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Guided waves based diagnostic imaging of circumferential cracks in small-diameter pipe

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ABSTRACT

To improve the safety and reliability of pipeline structures, much work has been done using ultrasonic guided waves methods for pipe inspection. Though good for evaluating the defects in the pipes, most of the methods lack the capability to precisely identify the defects in the pipe features like welds or supports. Therefore, a novel guided wave based cross-sectional diagnostic imaging algorithm was developed to improve the ability of circumferential cracks identification in the pipe features. To ensure the accuracy of the imaging, an angular profile-based frequency selection method is presented. As validation, the approach was employed to identify the presence and location of a small circumferential crack with 1.13% cross sectional area (CSA) in the welding zone of a 48 mm diameter type 304 stainless steel pipe. Accurate identification results have demonstrated the effectiveness of the developed approach.

1. Introduction

Circumferential cracking is a fairly common failure mechanism of pipes. The horizontally banded cracking arises from the combination of a corrosion mechanism and cyclic stress. These cracks could cause the leakage of pipe and the collapse of the whole structure. To improve the safety and reliability of pipeline structures, much work has been done using ultrasonic guided waves methods for pipe inspection [1–8]. In guided wave based pipe inspection, a ring of transducers is involved to attach at one location on the pipe. The transmitted guided waves propagate along the pipe and the reflections will be caused by the reflectors in the pipe such as welds, tees and defects. The received echo signals contain information about the size and location of the reflectors. The reflection arrival time gives an indication of the axial location of the reflector and the amplitude of the reflection gives an indication of the severity of the cross sectional area change. However, the reflection from pipe weld/support usually covers up the reflections from the defects in the pipe features since the amplitude of former one is larger than the latter ones. Therefore it is difficult to extract the accurate information about defects in the pipe features from the reflected signals. In general, though good for evaluating the defects in the pipes, most of the methods lack the capability to precisely identify the defects in the pipe features. The aim of the work presented in this paper is to develop a guided wave monitoring method, based on the current guided wave hardware, which has improved the ability of circumferential cracks identification in pipe features.

For identifying defects, ultrasonic guided-wave diagnostic imaging has shown significant potential [9–11]. Much of the work done using guided-wave diagnostic imaging technique has concentrated on plates and aircraft wing-like structures [12–17], but a considerably less amount of work has been done on pipe-like structures [2,18–20], especially on the defects in pipe features. Zhao et al. introduced a reconstruction algorithm for probabilistic inspection of damage (RAPID) technique for active health monitoring of an aircraft wing [12]. Van Velsor et al. proposed an adaptation of this technique for the structural health monitoring (SHM) of predetermined critical zones of pipeline [19]. A circular array was attached to the curved surface of the pipe, and the hollow cylinder guided waves were approximated as Lamb waves. Consequently, the same equations on plate-like structures were used for the RAPID of pipes. Though good for locating defects in large-diameter pipes, the adaptation of the RAPID technique lacks the capability to precisely locate defects in small-diameter pipes since the approximation of the hollow cylinder guided waves by Lamb waves are less suitable in smaller diameter pipes and it is impracticable to attach the circular array to the curved surface of the small-diameter pipe. In addition, a major advantage of the RAPID

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technique is that wave diffraction is accounted for by the elliptical location-probability distribution [19]. However, the acoustic fields in a pipe generated by a partial-loading source includes axisymmetric modes as well as non-axisymmetric flexural modes. The circumferential distribution of the total acoustic field, also referred as an angular profile, diverges circumferentially while guided waves propagate with dependence on the factors such as mode, frequency, cylinder size and propagation distance. If the major lobe of the superposition angular displacement profile is located near or on the defect, it will produce a large response. Therefore, multiple wave modes in the pipes and their interactions with damage may cause complex location-probability distribution, imposing additional difficulties on practical application. Moreover, the RAPID algorithm usually requires a relatively large number of actuator–sensor paths to cover the monitoring area.

This paper concentrates on the diagnostic imaging of circumferential cracks in pipe features using a novel RAPID algorithm with a sparse sensor configuration. The main contribution of this study is that an angular profile-based frequency selection method is presented to ensure the accuracy of the imaging. As validation, the approach was employed to identify the presence and location of circumferential crack in the welding zone of a 48 mm diameter type 304 stainless steel pipe. Identification results have demonstrated the effectiveness of the developed approach for identifying circumferential cracks in pipe features.

The paper is organized as follows. Section 2 analyses the characteristics of guided waves in small-diameter pipes. Section 3 describes the fundamental idea of the RAPID, focuses on the solution strategy for improving the RAPID, and outlines the imaging process. Section 4 gives a detailed experiment setup to illustrate the effectiveness of the proposed method, while Section 5 presents an experiment and makes discussions. Finally we conclude this paper.

2. Characteristics of guided waves in small-diameter pipes

For a cylindrical waveguide, the propagation modes can be classified as longitudinal-type modes $L(M,n)$ and torsional-type modes $T(M,n)$ [3]. Fig. 1 shows the phase velocity dispersion curves over a frequency range of 0–1 MHz for a 48 mm-diameter type 304 stainless steel pipe (wall thickness 2 mm). When $M = 0$, $L(M,n)/T(M,n)$ is an axisymmetric mode; when $M \neq 0$, $L(M,n)/T(M,n)$ is a non-axisymmetric mode, which is also known as a flexural mode. The phase velocity of non-axisymmetric mode gets closer to that of the corresponding axisymmetric mode. In this paper, only longitudinal-type modes $L(M,n)$ are investigated.

