Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 70 (2015) 338 – 342

Physics Procedia

2015 International Congress on Ultrasonics, 2015 ICU Metz

Inspection of pipelines using the first longitudinal guided wave mode

P. S. Lowe[a, b] *, R. Sanderson[b], S. K. Pedram[a, b], N. V. Boulgouris[b], and P. Mudge[b]

[a]*Brunel University, Kingston Lane, Uxbridge, Middlesex UB8 3PH, UK*
[b]*TWI Ltd, Granta Park, Great Abington, Cambridge, CB21 6AL, UK*

Abstract

Inspection of cylindrical structures using the first longitudinal Ultrasonic Guided Wave (UGW) mode has so far been predominantly neglected. This is due to its attenuative and dispersive behaviour, at common UGW operating frequencies (20-100 kHz). However, with the current knowledge on the level of attenuation in the first longitudinal wave mode and dispersion compensation techniques, the first longitudinal guided wave mode no longer need to be neglected. Furthermore, the first longitudinal guided wave mode has higher number of non-axisymmetric modes compared to other axisymmetric modes in the operating frequency. This will enhance the flaw sizing capability which makes the first longitudinal guided wave mode a viable prospect for UGW inspection of cylindrical structures. This study has been performed to investigate the potential of exciting the first longitudinal guided wave mode in isolation. Numerical investigations have been conducted to investigate the pure excitation of the first longitudinal guided wave mode. It has been shown that the first longitudinal guided wave mode can be used in UGW inspection effectively in isolation by adopting transducers with out of plane vibration for excitation. This can reduces the cost and weight of UGW inspection tooling. Numerical results are empirically validated.

Peer-review under responsibility of the Scientific Committee of ICU 2015

Keywords: Pipeline inspection, finite element modeling, ultrasonic guided waves, compression transducers, pure excitation

1. Introduction

Research on UGW inspection has expanded over recent decades, including the use of low frequency ultrasound to screen large specimens *e.g.* pipes. Pipelines are widely used to transport energy products such as water and crude

* Corresponding author. Tel.: +44-122-3899-000
E-mail address: eepgpsw@brunel.ac.uk

Peer-review under responsibility of the Scientific Committee of ICU 2015
doi:10.1016/j.phpro.2015.08.079

oil. As pipelines age, corrosion flaws can develop and it is therefore important to find techniques to inspect them efficiently. Pipelines in the industries are commonly inaccessible and insulated. Because of that, UGW has become more attractive as a non-destructive testing technique in the past two decades. Guided wave based techniques offer the advantage of full volumetric inspection from a single test location.The UGW technique works on elongated geometries with a constant cross-section, *e.g.* pipes. Sound generated in these geometries is constrained to propagate along the axis of the body, and similarly return back to the generation position when an impedance change (discontinuity) is encountered. UGW can only exist where there is a boundary in which to propagate. These boundaries are said to form a 'waveguide'. Depending on the waveguide geometry, material properties and the excitation frequency, the possible number of wave modes will vary.

Nomenclatures for identifying guided wave modes in cylindrical structures are essential as there are a high number of wave modes with varying displacement characteristics. Nomenclature used throughout this study was suggested by Meitzler [1] and applied by Silk and Bainton [2]. According to this nomenclature, vibration modes in cylindrical structures are based on the following format, *X(n,m)*. *X* represents the character to denote whether the vibration modes are longitudinal and axisymmetric, *L*, torsional and axisymmetric, *T*, or non-axisymmetric (flexural), *F*. The *n* is a positive integer giving the identification of harmonic variations of displacement around the circumference and *m*, again a positive integer, is to indicate the incremental order of the modes of vibration within the wall. In typical pipeline sizes and test frequencies (20-100 kHz) the three axisymmetric guided wave modes that can be excited are L(0,1), L(0,2) and T(0,1) [3, 4].

Dispersion of UGW can occur as they propagate through the test structure. Dispersion can limit inspection resolution because of losses in signal amplitude relative to the noise level. Also, the level of dispersion in a particular wave mode will affect data interpretation [5, 6, 7]. Fig. 1 illustrates the phase velocity dispersion curves for an 8inch Schedule 40 steel pipe (outer diameter: 219.1mm and wall thickness: 8.18mm) calculated using the RAPID (Rapid Automated Pipe Dispersion Curve Generator) software [8]. In Fig. 1, black lines represent axisymmetric modes present in the typical UGW operating frequency range (20-100kHz) and blue lines represents family of flexural wave modes. The Fig. 1 has been used to illustrate the higher number of flexural wave modes associated with the L(0,1) mode. The number of flexural wave modes at a range of frequencies have been recorded for each of the L(0,1), T(0,1) and L(0,2) wave mode families. This is shown graphically in Fig. 2. In typical UGW operating frequencies, the L(0,1) wave mode has four times more flexural wave modes than L(0,2) and two times more flexural wave modes than T(0,1) wave mode. The higher numbers of flexural wave modes are likely to result in better flaw sensitivity [9, 10]. This indicates that, there are potentially beneficial properties of the L(0,1) wave mode to increase the resolution and achieve higher flaw sensitivity of UGW inspection. Research has been performed to compensate the dispersion [5] and attenuation [11] of L(0,1) wave mode. Therefore, the dispersion and the attenuation is no longer an impediment to use the L(0,1) for UGW inspection of cylindrical structures.

