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Research on Three-dimensional Information Acquisition of Changes in the Pipe Cross Section based on Circumferential Scanning and Phase Characteristics

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ABSTRACT

The pipelines are commonly existing in the oil, gas and chemical industry. Ultrasonic guided wave with large-scale and long-distance detection capacity is extensively used for the nondestructive testing of all kinds of pipelines. In the past the majority of published works on the reflection from defects have been done mainly by studying amplitude characteristics of reflection coefficient. Phase characteristics is one of the most important relationships between an incident wave and its reflection wave in inspecting pipelines. From the standpoint of reflection coefficient and acoustic impedance, the phase characteristics are investigated by theoretical analysis in this paper firstly. Then a method based on the phase characteristics of guided wave is proposed for pipes inspection, and its stability and validity are verified by numerical experiments, and the fundamental torsional mode T(0, 1) interacting with rectangular notches with different geometries in pipes are carried out in finite element software ABAQUS. By calculating the similarity coefficient of guided-wave reflection signals and reference signals, the types of the defects can be confirmed and recognized, and the results including circumferential information of the pipes are visualized by guided-wave B-scan imaging technique. The research has important value in engineering application and the proposed method provides a new research perspective for the detection and characterization of defects in pipelines.

Keywords: phase characteristics, ultrasonic guided wave, NDT, acoustic impedance

1. INTRODUCTION

Ultrasonic guided wave technique is current in routine use for nondestructive testing (NDT) and structure health monitoring (SHM) of the oil, gas, chemical and petro-chemical industries [1]. In the past few years, its application in inspecting pipeline are mainly focus on researches of guided wave propagation characteristics, the inspection systems and special transducers [2-5]. With respect to the propagation characteristics of guided wave in different mediums, many researchers [6-8] have investigated them by studying the amplitude of reflection coefficient (RC). In fact, the interactions of guided wave with different shapes in pipes not only accompany the variation of amplitude of the RC also lead to the variation of phases of the RC. The amplitude parameters of the RC are usually used to quantify the defects, and the phase can be utilized to determine the types of the defects. However, research on the later issue is relatively little.

2. The proposed method based on phase characteristics for inspecting pipes

2.1 Phase Characteristics of Guided Wave from a Rectangular Notch

Guided wave propagated in a pipe is similar to the plane wave when its wavelength is very much bigger than thickness of the pipe. During the propagation along the pipe, it will reflect when encountering with the interface of different acoustic impedance. The acoustic pressure of incident wave, reflection wave and transmission wave are defined as the following form of simple harmonic waves respectively.

$$\begin{cases} p_i = \mathrm{P}_{i0}\exp(i(\omega t - kx)) \\ p_r = P_{r0}\exp(i(\omega t + kx)) \\ p_t = P_{t0}\exp(i(\omega t - kx)) \end{cases} \quad (1)$$

According to the relationship between sound pressure and acoustic impedance [9], the corresponding particle velocities can be depicted as:

$$\begin{cases} v_i = {P_{i0}}/{\rho c}\exp(i(\omega t - kx)) = \mathrm{A}\exp(i(\omega t - kx)) \\ v_r = -{P_{r0}}/{\rho c}\exp(i(\omega t + kx)) = B\exp(i(\omega t + kx)) \\ v_t = {P_{t0}}/{\rho c}\exp(i(\omega t - kx)) = \mathrm{C}\exp(i(\omega t - kx)) \end{cases} \quad (2)$$

Where ρ is the density of the pipe, c is acoustic velocity. Considering the boundary condition should be continuous at the interface, namely the sound pressure and volume velocity are continuous as Eq. (3).

$$\begin{cases} p_i(0) + p_r(0) = p_t(0) \\ s_1 \times (v_i(0) + v_r(0)) = s_2 \times v_t(0) \end{cases} \quad (3)$$

Where S_1 and S_2 are the cross-sectional area of the pipe at the front and back edges of the interface respectively. Further assumed $s = {s_1}/{s_2}$,we get the RC:

$$\mathrm{RC} = {\mathrm{P}_{r0}}/{P_{i0}} = \frac{s-1}{s+1} = R_e + \mathrm{j}I_m \quad (4)$$

Where R_e and I_m are the real and imaginary parts of RC.

Therefore, the impedance angle and module of RC are calculated respectively as:

$$|\theta| = |\arctan(I_m/R_e)| = |\theta_{\mathrm{Re}} - \theta_{\mathrm{In}}| \quad (5)$$
$$|\mathrm{RC}| = \sqrt{I_m^{\ 2} + R_e^{\ 2}}$$

θ_{In} and θ_{Re} are phases of incident wave and reflection wave respectively. The phase characteristics of guided wave reflected from a rectangular notch can be obtained as follows:

(a) If $s_1 < s_2$, namely $RC < 0$, so $|\theta| = |\arctan(I_m/R_e)| = |\theta_{\mathrm{Re}} - \theta_{\mathrm{In}}| =$ (2k-1) π, k=1,2,..,n.

