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Numerical simulation of micro-crack identification in pipes with nonlinear guided waves

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ABSTRACT: Pipelines are crucial infrastructure and in-service pipelines are suffering from a variety of damage caused by corrosion, aging or impact. It is of vital importance to inspect the defects before they deteriorate. Recently, nonlinear guided wave technique has driven a lot of attention for the inspection of micro breathing crack at its early age, such as fatigue crack, which is difficult to detect with conventional linear guided wave technique. Nonlinear ultrasonic guided waves have shown great capability using nonlinear ultrasonic behaviour including higher-harmonic generation, sub-harmonic generation, nonlinear resonance or mixed frequency response. These approaches have been studied in plate-like structures by many researchers. However, limited studies were found for pipe structures due to more complex wave modes than those in plate-like structures. In this study, the interaction between nonlinear guided waves and the breathing cracking was numerically simulated for the investigation of mix frequency response and second harmonic generation. The results showed that with proper selection of the excitation wave mode and frequency, both of these two methods can detect the damage efficiently. In particular, a periodic increase in the nonlinear parameters in terms of crack length was observed for the second harmonic generation method.

1 INTRODUCTIN

Guided wave inspection is an attractive and cost-effective technique for pipeline inspection, since guided waves can propagate over a long distance underneath insulation and can be excited and received by transducers at locations where only a small part of insulation needs to be removed. Many studies have been conducted for the pipeline inspection with guided wave technique successfully [Demma, et al. (2004); Løvstad and Cawley (2012); Wang, et al. (2010)]. Recently, nonlinear guided wave technique has driven a lot of attention for the inspection of micro crack at its early age, which shows higher sensitivity compared with conventional linear guided wave technique. Many studies have been conducted with this technique in plate-like structures [Aymerich and Staszewski (2010); Klepka, et al. (2012); Sohn, et al. (2013)]. However, due to the curvature of the surface of pipelines, as well as the inherent properties of guided waves such as dispersion, attenuation and boundary reflection, guided wave modes in pipe structures are generally more complex than those in plate-like structures. Thus, interpretation of the received signal for pipe inspection is always difficult. For nonlinear inspection with higher harmonic technique, a group of studies have been carried out experimentally for thermal fatigue damage assessment in an isotropic pipe utilising the cumulative effect of second harmonic due to material nonlinearity [Li and Cho (2014)]. While there is less study in pipeline inspection for the application of nonlinearity caused by local damage such as fatigue crack known as contact acoustic nonlinearity (CAN). Some experiments with mixed frequency response method have been undertaken to detect the micro cracks in pipelines [Donskoy and Sutin (1998); Jiao, et al. (2011)]. However, a few numerical analysis was carried out for mixed frequency response or higher harmonic generation methods in pipelines.

In this study, finite element method was used to investigate the nonlinear guided waves for the identification of micro-crack in a steel pipe. The theoretical background was first introduced in Section 2, followed by the numerical analysis including both mixed frequency response and higher harmonic generation methods in Section 3. Finally, the conclusion was presented in Section 4.

2 THEORITICAL BACKGROUNDS

2.1 Contact acoustic nonlinearity (CAN)

CAN occurs when ultrasonic waves pass through the interface between two surfaces of a micro-crack. As the incident wave approaches a contact interface, the compressional and tensile parts will cause the closing and opening of the crack, which induces the localised nonlinearity. A popular model for CAN was called bi-linear stiffness model [Solodov, et al. (2010)]. It had different stiffness under compression and tensile phases of a wave and the crack became similar to a "mechanical diode" (Figure 1(a)). The stress-strain relation can be expressed as

$$\sigma = C^{II}\left[1 - H(\varepsilon - \varepsilon^0)\left(\frac{\Delta C}{C^{II}}\right)\right]\varepsilon, \quad (1)$$

where $H(\varepsilon)$ stands for the Heaviside unit step function, ε^0 represents the initial contact strain, C^{II} is the intact second-order linear elasticity of material and $\Delta C = \left[C^{II} - \left(\frac{d\sigma}{d\varepsilon}\right)_{\varepsilon>0}\right]$.

