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Defect mapping in pipes by ultrasonic wavefield cross-correlation: A synthetic verification

Luan T. Nguyen[a,*], Georg K. Kocur[b], Erik H. Saenger[a,c]

[a] International Geothermal Centre, Bochum University of Applied Sciences, Lennershofstr. 140, 44801 Bochum, Germany
[b] Institute of General Mechanics, RWTH Aachen University, Templergraben 64, 52062 Aachen, Germany
[c] Ruhr-University Bochum, Universitaetstr. 150, 44801 Bochum, Germany

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ABSTRACT

This work presents a reverse-time imaging technique by cross-correlating the forward wavefield with the reverse wavefield for the detection, localization, and sizing of defects in pipelines. The presented technique allows to capture the wavefield reflectivity at the places of ultrasonic wave scattering and reflections. Thus, the method is suitable for detecting pipe defects of either point-like or finite-size types using data from a pulse-echo setup. By using synthetic data generated by 3D spectral element pipe models, we show that the 3D wavefield cross-correlation imaging is capable in the case of cylindrical guided ultrasonic waves. With a ring setup of transducers, we analyze the imaging results obtained from the synthetic single-transducer and all-transducer firings. The presented pipe flaw imaging method is straightforward to carry out using a suitable wave equation solver. Also, the method does not suffer from long iterative runs and numerical convergence issues commonly connected with imaging methods based on either deterministic optimization or statistical inference. The imaging procedure can be fully baseline-free by performing data processing to remove direct arrivals from the ultrasound data.

1. Introduction

Guided ultrasonic waves are stress waves that propagate in a bounded solid medium. The use of ultrahigh frequency guided waves in nondestructive testing (NDT) of plate-like structures allows long-distance inspection capability, thus reducing the time and effort in collecting the ultrasound data and later in imaging possible defects. However, those guided waves propagate multi-modally and dispersively [1], making interpretation of the ultrasound recordings complicated. Most often, ultrasonic excitations of the first few guided wave modes are used for ease of the ultrasound data analysis and interpretation [2]. If higher wave modes cannot be avoided (due to constraints of the inspected structures or transducers' bandwidths, and wave mode conversions), dispersion compensation and separation of propagation modes are sometimes needed [3,4].

Analytical, experimental, and numerical analyses of guided elastic waves in cylindrical rods and hollow cylinders [5–7] revealed complicated dispersive and multi-modal characteristics of cylindrical waves. Compared with Lamb waves in thin plate-like structures, cylindrical waves exhibit more complicated guided modes and dispersion characteristics which we will discuss later in this work. Flaw detection in pipework using guided waves has received great attention (see [8] and the references therein). Most often, the degree of a defect is quantified based on a reflection coefficient expressed as a function of the geometrical extent of the defect [9,10].

To map defects in pipes, Leonard and Hinders [11] applied a type of travel time 'cross-hole' tomography on the helical wave paths for building a tomographic flaw map of pipes. Gaul et al. [12] applied a synthetic focusing algorithm to the measured signals of the guided elastic waves in pipes. Willey et at. [13] used multiple helical transmission data acquired from a two-ring setup to invert for the wall thickness profile of the pipe. In another approach, Wang et al. [14] used a non-ring sparse sensor network of transducers to image pipe damage in an unwrapped grid based on the correlation of the first arrival waves. Also based on a sensor network of a non-ring configuration, Dehghan-Niri and Salamone [15] proposed to enhance damage-sensitive features, which are input to a reconstruction algorithm based on a waveform difference in baseline and measurement, by using multiple helical paths of the cylindrical waves. Hayashi [16] introduced a fast pipe thinning mapping method using amplitude spectrum peaks obtained from a laser based ultrasonic scanning system. Bagheri et al. [17] used the continuous wavelet and Hilbert transforms to extract damage-sensitive features and combined with a metaheuristic optimization and a probabilistic approach to construct an image of defects in pipe.

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[*] Corresponding author.
E-mail addresses: luan.nguyen@hs-bochum.de (L.T. Nguyen), kocur@iam.rwth-aachen.de (G.K. Kocur), erik.saenger@rub.de (E.H. Saenger).

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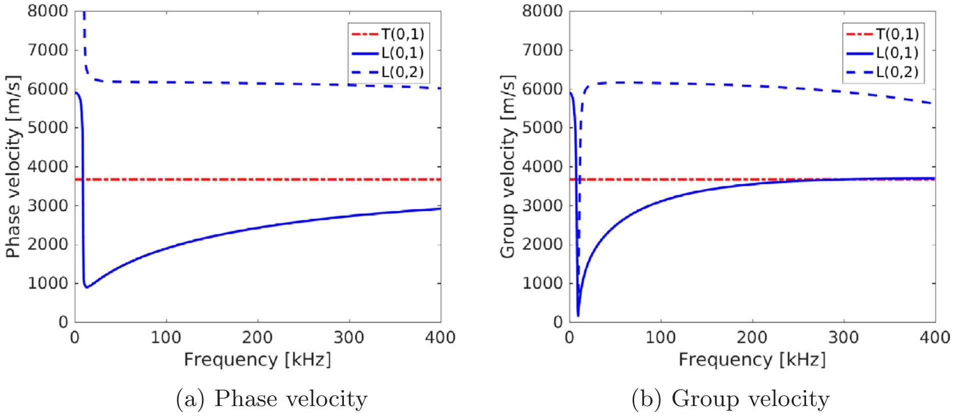

(a) Phase velocity (b) Group velocity

Fig. 1. Phase velocity (a) and group velocity (b) dispersion curves of the $T(0, 1)$, $L(0, 1)$, and $L(0, 2)$ modes of the investigated pipe model.

