Ultrasonics xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Ultrasonics

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

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Corrosion and erosion monitoring in plates and pipes using constant group velocity Lamb wave inspection

Peter B. Nagy [a,b,*], Francesco Simonetti [a,b], Geir Instanes [b,c]

[a] Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, Cincinnati, OH 45221, USA
[b] Cincinnati NDE, Cincinnati, OH 45244, USA
[c] ClampOn AS, 5162 Laksevaag, Bergen, Norway

A R T I C L E   I N F O

Article history:
Available online xxxx

Keywords:
Lamb waves
EMATs
Corrosion monitoring

A B S T R A C T

Recent improvements in tomographic reconstruction techniques generated a renewed interest in short-range ultrasonic guided wave inspection for real-time monitoring of internal corrosion and erosion in pipes and other plate-like structures. Emerging evidence suggests that in most cases the fundamental asymmetric A_0 mode holds a distinct advantage over the earlier market leader fundamental symmetric S_0 mode. Most existing A_0 mode inspections operate at relatively low inspection frequencies where the mode is highly dispersive therefore very sensitive to variations in wall thickness. This paper examines the potential advantages of increasing the inspection frequency to the so-called constant group velocity (CGV) point where the group velocity remains essentially constant over a wide range of wall thickness variation, but the phase velocity is still dispersive enough to allow accurate wall thickness assessment from phase angle measurements. This paper shows that in the CGV region the crucial issue of temperature correction becomes especially simple, which is particularly beneficial when higher-order helical modes are also exploited for tomography. One disadvantage of working at such relatively high inspection frequency is that, as the slower A_0 mode becomes faster and less dispersive, the competing faster S_0 mode becomes slower and more dispersive. At higher inspection frequencies these modes cannot be separated any longer based on their vibration polarization only, which is mostly tangential for the S_0 mode while mostly normal for the A_0 at low frequencies, as the two modes become more similar as the frequency increases. Therefore, we propose a novel method for suppressing the unwanted S_0 mode based on the Poisson effect of the material by optimizing the angle of inclination of the equivalent transduction force of the Electromagnetic Acoustic Transducers (EMATs) used for generation and detection purposes.

1. Introduction

Corrosion and erosion detection and monitoring are essential prognostic means of preserving material integrity and reducing the life-cycle cost of industrial infrastructure, ships, aircraft, ground vehicles, pipelines, oil installations, etc. Long-range guided wave inspection has the potential to extend ultrasonic corrosion measurements in pipes over very long distances [1–6]. Carefully selected extensional, flexural, or torsional ultrasonic guided waves in the pipe wall provide an attractive solution for long-range corrosion monitoring because they can be excited at one location on the pipe and will propagate along the pipe, returning echoes indicating the presence of corrosion or other pipe features. However, reflection measurements are rather sensitive to the presence of a distinct sharp transition between sections of different thickness. Transmission measurements in pitch–catch mode work better when no such localized transition exists and the wall thickness varies in a gradual manner.

Dry-coupled piezoelectric transducer systems were shown to detect corrosion in chemical plant pipework using cylindrical Lamb waves in pulse-echo mode over distances approaching 50 m in steel pipes [7] and they can propagate through multiple bends [8]. It was also shown that low-frequency axisymmetric modes can propagate over long distances even in buried, water-filled iron pipes [9]. Most of such inspections are based on reflection measurements in pitch–catch mode [2,6,10,11]. Carefully selected extensional, flexural, or torsional ultrasonic guided waves in the pipe wall provide an attractive solution for long-range corrosion monitoring because they can be excited at one location on the pipe and will propagate along the pipe, returning echoes indicating the

* Corresponding author at: Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, Cincinnati, OH 45221, USA. Tel.: +1 513 556 3353; fax: +1 513 556 5038.
E-mail address: peter.nagy@uc.edu (P.B. Nagy).

http://dx.doi.org/10.1016/j.ultras.2014.01.017
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presence of corrosion or other pipe features. However, reflection measurements are rather sensitive to the presence of a distinct transition between sections of different thickness. Transmission measurements in pitch–catch mode work better when no such localized transition exists and the wall thickness varies in a gradual manner [12]. It was shown that ultrasonic guided wave attenuation measurements can be also exploited for the detection of wall loss due to corrosion [13].

Various wave modes can be used to best detect thinning of the pipe wall based on mode cutoff, group and phase velocity, transmission coefficient or attenuation measurements. For example, by carefully selecting the inspection frequency to match the range of wall thickness in the pipe, one can measure the group velocity of the S_0 mode for corrosion monitoring [14]. Ultrasonic guided wave inspection methods can be also distinguished based on the generation and detection principles they rely on as well as the different physical principles of the transducers used. Conventional normal and angle beam transducers exhibit very different spatial and temporal frequency characteristics that can be analyzed using source influence theory [15]. Typically, inspection is based on a single carefully selected guided mode. However, in some cases, a multi-mode approach is adapted, e.g., by using a linear array comb transducer [16]. Guided waves generated by axisymmetric and non-axisymmetric surface loading have their distinct advantages and disadvantages [17]. Time-delay periodic ring arrays have been used to generate axisymmetric guided wave modes in hollow cylinders [18].