When a radial direction partial-loading source is applied to generate the axisymmetric $L(0,2)$ mode, it also generates the non-axisymmetric flexural mode guided waves $L(M,2)$ with different amplitudes due to the close phase velocity. Although longitudinal modes of other orders, such as $L(0,1)$ might also be generated by the same source loading, the phase velocities of these modes differ much more from the phase velocity of $L(M,2)$ mode and thus their amplitudes are trivial [3]. Therefore the total field generated by a radial direction partial-loading source can be represented as the superposition of axisymmetric mode $L(0,2)$ and corresponding non-axisymmetric flexural modes $L(M,2)$ with different amplitudes and phase velocities [21]:

$$Ve^{i(\omega t)} = \sum_M a^M V_n^M(r,\theta) e^{i(\omega t - k_n^M z)}, \tag{1}$$

where ω and k are the angular frequency and wave number, respectively. a^M is the amplitude of an arbitrary $L(M,2)$ mode, it can be calculated based on the Normal Mode Expansion (NME) method if the source loading conditions are provided [21]. $V_n^M(r,\theta)$ is the displacement distribution of a $L(M,n)$ mode, it can be written as [22]:

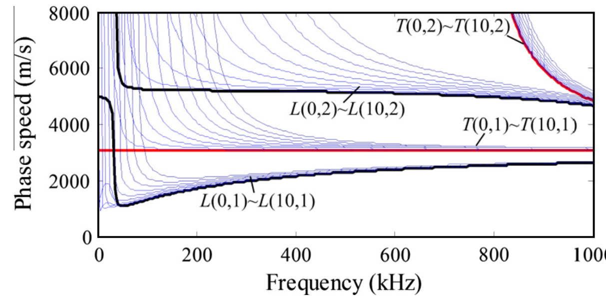

Fig. 1. Phase velocity dispersion curves of 48 mm-diameter 304 stainless steel pipe (modes only shown up to 10th order).

$$V_n^M(r,\theta) = R_{nr}^M(r)\cos(M\theta)\mathbf{e}_r + R_{n\theta}^M(r)\sin(M\theta)\mathbf{e}_\theta + R_{nz}^M(r)\cos(M\theta)\mathbf{e}_z, \tag{2}$$

where $R_{nr}^M(r)$, $R_{n\theta}^M(r)$, $R_{nz}^M(r)$ are the wave structure functions across the wall thickness for the $L(M,n)$ mode. $\cos(M\theta)$ and $\sin(M\theta)$ are the circumferential distributions of the $L(M,n)$ mode [23]. The calculation of wave structure functions requires solving the boundary condition problem of hollow cylinder guided waves which can be found in Gazis's paper [22].

In large diameter pipes, the pipe can be treated as a curved plate since the diameter of a pipe is much larger than the wall thickness. Thus the hollow cylinder guided waves can be treated as the corresponding Lamb waves that propagate along the contour of the pipe when the wavelength is comparable to and less than the wall thickness. The phase velocity of the corresponding hollow cylinder guided wave mode $L(M,n)$ can be calculated as follows [3]:

$$c_n^M = \frac{c_n}{\sqrt{1-\left(M\frac{c_n}{2\pi f a}\right)^2}}, \quad M = 0, 1, 2, 3, \ldots \tag{3}$$

where c_n^M is the phase velocities of $L(M,n)$, c_n is the phase velocity of the corresponding Lamb wave mode in an unbounded plate. When $n = 1$, c_n is the phase velocity of anti-symmetric A_0 mode Lamb wave; When $n = 2$, c_n is the phase velocity of symmetric S_0 mode Lamb wave. f is the frequency, and $a = b - h/2$, b and h are the outer diameter and wall thickness respectively. However, the approximation of the hollow cylinder guided waves by Lamb waves is not accurate for the small diameter pipes. Fig. 2 plots the phase velocity differences in percentage between the calculation results of $L(M,2)$ based on the exact dispersion equations and the simpler Eq. (3). The plate thickness and pipe wall thickness are both 2.0 mm. Fig. 2 shown that though the results from Eq. (3) match with the exact solutions in large diameter pipes, the phase velocity difference becomes larger when diameter decreases. Therefore, the Lamb wave-based RAPID algorithm should be improved for

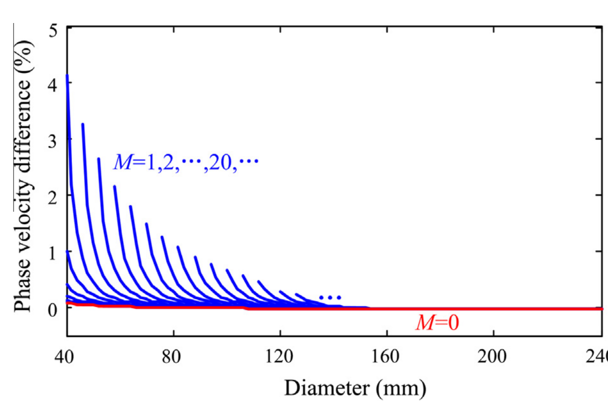

Fig. 2. Phase velocity differences between the calculation results of $L(M,2)$ based on the exact dispersion equations and the simpler Eq. (3).