Time reversal in the manner of Fink [18] has also been found useful for NDT of thin-walled structures. By the time reversal principle, the recorded acoustic/elastic waveforms, if being time-reversed and re-emitted at the receiving positions, form a wavefield that retraces its path back to the source location. When focused, the reverse wavefield becomes spatially concentrated and temporally compressed to reconstruct the original excitation pulse. Ing and Fink [19] experimentally showed that this time reversal invariance also holds for the dispersive Lamb waves. These features are important for the exptrapolated reverse wavefield used in this work to be correctly back-propagated toward scattering and reflecting points. Other reports on structural health monitoring [20–22] showed that the time reversal principle can be applied to plates and composite structures for achieving baseline-free flaw detection even though dispersion does disturb refocusing of time reversed wave propagation. Xu and Giurgiutiu [22] and Park et al. [23] pointed out that time reversal creates sidebands around the true reconstructed impulse if more than one mode of the guided waves is excited. For pipe inspection, Hayashi and Murase [24] used the torsional $T(0, 1)$ mode for building a tomographic map of the pipe defects using the time reversal principle. Using the same cylindrical wave mode, Davies and Cawley [25] applied synthetic focusing based on time reversal operation in the frequency-wavenumber domain for pipe defect mapping. To the best of the authors' knowledge, in NDT applications for both plates and pipes, however, the time reversal principle is mostly limited to the location of point-like acoustic sources and scatterers and the reconstruction of the source wavelets.

This work introduces the use of the wavefield cross-correlation method for flaw detection and sizing in waveguides with a particular application for the inspection of pipework. We show that the so-called reverse-time migration, which is based on a zero-lag cross-correlation between the forward wavefield and the reverse wavefield, can be efficiently used for detecting, locating, and sizing flaws of abrupt material changes such as cracks, eroded/corroded voids, and local material damages caused by, for example, impacts in pipes. As this is a method for imaging of reflectors, it can be used to detect and locate both point-like scatterers and finite-size defects.

In the following, we review the characteristics and modeling possibilities of guided wave propagation in pipes and detail the wavefield cross-correlation imaging condition in Section 2. An in-depth demonstration of the imaging principle and how the choice of broadband and narrowband source wavelets influences the imaging results are presented in Section 3. Also in Section 3, we test the capability of the presented wave-equation based imaging method and especially use an all-transducer (supershot) configuration for imaging of a finite-size defect and multiple defects. Section 4 concludes the present work and discusses issues that may emerge and strategies to overcome them in actual ultrasound NDT pipe inspection.

2. Simulation approach and imaging method

2.1. Guided wave propagation in pipes

The motions of elastic wave propagation in a pipe, as for other thin-walled structures, are guided within the pipe wall. However, unlike in plates, there exist three distinct families of wave modes in pipes: the axisymmetric longitudinal modes $L(0, m)$, the non-axisymmetric flexural modes $F(n, m)$, and the torsional modes $T(0, m)$ (where m and n are the radial and circumferential mode parameters, respectively [26]). The longitudinal wave modes $L(0, 1)$ and $L(0, 2)$ correspond to the fundamental anti-symmetric A_0 and symmetric S_0 Lamb modes, respectively. The torsional mode $T(0, 1)$ is equivalent to SH waves in a plate. Detailed solutions of the elastic wave problem in hollow and solid cylinders are studied in [6,7] and their modal relation to those in plates are discussed in [26–28]. Generally, the results show, for the same ratio of thickness-to-diameter, the dispersion characteristics of the axisymmetric longitudinal modes in cylindrical waves are comparable to those of Lamb waves in a plate at the high-frequency range. The similar behavior is observed if the thickness-to-diameter ratio decreases. The significant difference in the dispersion characteristics between the cylindrical modes and Lamb modes lies in the low-frequency range. For example, as the frequencies decrease, the phase velocity of the $L(0, 1)$ mode of cylindrical waves approaches the S_0 Lamb mode instead of approaching zero propagating velocity as for the A_0 Lamb mode. Fig. 1 shows the dispersion curves of the modes $T(0, 1)$, $L(0, 1)$, and $L(0, 2)$ calculated by the PCdisp program [29] for a 4 mm wall thickness pipe with a diameter of 200 mm and the material properties shown in Table 1.

For NDT using ultrasound data, the choice of the excited mode(s) is important for achieving low attenuation and dispersion effects, and even avoiding wave energy leakage if the investigated pipe is submerged under water or buried underground. In particular, if the pipe is surrounded by a liquid, the torsional $T(0, 1)$ mode is preferred as this non-dispersive transverse mode does not 'leak' into a non-viscous liquid. Consideration on the choice between the $L(0, 1)$ mode and $L(0, 2)$ mode is based on the operating frequency taken into account that the $L(0, 2)$ mode travels much faster but with a rather smaller amplitude compared to that of the $L(0, 1)$ mode.

Regarding the modeling techniques for thin-walled and large-diameter pipes, some authors consider guided wave propagation in pipes

Table 1
Material properties and dimensions of the steel pipe model.

P-velocity c_p [m/s]	S-velocity c_s [m/s]	Density ρ [kg/m^3]	Diameter d [mm]	Wall thickness w [mm]
5900	3200	7820	200	4