If the input strain was $\varepsilon(t) = \varepsilon_0 \cos\omega_0 t$, it would lead to a modulation of stiffness C(t) (Figure 1(b)) and the nonlinear part in the spectrum contained a number of higher harmonics whose amplitudes were modulated by a sinc-envelope function (Solodov, et al. 2010), as shown in Figure 1(c).

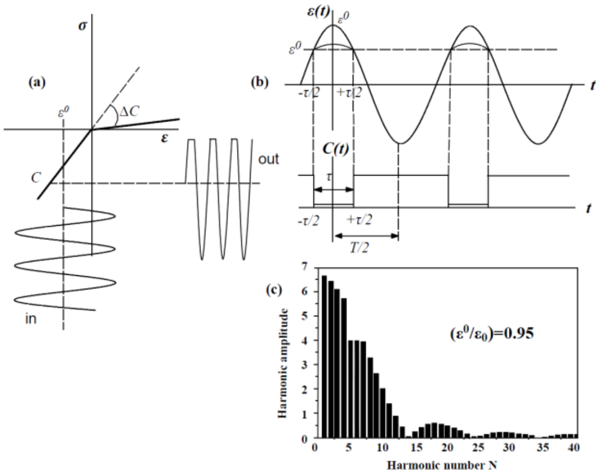

Figure 1 (a) Mechanical-diode" effect; (b) modulation of C(t); (c) high harmonic spectrum (Solodov, et al. 2010).

2.2 Methods for evaluation

To evaluate the nonlinearity caused by the micro-crack, two different methods were used in this study: (1) mixed frequency response and (2) second harmonic generation.

Mixed frequency response uses a low-frequency hammer impact or vibration or wave (pumping signal) with frequency f1 and a high-frequency wave (probing signal) with frequency f2 excited simultaneously in the investigated structure. The output signal perceives modulated sidebands with frequency (f2±f1) around the input high frequency if there is nonlinearity in the structure. Usually, the severity of the damage can be evaluated by a modulation index (MI) in comparison with the baseline data. One of the most commonly used damage indices is [Pieczonka, et al. 2016)]

$$\mathrm{MI} = \frac{\sum_{i=1}^{n}\left(A_{LSB}^{i}+A_{RSB}^{i}\right)}{A_{HF}}, \quad (2)$$

where A_{LSB}^{i} and A_{RSB}^{i} are the amplitudes of i^{th} pair of left and right modulation sidebands and A_{HF} is the amplitude of high-frequency component of the probing signal.

On the other hand, after the wave interacts with the breathing crack, the output signal will contain higher harmonics. Such a nonlinearity can be explained by two physical mechanisms, i.e. classical nonlinear elasticity and CAN [Jhang (2009)], which was mainly considered. The nonlinear parameter β is used to describe this type of nonlinearity [Brillouin (1964); Murnaghan (1937)]:

$$\beta = \frac{8}{k^2 x}\frac{A_2}{{A_1}^2}, \quad (3)$$

where A_1 is the amplitude of the fundamental frequency; A_2 is the amplitude of the second harmonic; x represents the propagation distance and k is the wavenumber of the wave at the fundamental frequency.

To obtain a strong cumulative second harmonic, two conditions must be satisfied for above two methods [Liu, et al. (2013); Liu, et al. (2014a); Liu, et al. (2014b)]: 1) synchronism 2) non-zero power flux. Furthermore, for the mixed frequency response method, apart from two criteria above, when two waves are excited for the modulation, the signals must arrive at the crack simultaneously [Lim, et al. (2014)].

3 SIMULATION STUDY

3.1 Numerical analysis for acoustic and ultrasonic modulation

3.1.1 Simulation model

A steel pipe with 194 mm in outer diameter, 10 mm in wall thickness and 2 m in length was simulated with Abaqus/Explicit 6.14. The density is 7800 kg/m^3 while Young's Modulus and Poisson's ratio is 206 GPa and 0.28, respectively.

The maximal element size was defined as small enough to be comparable with the smallest wavelength of the wave that exists in the computation domain. Also, the time step was short enough to meet the convergence criterion. The maximum element size and minimum time step Δt were therefore calculated by [Diligent, et al. (2002)]

$$L_{max} \leq \frac{\lambda_{min}}{7} \quad (4)$$

$$\Delta t \leq \frac{L_{max}}{c_g} \quad (5)$$

where λ_{min} is the shortest wavelength of any waves which may travel in the structure, and L_{max} is the largest element size in the model; c_g is the fastest group velocity of the wave. As a result, the maximum element size is taken as 2 mm and the minimum time step is $1 \times 10^{-7} s$.

