Journal of Sound and Vibration 420 (2018) 1–20

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Guided wave imaging of oblique reflecting interfaces in pipes using common-source synthetic focusing

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ARTICLE INFO

Article history:
Received 23 May 2017
Received in revised form 31 December 2017
Accepted 7 January 2018

Keywords:
Guided wave
Defect image
Mode conversion
Oblique defects
Synthetic focusing

ABSTRACT

Cross-mode-family mode conversion and secondary reflection of guided waves in pipes complicate the processing of guided waves signals, and can cause false detection. In this paper, filters operating in the spectral domain of wavenumber, circumferential order and frequency are designed to suppress the signal components of unwanted mode-family and unwanted traveling direction. Common-source synthetic focusing is used to reconstruct defect images from the guided wave signals. Simulations of the reflections from linear oblique defects and a semicircle defect are separately implemented. Defect images, which are reconstructed from the simulation results under different excitation conditions, are comparatively studied in terms of axial resolution, reflection amplitude, detectable oblique angle and so on. Further, the proposed method is experimentally validated by detecting linear cracks with various oblique angles (10–40°). The proposed method relies on the guided wave signals that are captured during 2-D scanning of a cylindrical area on the pipe. The redundancy of the signals is analyzed to reduce the time-consumption of the scanning process and to enhance the practicability of the proposed method.

1. Introduction

Guided waves have been widely used for the non-destructive evaluation (NDE) of pipes [1]. During large-range inspection, the guided-wave-based techniques require much less time than the point-by-point tests. Additionally, guided wave inspection can cover the regions that are conventionally inaccessible, e.g., the buried, coated or supported parts of a pipe. However, the interpretation of guided wave signals is difficult because it relies on the calculation of the dispersion curves of multiple modes [2]. The dispersion curves are highly dependent on the mechanical and geometrical properties of the wave-guide structure. For hollow cylinders, the guided wave modes can be classified into longitudinal, torsional and flexural ones [3].

Since the late 1990s, time-domain guided-wave signals have been used for defect detection in pipes. Experimental investigations of the reflection from circumferential cracks were reported by Cawley's team [4], and the cross-circumferential-order mode conversion was observed [5]. The effects of defect size on the reflection coefficient were thoroughly discussed under various operating frequencies [6]. The propagation and attenuation of guided waves in a buried pipe were also investigated [7]. These traditional techniques locate the potential defects via the echoes in one-dimensional signals, which are insensitive to small-sized defects. Moreover, time-domain signals are simple but abstract, and can be effectively interpreted only by experienced researchers or well-trained inspectors.

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https://doi.org/10.1016/j.jsv.2018.01.012

To enhance the sensitivity to small defects, reflection-based guided wave imaging techniques which employ the concept of focusing were developed. These techniques can be classified into active focusing and synthetic focusing. Active focusing is implemented by applying pulse signals to phased array transducers with pre-determined amplitudes and time delays. The amplitudes and time delays can be obtained by deconvolution of the dynamic response data, which are calculated by normal mode expansion [8–10] or semi-analytical finite element simulation [11]. Additionally, the amplitudes and time delays can also be determined by employing the time-reversal method [12,13]. In contrast to active focusing, synthetic focusing is a post-processing technique, and it can be classified into common source method (CSM), synthetic aperture focusing method and total focusing method [14]. In the field of pipe inspection, CSM is mostly used.

CSM synthetic focusing is based on signals of two dimensions — one time coordinate and one spatial coordinate. To obtain such signals for the imaging of pipe defects, circumferential scanning needs to be implemented. A CSM-based waveform prediction method has been proposed for the reconstruction of synthetically focused defect images [15]. The imaging of circumferential cracks with different depths and circumferential extent has been systematically studied [16]. The method was further employed for the detection of axial defects in pipes [17]. Compared to active focusing, synthetic focusing technique does not need multi-channel stimulation source, and thus is more economical.

