NDT&E International 65 (2014) 8–21

Contents lists available at ScienceDirect

NDT&E International

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

Guided wave tomography of pipes with high-order helical modes

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ARTICLE INFO

Article history:
Received 26 September 2013
Received in revised form
23 March 2014
Accepted 28 March 2014
Available online 4 April 2014

Keywords:
Tomography
Guided waves
Corrosion and erosion monitoring
Thermal variation
EMAT

ABSTRACT

The transmission of guided ultrasonic waves across corrosion or erosion damage encodes information about the defect depth. Tomography maps the depth profile from multiple transmission experiments performed under different insonification angles by solving the so-called inverse problem; the accuracy of the depth estimation being dependent on the range of angles available for the inversion. Practical application of tomography to tubular structures, such as pipes and bends, requires the use of two ring arrays of ultrasonic transducers at the two ends of the pipe section to be inspected. However, such a configuration leads to an insufficient angular coverage when considering the signals that travel along the shortest temporal path between a pair of transducers. This paper introduces a general inversion method that extends the range of insonification angles by exploiting the information carried by the signals that wrap around the pipe multiple times before reaching the receive array, thus resulting in superior image resolution and increased depth estimation accuracy. In addition, to address typical thermal fluctuations encountered during continuous monitoring, a strategy that combines a temperature compensation scheme with the intrinsic thermal stability of electromagnetic acoustic transducers (EMATs) is developed and tested with full-scale experiments performed on a schedule of 40, 8″ diameter steel pipe instrumented with two ring arrays of EMAT transducers. It is shown that for an irregularly shaped defect the proposed inversion method yields maximum depth estimations that are as accurate as single point ultrasonic thickness gaging measurements and over a wide temperature range up to 175 °C. The results indicate that advanced inversion schemes in combination with EMAT transduction offer great potential for continuously monitoring the progression of corrosion or erosion damage in the oil and gas industry.

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1. Introduction

Throughout the oil and gas industry monitoring the rate of corrosion and erosion of pipelines plays a central role in managing the integrity of both upstream and downstream assets [1,2]. Although various ultrasonic [3] and electromagnetic [4] thickness gaging devices are commercially available, the need for scanning a handheld sensor across the area to be inspected makes them not suited for continuous monitoring and limits their applicability when physical obstacles prevent direct access to the pipe. Moreover, remote location of the test area poses additional challenges in refineries where scaffoldings are often required or in subsea testing where divers or robotic systems need to be deployed at great depths. Another major limitation of current manual devices is operator dependence; results may vary significantly depending on probe orientation and position relative to the test area, thus requiring highly skilled operators.

To overcome some of the limitations of manual inspections, permanently installed sensors are now being used in a number of industrial applications under the structural health monitoring paradigm. Commercial devices use electrodes welded onto the pipe to inject current according to the potential drop technique [5,6] or ultrasonic transducers directly bonded or clamped onto the pipe [7] or attached through buffer waveguides to operate at higher temperatures [8]. While these sensors can provide accurate wall thickness estimations, their coverage is limited to the area beneath the transducer which may render the inspection ineffective if the transducer is not positioned at the point of maximum wall thickness loss or worse if it misses the damage area entirely. Moreover, these sensors are not suited for monitoring inaccessible regions such as pipe supports or concrete penetrations.

To increase area coverage, guided ultrasonic waves provide an attractive solution since they can propagate over a large distance from a single transducer position [9]. Indeed, the long-range

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http://dx.doi.org/10.1016/j.ndteint.2014.03.010
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inspection capabilities of guided waves are now routinely used for the detection of defects in pipelines [10–12]. However, current long-range screening systems cannot provide accurate estimations of defect depth especially in the presence of complex morphologies [13]. On the other hand, the constant group velocity (CGV) method [14,15] provides a medium range solution, typically over a distance of several pipe diameters, for the estimation of the average wall thickness loss between a pair of guided wave transducers arranged in a pitch-catch configuration. While average wall thickness loss may be sufficient to assess large and relatively uniform defects, more spatially localized information is needed to estimate the maximum depth of irregular defects.