(b) Similarly, if $s_1 > s_2$, namely $RC > 0$, so $|\theta| = |\arctan(I_m/R_e)| = |\theta_{\mathrm{Re}} - \theta_{\mathrm{In}}| = 2\mathrm{k}\pi$, k=0,1,..,n.

(c) If $s_1 = s_2$, RC=0, this indicates there is no reflection at the interface.

(d) If $s_1 \gg s_2$ or $s_1 \ll s_2$, this means the incident wave would reflect totally.

2.2 The proposed method

A method based on the above phase relationship is proposed for pipes inspection. By calculating the similarity coefficient (here we choose Pearson correlation coefficient depicted in Eq. (6) as the similarity coefficient) of guided-wave reflection signals and reference signals (incident wave signals) to obtain the phases.

$$r(X_{in}, Y_{ref}) = \frac{\mathrm{cov}(X_{in}, Y_{ref})}{\sigma_{X_{in}}, \sigma_{Y_{ref}}} \quad (6)$$

Where cov(X_{in}, Y_{ref}) and σ are covariance and standard deviation of guided wave signal X_{in} and reference signal Y_{ref}. Then the types of defects can be recognized according to $r(X_{in}, Y_{ref})$, finally the results are visualized by guided-wave B-scan imaging technique.

3. RESULTS AND DISCUSSION

In this section, the phase characteristics are investigated by simulating the propagation and reflection of guided wave in sample pipes with different notches. The three-dimensional solid and finite element model of the sample pipes were constructed in ABAQUS. Based on reference [10], we choose the fundamental torsional mode T(0,1) as the inspection mode. To observe the changes of the phases and waveforms of guide waves clearly, Gabor pulse signals with good time-frequency localization was set as the exciting pulse wave:

$$g_{Gr}(t) = \exp^{-(t-\mu)^2/2\sigma^2} \cos\left(2\pi f_c (t-\mu) + \theta\right) \quad (7)$$

Where σ, μ, f_c and θ represent the width of the pulse, time shift, center frequency and phase, respectively.

3.1 Finite element model

As the three-dimensional schematic diagram shown in Fig. 1, a sample pipe with inner radius D and outer radius r is in length of L. The notch region, located in S=0.6m, is characterized by the parameters of the axial length N=0.2m, radial depth M and circumferential extent α respectively. Circumferential grid nodes on one end of the pipe are chosen as the excitation nodes, and later the T(0,1) are excited by loading the exciting pulse wave on the excitation nodes. Receiving nodes of guided wave are P=0.4m distance from the end.

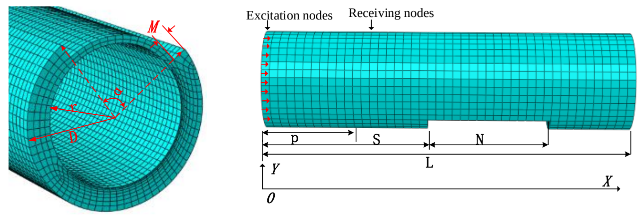

FIGURE 1: Schematic illustration of the finite element modeling of the sample pipe

Three cases depicted in Tab.1 are investigated by the T(0,1) exciting with a single cycle Gabor pulse of f_c= 38 kHz and 48 kHz, respectively. And the results are presented and discussed below.

Tab.1 Geometrical and Physical Parameters of the Sample Pipe

	Outer radius (D)/mm	Inner radius (r)/mm	Circumferential extent/rad	Axial length (N)/mm	Thickness (m) /mm	Length (L)/mm	Length (S)/mm	Density Kg/m^3	Distance (P) /m	Poisson's ratio	Young's modulus /GPa
Case 1	12	10	pi 2pi/3	200	1	2000	600	7800	0.4	0.28	210
Case 2	12	10	pi 2pi/3	200	2	2000	600	7800	0.4	0.28	210
Case 3	12	10				1000		7800	0.6	0.28	210

Case 1: ***Part-thickness rectangular notch***

The geometrical and physical parameters of the steel pipe used in case 1 are shown in Tab. 1. Based on the wave structural characteristics of the torsional guided wave mode [10], the T(0,1) are generated by uniformly applying the Gabor pulse with parameters (σ, μ, θ, f_c)= (3.6e-5s, 5.67e-6s, $\pi/2$ rad, 38 kHz), (3.6e-5s, 4.67e-6s, $\pi/2$ rad, 48 kHz) depicted in Eq. (7) on the excitation nodes in ABAQUS, and the incident and reflection wave signals obtained by the receiving nodes are shown in Fig. 2. It is obvious that the waveforms and phases of incident waves are in the same phase with the reflection from the front edge of the notch but in the opposite with the reflection from the back edge of the notch.