The frequency input was determined based on the criterion mentioned in Section 2.2 and selected from dispersion curves. The high frequency input was 100 kHz, while the low frequency input was 10 kHz. Both of them were L(0, 2) longitudinal wave mode. Two input signals were combined together and excited at same location as shown in Figure 2. They were put at the same location since two input waves had similar group velocity. The actuator was simulated with the same dimension (20 mm by 5 mm) of the real piezoelectric lead zirconate titanate element (PZT) to be used in the experimental verification in future. The sources were generated as point load applied at the short edge of the actuator along the axial direction of the pipe to simulate the longitudinal wave. Different durations of the input signal was applied to see their effects on modulations, including 1 ms, 0.5 ms, 0.2 ms and 0.1 ms. All the input signals were tone burst signals and for example, the input signals for 1 ms are shown in Figure 3.

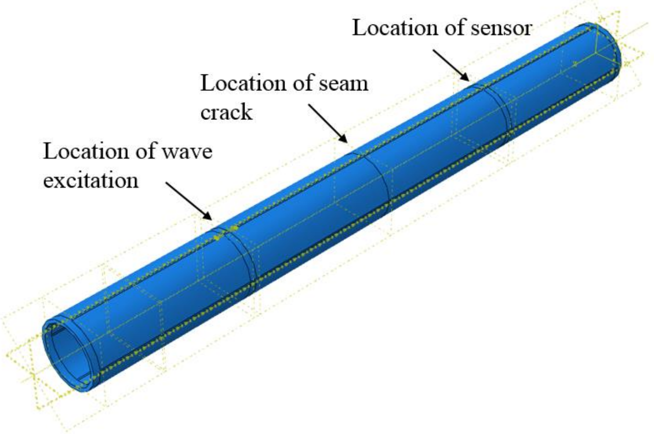

Figure 2 Location of actuator and sensor.

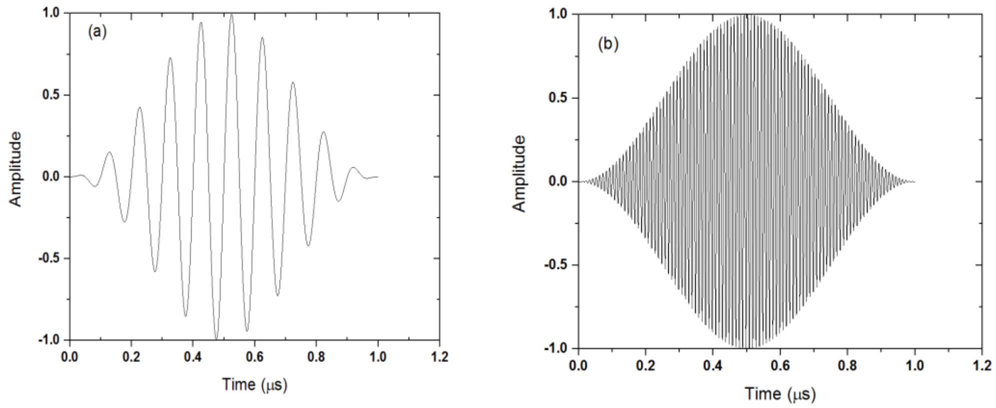

Figure 3 Input signal: (a) 1 ms (10 cycles) 10 kHz tone burst signal (b) 1 ms (100 cycles) 100 kHz tone burst signal.

To model a micro breathing crack in the pipe, a seam crack definition was used on each surface of the crack, to enable the breathing behavior when waves interacted with the crack [Hong, et al. (2014)]. Meanwhile, a surface to surface contact interaction and associated properties were defined on the crack interface to achieve the modeling of CAN. The crack was through wall thickness and 5 mm in length in the circumferential direction, located at the middle of the pipe (Figure 2).