The possibility of providing spatially localized information with guided waves through the combination of multiple transmission measurements and tomographic techniques was realized in the early 1990s by Hutchins's group [16] and has since received much attention [17–23]. The majority of research works on guided wave tomography (GWT) has focused on flat plate geometries and it has now been demonstrated that highly accurate depth maps can be obtained by implementing tomographic algorithms that can take into account refraction and diffraction effects [23]. On the other hand, fewer works have investigated GWT applications to pipes. Here, a pair of transmit- and receive-ring arrays of ultrasonic transducers encircles the pipe and delimits the section to be monitored. The arrays are used to transmit guided wave signals from any transducer of the transmit array to any transducer of the receive array thus insonifying potential defects from multiple angles. Assuming that the pipe wall thickness is small compared to its radius, GWT can be implemented by ideally unwrapping the section of pipe between the arrays and treating it as a flat plate. The ring arrays therefore transform into two parallel linear arrays and the GWT problem reduces to the classical borehole tomography configuration used for seismic profiling [24]. The borehole configuration leads to what is known as the limited view problem [25,26] since it is not possible to perform transmission measurements at insonification angles approaching the direction parallel to the arrays, i.e. the circumferential direction in the pipe. The missing angles cause image degradation and hence affect depth estimation accuracy. Leonard and Hinders [19] and Volker and Bloom [22] suggested that the accuracy of GWT may be improved by exploiting the information contained in higher-order helical modes; however, they did not provide a methodology to do so and the extent of the potential benefits gained from the higher modes remained unclear.

This paper introduces a general inversion method to extract the information contained in higher-order helical modes and hence ameliorate the accuracy of GWT of pipelines. The proposed method is based on the observation that for a given transmit–receive transducer pair there exists infinite helical wave paths that connect the transmitter to the receiver each corresponding to a different number of turns around the pipe. The higher the order of the helical path, the larger the number of turns around the pipe and hence the better the ray coverage in the circumferential direction. As a result, the higher-order modes provide a means to artificially expand the aperture of the parallel arrays and therefore enhance the spatial resolution and depth estimation accuracy of GWT.

The paper also addresses the instability caused by typical thermal fluctuations experienced in field applications which are known to affect many guided wave based structural health monitoring systems [27]. For this purpose, a strategy that combines a temperature compensation scheme with the intrinsic thermal stability of electromagnetic acoustic transducers (EMATs) is developed and integrated in the inversion.

The theory of high-order helical-mode tomography is formulated in Section 2 which is followed by a numerical analysis in Section 3. Full-scale experimental validation including a thermal stability analysis is conducted using the setup described in Section 4. Section 5 applies signal pre-processing techniques to the measured signals to perform temperature compensation and extract the input data for the inversion algorithms. Experimental wall thickness loss maps and monitoring results are presented in Section 6 with general remarks on EMAT transducer stability and resolvability of high-order modes given in Section 7. Conclusions are presented in Section 8.

2. Theory

In order to reconstruct wall-thickness maps from guided wave transmission signals, it is necessary to formulate an inverse problem which can interpret the information contained in the ultrasonic waveforms and translate it into a representation of the defect's geometry. To this end, a forward model is used to describe how the probing waves interact with the defect and to provide the inversion scheme with the '*key*' to decode the defect geometrical information from the measured ultrasonic signals. The forward model and inversion scheme are discussed next.

2.1. Forward model

The aim of this section is to model the propagation of guided waves between the transducers of the transmit and receive arrays.

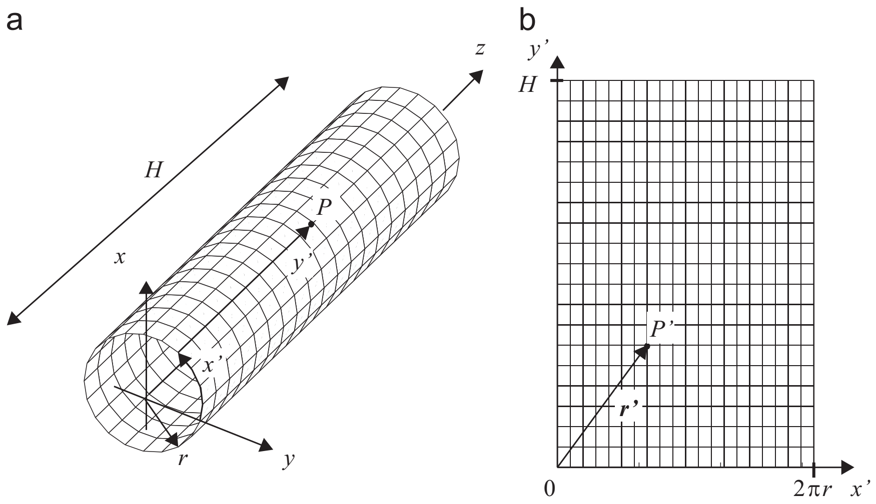

Fig. 1. Coordinate systems used to form the parameterization of a circular cylinder. (a) 3-D physical space; (b) 2-D acoustic domain.

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