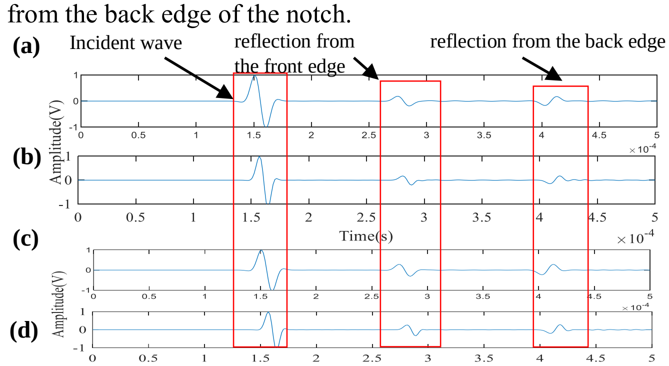

FIGURE 2: Incident wave with varying frequencies and reflection from different notches (a) $\alpha=\pi$rad and f_c=38kHz; (b) $\alpha=\pi$rad and f_c=48kHz; (c) $\alpha=2\pi/3$ rad and f_c=38kHz ; (d) $\alpha=2\pi/3$ rad and f_c=48kHz ;

Case 2: ***through-thickness rectangular notch***

Similarly, the 3D finite element model is constructed in ABQUS according to the parameters of the case 2 shown in Tab. 1. The phase characteristics of reflection from front and back edges of the notch match well with the theoretical analysis shown in Fig. 3.

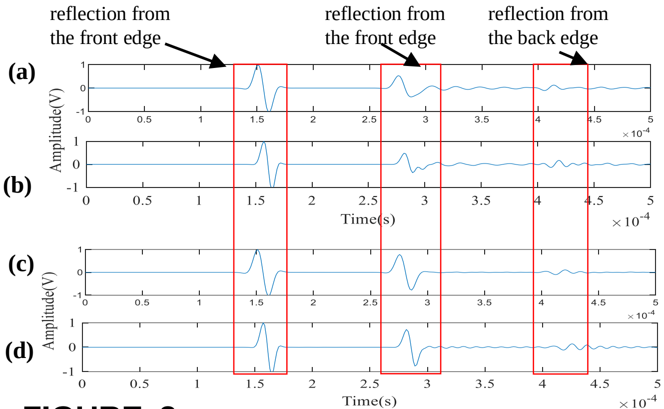

FIGURE 3: Incident wave with varying frequencies and reflection from different notches (a) and f_c=38kHz; (b) and f_c=48kHz; (c) and f_c=38kHz ; (d) and f_c=48kHz ;

Case 3: ***Interaction with an end of a pipe***

The end of a pipe is very important geometrical feature, guided wave will reflect totally when encountering with it. Therefore, the reflection from an end are usually of more energy and amplitude, which have important value in the analysis of reflection signals. After simulation in ABAQUS, Fig. 4 shows the results of T(0,1) propagation in the steel pipe whose parameters are shown in Tab.1. Compared the waveforms of reflection with that of the incident wave, it reveals that reflection from an end of a pipe have the same phase with the incident wave.

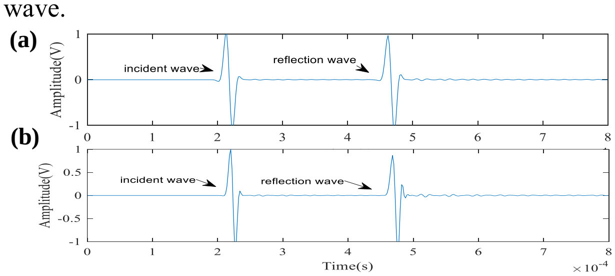

FIGURE 4: Incident wave with varying frequencies and Reflection from the ends (a) f_c =38kHz; (b) f_c =48kHz;

3.2 Discussion

The ripple waves shown in Fig. 3 and 4 are mainly due to the guide-wave multiple reflections. Eqs. (4) and (5) reveal the corresponding relationship between incident wave and its reflection from the notch. The simulation results agree well with the theoretical analysis by comparing the reflection wave with the incident wave. Fig. 5 shows the B-scan imaging of the pipe with two defects. In actual guided-wave inspection, the phase characteristics can be utilized to confirm and recognize the types of the reflection components (such as notches, cracks, welds, etc.) by calculating the similarity coefficient and phase relationship of incident wave and its reflection wave.

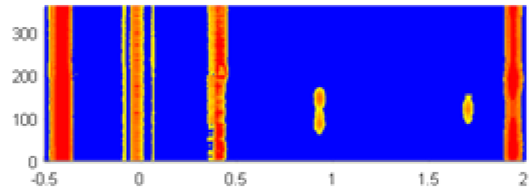

FIGURE 5: B-scan imaging of the pipe

4. CONCLUSION

We study the phase characteristics of incident wave and its reflection wave from a rectangular notch in a pipe. The proposed method for inspecting pipes is verified by simulating the interaction of the guided waves with rectangular notches in ABAQUS. The agreement between theoretical analysis and numerical results is well confirming that the phase characteristics is able to recognize the types of the defects.

ACKNOWLEDGEMENTS

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