3.1.2 Results

For the received signal in time domain, there is no big difference between the damaged specimen and the benchmark whatever the duration of input signals, as shown in Figure 4 for the case of 1 ms cycles. However, in the frequency domain, when the input signal was shorter (0.2 ms), the sidebands disappeared beside the main frequency component (Figure 5). And the modulation indices for the first three cases are 0.0204, 0.0146 and 0.0121 respectively. This may because the longer interaction time between the input signals, the higher the energy of modulation. And also, the longer duration of the input signal, the narrower bandwidth of it.

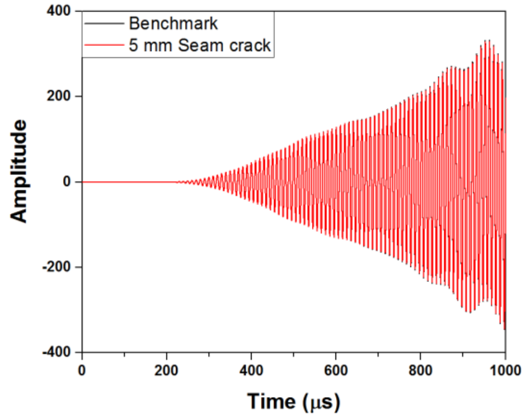

Figure 4 Received signal in the time domain for 1 ms input signal case.

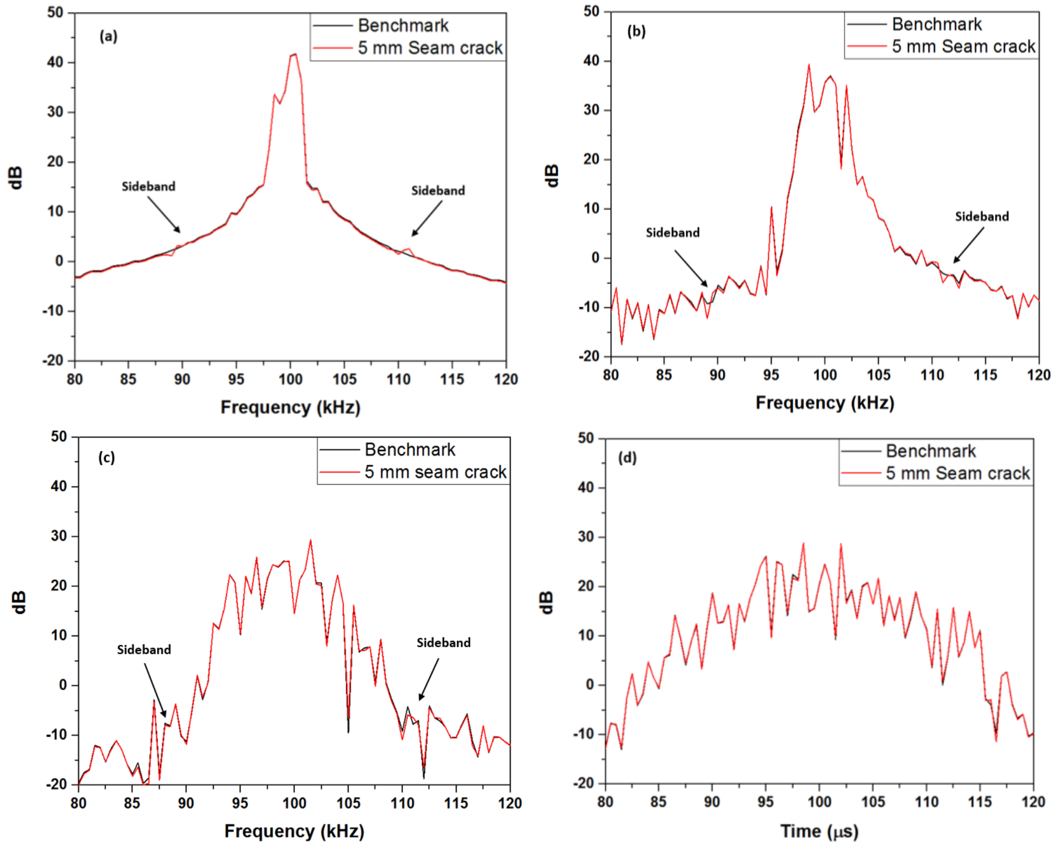

Figure 5 Received signal in the frequency domain (a) 1 ms input (b) 0.5 ms input (c) 0.2 ms input and (d) 0.1 ms input.

