack is a through-thickness seam with zero-width, and its length is 5mm, the dynamic responses were described in Fig.8. It can be seen that the signals are very similar between the damaged pipe and intact one. However, the Fourier spectrum analysis confirmed that the signal received from the micro-cracked pipe contained a second harmonic component, which was introduced by the micro-crack, although the phenomenon is less obvious when the crack length becomes shorter. The micro-crack which cannot be easily detected using linear ultrasonic guided waves is therefore highlighted by the nonlinear ultrasonic technique.

In comparison with the first and second cases, it is understood that the amplitude of ultrasonic waves is smaller than the distance between two surfaces of the notch with a width of 2mm. As a result, no wave can transmit directly through the notch and the waves would show linear properties only. On the other hand, when the second case is compared with the third one, it can be observed that the longer the micro-crack, the larger the amplitude of the second harmonic component, indicating the increase in acoustic nonlinearity. The presence of second harmonic components can therefore be used as an indicator to detect and identify the existence of a micro-crack in a pipe. These simulation results are in accordance with the simulation results reported by Soshu et al (2006), who used nonlinear Lamb waves to detect a closed crack in a thin plate, where the CAN effect was detected by high harmonics which increased with the length of the micro-crack.

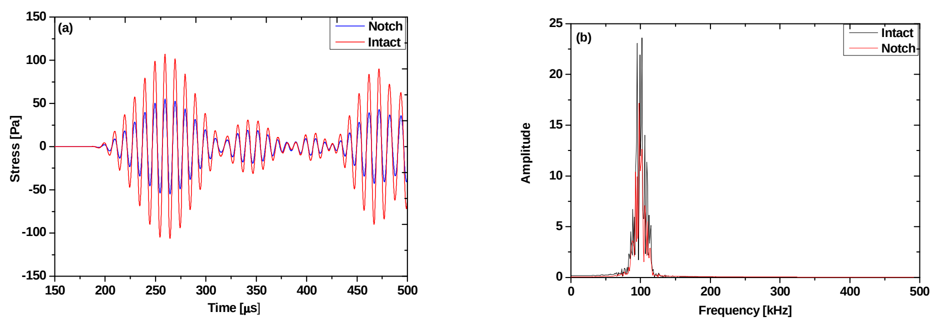

Fig.6 Signals from the pipes: (a) time domain; (b) frequency domain.

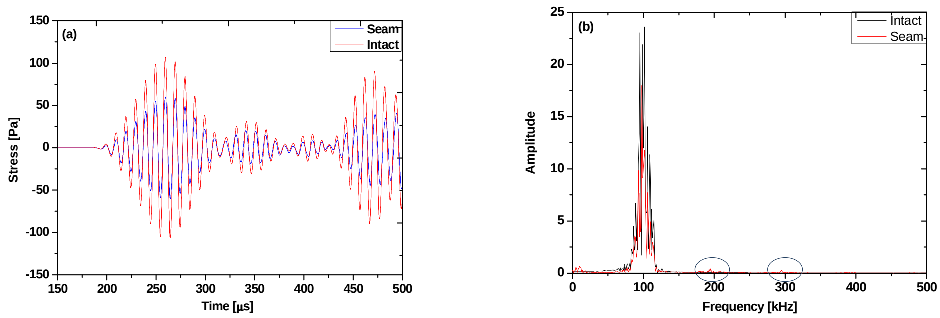

Fig. 7 Signals from the pipes: (a) time domain; (b) frequency domain.