One limitation of CSM synthetic focusing is that it is not applicable to the detection of oblique reflectors. CSM assumes that only specific guided wave modes, which are in the same mode-family as the incident mode, exist in the reflected wave. However, this assumption is not satisfied for oblique reflectors. For example, under T(0,1) mode incidence, the reflection from an oblique crack generates F(n, 2) and F(n,3) modes, which belong to the 2nd and 3rd mode-family respectively. The signal components of unwanted modes produce false defect patterns in the reconstructed images. To solve this problem, mode separation is needed to obtain guided wave signals containing only single-mode-family components. This can be achieved by sorting the wave packets by their arrival times [18], or by using time-frequency analysis techniques [19–21]. These methods are based on the difference in group velocity, while another approach is to utilize the difference in wavenumber. To transform the guided wave signals into the wavenumber domain, it is essential to scan along the propagation direction. In a previous study, Lamb wave signals captured from multiple positions aligned along the propagation direction were transformed into the 2-D spectral domain of wavenumber and frequency, and the signal components of each mode were separated [22]. Similarly, axially aligned ring arrays were used for the mode-separation of guided waves in pipes [23,24].

In this paper, the CSM synthetic focusing method is combined with the wavenumber-based mode separation method, for the imaging of defects with oblique reflecting interfaces. A 2-D (circumferential and axial) scanning scheme is used for signal acquisition. Single-mode-family and single-axial-direction components are extracted from the recorded guided wave signals by applying specially designed spectral-domain filters. The rest of the paper is organized as follows: the principles of the imaging method are introduced in Section 2; the numerical and experimental validations are presented in Sections 3 and 4, respectively; the redundancy of the recorded guided wave signal data is analyzed in Section 5; and the conclusions of this paper are summarized in Section 6.

2. Imaging method

The commonly used nomenclature of guided wave modes in a pipe is derived from Meitzler's method [3]. In this paper, the L(0,1) and F(n,1) modes are referred to as the 1st mode-family; T(0,1) and F(n,2) modes are referred to as the 2nd mode-family; and L(0,2) and F(n,3) modes are referred to as the 3rd mode-family. The dispersion curves of the guided wave modes in each mode-family are separately presented in Fig. 1.

2.1. The spectral domain of guided wave signals

As shown in Fig. 2, the guided wave signals that are recorded at the position P (z, θ) are denoted as S (t, z, θ), where t represents time, z is the axial coordinate, and θ is the circumferential coordinate. Only the vibrations at the outer/inner surface of the pipe can be observed by ordinary techniques. As a result, the radial coordinate r is omitted when describing the guided wave signals in pipes.

S (t, z, θ) can be decomposed into a series of guided wave modes as follows:

$$S(t,z,\theta)=\sum_{m=1}^{+\infty}\iint\sum_{n=-\infty}^{+\infty}\alpha_{n,m}(\omega,k)\exp(in\theta+ikz-i\omega t)\mathrm{d}k\mathrm{d}\omega,\quad n\in\boldsymbol{Z}, \tag{1}$$

where n and m are the circumferential order and mode-family index of a guided wave mode, respectively. Specifically, $n=0$ represents axisymmetric modes; $n>0$ represents non-axisymmetric modes that travel along the clockwise helixes on the pipe; and $n<0$ represents non-axisymmetric modes traveling along the counter-clockwise helixes. The term $\alpha_{n,m}(\omega,k)$ is the amplitude of specific guided wave mode, and is a function of wavenumber k (only real-valued wavenumber is considered in this paper) and angular frequency ω. The $(k\cdot\omega)>0$ components represent the guided waves traveling along the positive axial direction, and the $(k\cdot\omega)<0$ components represent those traveling along the negative axial direction. The physical meaning of the mode-family index m is complicated; on the one hand, it distinguishes the torsional modes from the longitudinal ones, and on the other hand, it is related to the radial order of a mode.