Thus, to use mix frequency response method, the input signal should be long and stable to generate the sidebands, which however is not suitable to extract the time information in the time domain and to locate the damage location. In contrast, it is noted that as shown in Figure 6 for the first case, the second harmonic is more obvious than the sidebands. Therefore, second harmonic generation method was used to detect the severity of the CAN in the next section.

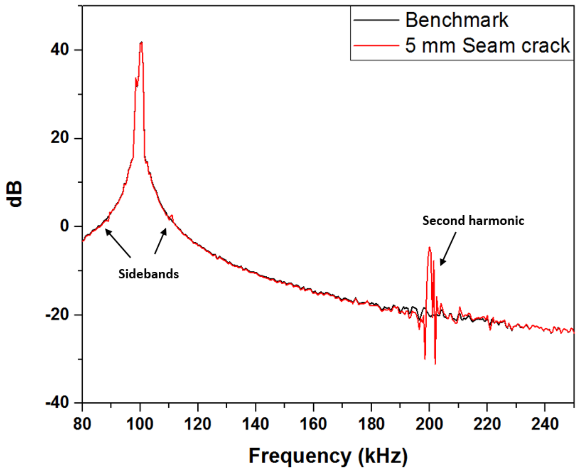

Figure 6 Received signal in the frequency domain with 1 ms input.

3.2 Numerical analysis for higher harmonic generation method

3.2.1 Simulation model

Another pipe model with 101.6 mm in outer diameter, 5.74 mm in wall thickness and 1 m in length was used. The material properties of the pipe and simulation method for the crack were same with Section 2.3.1. The maximum element size and minimum time step were selected as 0.5 mm and 5×10^{-8} based on Equations 4 and 5. With the criterion mentioned before, L(0, 4) and L(0, 5) modes were selected as the fundamental and secondary wave mode, and 0.71 MHz was the fundamental frequency. The wave was excited as a 15.5-cycle tone burst signal at one end of the pipe and both the transmitted and reflected signals were received. The location of crack, actuator and sensors are in Figure 7. It had a through thickness crack with zero width and variable length changing from 1 mm to 14 mm for the quantitative analysis of the nonlinear parameter in terms of crack length.

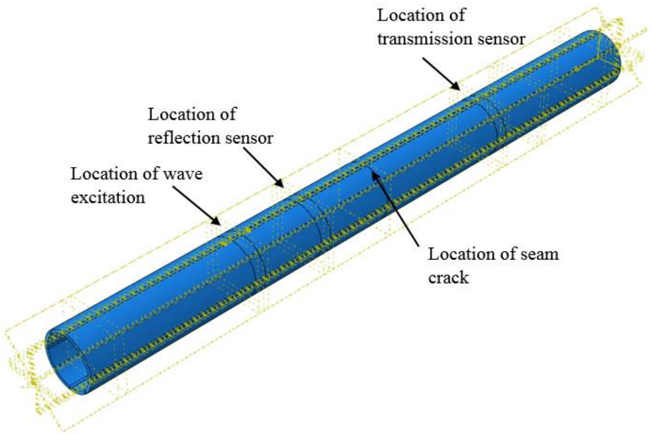

Figure 7 Simulation model of the steel pipe and the locations of actuator and sensors.

3.2.2 Results

The transmitted signal for the case of 5 mm seam crack is shown in Figure 8 presented by the stress in axial direction compared with the benchmark in which no micro crack is induced. There is no big difference between the current and benchmark signals in time domain. After a fast Fourier transform (FFT), it is clearly observed that for the damaged pipe in the frequency domain, there are both fundamental and second frequency components at 0.71 MHz and 1.42 MHz respectively. While for the benchmark signal, only component at fundamental frequency exists.

To quantify the relation between nonlinear parameter and the crack length, all the transmitted and reflected signals were processed with FFT and a relative nonlinear parameter $\beta' = \frac{A_2}{A_1{}^2}$ was calculated and plotted with crack length (Figure 9) where the horizontal axis is the ratio of crack length to wavelength of L(0, 4).