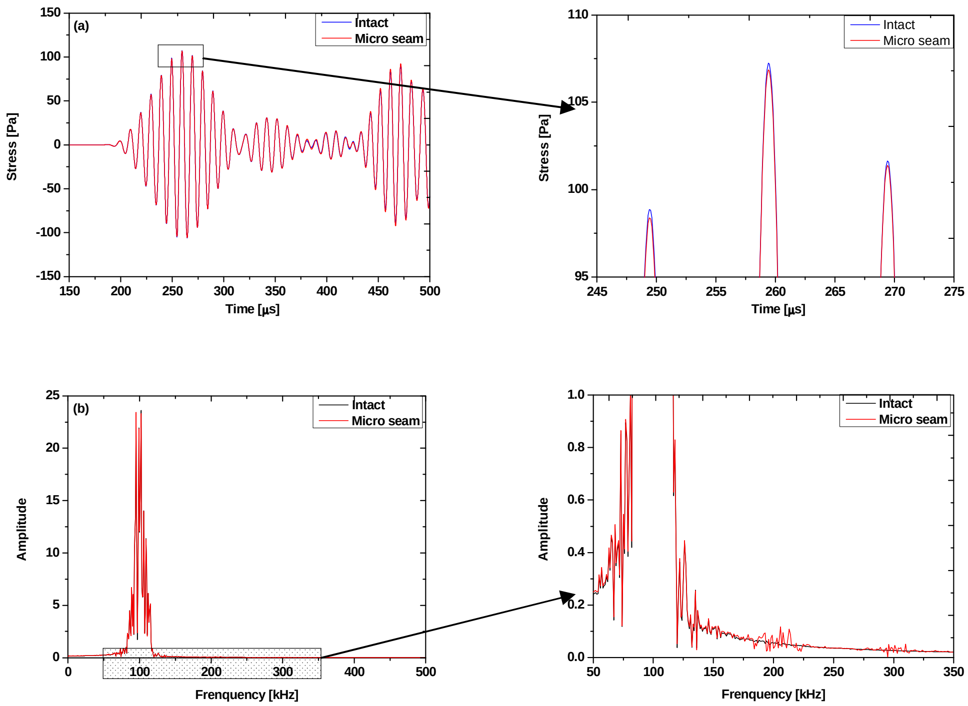

Fig. 8 Signals from the pipes: (a) time domain; (b) frequency domain.

3.2 Discussion

As observed, the second harmonic generation will be less obvious when the length of a micro-crack is quite marginal. However, when a low-frequency vibration was simultaneously applied at the pipe with the existence of a micro-crack, it is noticed that such an effect would be enhanced. In this study, a vibration with appreciable stress at 272 Hz, which is the first order resonant frequency, can cause the “breathing” of the micro-crack as well which can be recoganised another source of wave nonlinearity. Thus, when ultrasonic waves reach an imperfect contact interface, in addition to the nonlinearity caused by itself, where the compressional part of the waves that can transmit through it only, the existence of vibration can yield further nonlinearity in the collected waves. It can be seen from Fig. 9 that the second harmonic component becomes relatively apparent. It is appreciated that an applied low-frequency vibration signal changes the width of a crack depending on the compression and tension phases of the vibration. When a high-frequency signal is simultaneously applied to the crack, the interaction between the high-frequency ultrasonic waves and the crack would be significantly influenced by the different phases of the low-frequency vibration, where the high-frequency signal may be partially decoupled by the open crack during the tension phase of the low-frequency signal. In this case, even the compressional part of the ultrasonic waves cannot transmit through the crack. This is known as nonlinear acoustic vibro-modulation effect. It can be observed that there are more side lobes in Fig. 9 than in Fig. 8 at the high frequency of 100 kHz.

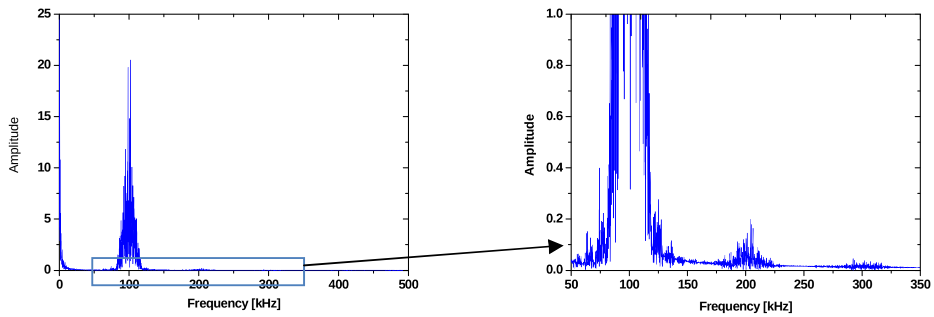

Fig.9 Frequency domain signals from the pipes with the existence of vibration signal.

4 CONCLUSIONS

The interaction between nonlinear ultrasonic guided waves and a micro-crack in a pipe was simulated using FEM, where the simulations of an intact pipe and a pipe with a crack of different sizes were conducted respectively.

The simulation results showed that the width and length of micro-crack in a pipe will have significant influence on acoustic nonlinearity. Fourier spectrum analysis revealed no higher harmonic component was identified in the undamaged pipe. However, second or higher harmonics introduced by CAN for the case of a micro-crack was clearly observed from the pipe with a micro-crack. In addition, when low-frequency vibration was simultaneously applied at the pipe with a micro-crack, the simulation results show that the low-frequency vibration could enhance the higher harmonics and highlight cracking identification. The simulation results in this study would provide a valuable basis for the application of nonlinear ultrasonic techniques for practical micro-cracking detection in pipelines generated by fatigue etc., which will be the focus of future work.

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