Most structural health monitoring (SHM) systems focus on crucial areas that are particularly susceptible for damage, e.g., erosion or corrosion. In such cases localized inspection strategies are preferable over long-range inspection that inevitably sacrifices detection sensitivity to maximize area coverage. Recently, Cawley et al. devised an optimal inspection strategy for designing a permanently installed corrosion/erosion monitoring (CEM) system [19]. When relatively small wall thickness loss is expected more or less uniformly distributed over the area of interest, a small number of spot sensors should be used. When the loss tends to be severe and concentrated at a few unpredictable locations, an averaging-type area monitoring system is preferable. The decision is harder when moderate loss is expected over a significant but unpredictable fraction of the surface [19]. Short-range ultrasonic guided wave tomography (GWT) is especially well suited to map the wall loss distributed over the targeted area from a limited number of transducer locations [20–24]. In a typical GWT configuration, a pair of transmitting and receiving ring arrays of ultrasonic transducers surrounds the area to be monitored. Different combinations of the array elements are used to transmit and receive guided wave signals to interrogate the area of interest from multiple directions. Each received signal carries information about the geometrical characteristics of the encountered defects, which is then decoded using appropriate reconstruction algorithms.

Ultrasonic guided waves are particularly well suited for inspection of pipelines. In relatively thin-walled pipes, the guided waves can be approximated as Lamb modes propagating along helical paths that allow the same mode to arrive to the receiver at different times [25]. Fig. 1 shows a schematic diagram of the three lowest-order helical paths along and around a cylindrical pipe. The propagation length of the nth-order helical path is.

$$\ell_n = \sqrt{z^2 + (a + \pi n D)^2}, \qquad (1)$$

where z and a are the axial and azimuthal distances between the transducers, respectively, D is the average diameter of the pipe, and n is the azimuthal order.

Although higher-order helical modes are somewhat more affected by the circumferential curvature of the pipe, in thin-walled

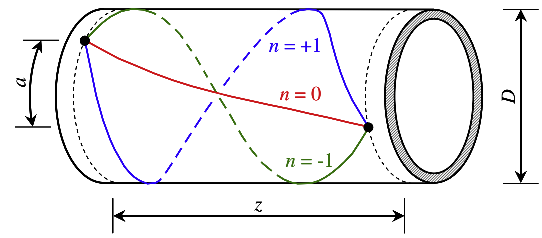

Fig. 1. A schematic view of the three lowest-order helical paths in a cylindrical pipe.

pipes their velocity is still almost the same as that of the zero-order mode that follows the most direct path between the transmitter and the receiver therefore all modes can be crudely approximated by the corresponding Lamb mode in a flat plate. The problem is complicated by the fact that a number of dispersive Lamb modes can propagate in each direction in a pipe of given material depending on its wall thickness and the inspection frequency range used by the monitoring system. Because of the highly dispersive nature of Lamb modes, fast modes following longer helical paths ($n = 1, 2, 3, \ldots$) can actually beat slower modes following the shortest direct route ($n = 0$), therefore the observed vibration at the location of the receiver is much more complicated than one would assume based on direct Lamb wave propagation only.

As an example, Fig. 2 shows the (a) phase and (b) group velocity dispersion curves, respectively, for Lamb waves in a steel plate. Both velocities were normalized to the shear velocity c_s of the material. In these calculations the longitudinal and shear bulk velocities were assumed to be c_d = 5900 m/s and c_s = 3200 m/s. Of particular interest in the following will be the region surrounding the point where the group velocity of the A_0 mode reaches its maximum, the so-called constant group velocity (CGV) point, which is around $fd \approx 1.4$ MHz mm for steel. This region is indicated by an open circle in Fig. 2.

Even without the added complexity of higher-order helical modes, separation of numerous dispersive Lamb modes presents a formidable problem and renders reliable inversion all but impossible. Therefore, most guided wave inspections are conducted at frequencies well below the cut-off frequency of the first-order asymmetric Lamb mode so that only the two fundamental, i.e., zeroth-order, Lamb modes are present. At low frequencies, the fundamental symmetric or S_0 mode is a simple dilatational plate vibration with weak dispersion and mostly in-plane vibration while the fundamental asymmetric or A_0 mode is a flexural plate vibration with strong dispersion and mostly out-of-plane vibration.Generally speaking, dispersion is good since it provides sensitivity to wall thickness variations, while out-of-plane displacement is bad since it provides strong coupling to the surrounding medium and results in strong attenuation through energy leakage. Consequently, neither of the fundamental modes is particularly useful below a certain minimum frequency, especially because the increasing wavelength limits the spatial resolution of any inspection scheme. As the frequency increases the differences between the S_0 and A_0 modes decrease and, in some respects, even reverse. The S_0 mode becomes more dispersive while the A_0 mode becomes less dispersive and the aspect ratio of their elliptically polarized surface displacement trajectories decreases. Reversal occurs roughly around the point when the clockwise rotation of the surface particle displacement produced by the S_0 mode changes to counterclockwise rotation ($c_p = \sqrt{2}c_s$) that is around $fd \approx 2.4$ MHz mm for steel. Above this frequency × thickness product, the S_0 mode exhibits lower group velocity than the A_0 mode, but this happens outside the interest of frequency range where only the two fundamental modes exist.

Please cite this article in press as: P.B. Nagy et al., Corrosion and erosion monitoring in plates and pipes using constant group velocity Lamb wave inspection, Ultrasonics (2014), http://dx.doi.org/10.1016/j.ultras.2014.01.017