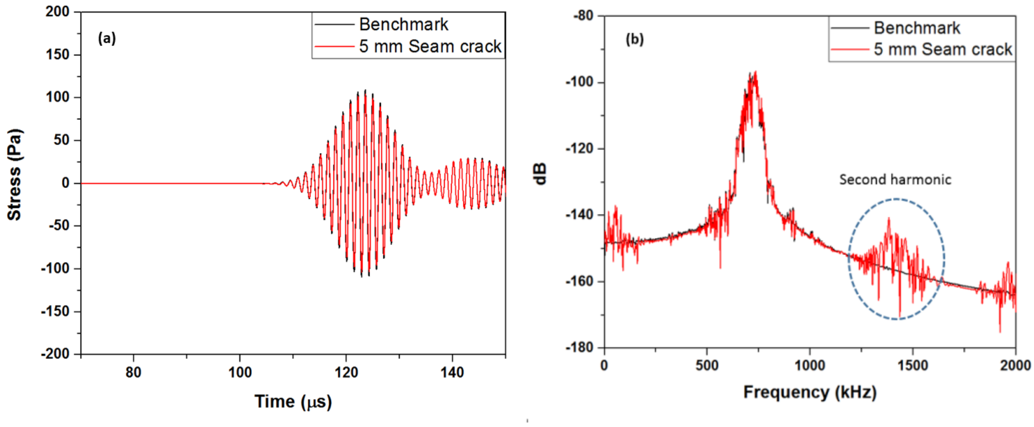

Figure 8 Transmitted signal in (a) time domain and (b) frequency domain

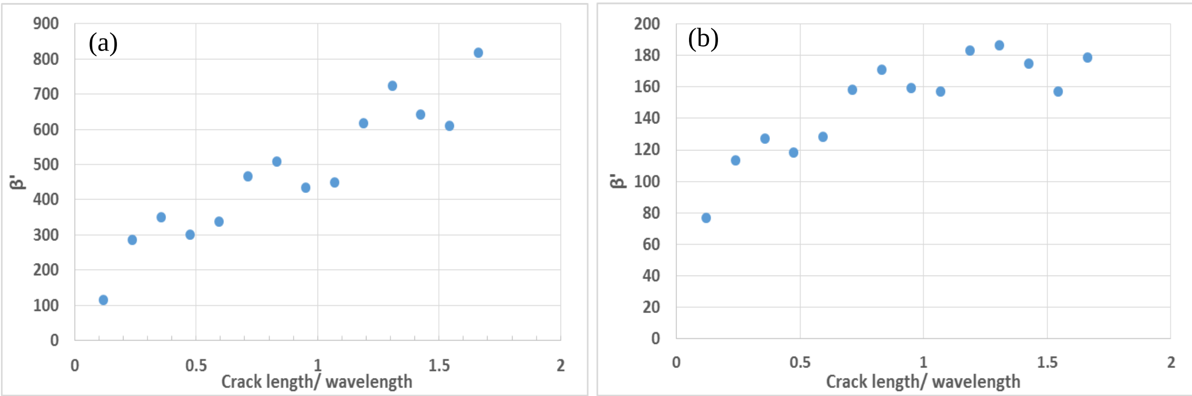

Figure 9 Nonlinear parameter β' in terms of crack length for (a) transmitted signal and (b) reflected signal.

It can be seen from the figure that the nonlinear parameter increases periodically with the length of crack. It seems that β' reaches minimum values when the crack length is at around 0.5n (n=1, 2…) of wavelength and the maximum values are around 0.3+0.5n (n=1, 2..) of the ratio of crack length to wavelength. The results are different compared with a similar study in aluminium plate [Wang and Su (2016)], in which the relation is nearly increasing monotonously. This may be because of the curvature of the pipe and the multi-paths of wave propagation in a pipe structure. Future work will focus on theoretical analysis and experimental verification.

4 CONCLUSION

This study used a finite element model to simulate the nonlinear guided wave propagation and interaction with the micro-crack for its identification with mixed frequency response and second harmonic generation methods. The quantitative relation of nonlinear parameter and the crack length was also analysed with second harmonic generation method. The results showed that both two methods can detect the crack with appropriate selection of wave mode and input frequency, and the relative nonlinear parameter increases periodically with the crack length, which was different to the results of plate-like structures, worthy of further analysis.

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