In the present paper, a Finite Element Analysis (FEA) has performed to investigate the potential of exciting the L(0,1) in isolation. Based on the FEA results, new UGW transducers are developed to excite the L(0,1) in isolation and validated empirically.

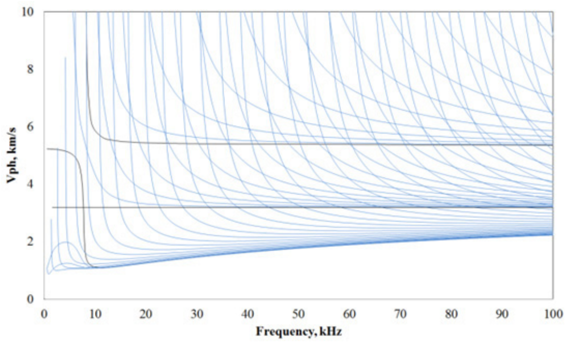

Figure 1: Phase velocity dispersion curves for an 8 inch schedule 40 steel pipe (outer diameter: 219.1mm and wall

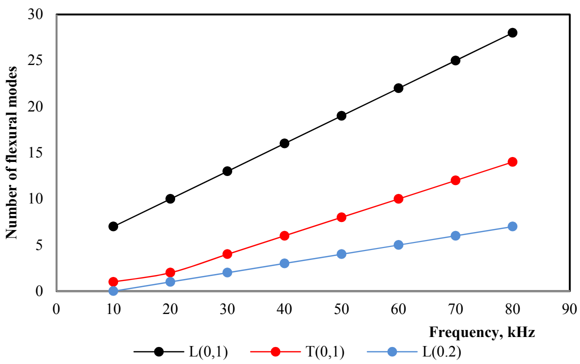

Figure 2: Variation of the number of flexural wave modes with corresponding frequency of 8inch Schedule 40 steel pipe (outer diameter: 219.1mm and wall thickness: 8.18mm)

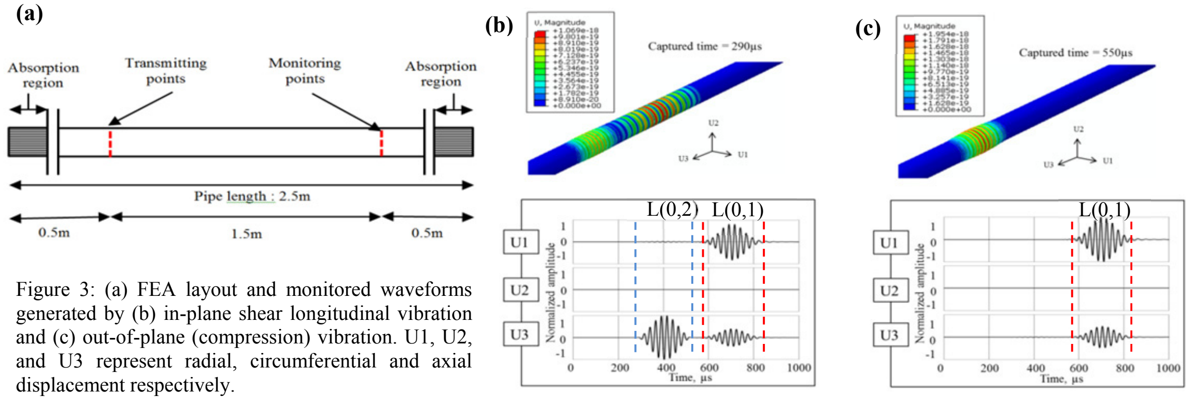

Figure 3: (a) FEA layout and monitored waveforms generated by (b) in-plane shear longitudinal vibration and (c) out-of-plane (compression) vibration. U1, U2, and U3 represent radial, circumferential and axial displacement respectively.

2. Finite element analysis

The FEA has been performed to study the potential of exciting the L(0,1) in isolation. A 3D model was built using ABAQUS/EXPLICIT version 6.13 Finite Element (FE) software [12]. A pipe was modelled as a nominal 8inch schedule 40 steel pipe (outer diameter: 219.1mm and wall thickness: 8.18mm) with an axial length of 2.5m. The material properties used for steel were assumed as follows: Density (ρ) = 7830kg/m^3, Young's modulus (E) = 207GPa and Poisson's ratio (V) = 0.3. A linear eight node brick element (C3D8) has been used to reduce the computation time. Number of elements was calculated to use at least eight elements to represent the smallest wavelength in the operating frequency. This type of mesh refinement has been adequately used in previous studies [13, 14, 15]. To avoid reflections from the free edge of the pipe, an absorption region was used as shown in Fig. 3(a) without modelling a lengthier pipe for computational efficiency. The absorbing boundary was achieved by use of the 'infinite element' (ABAQUS element type CIN3D8 [12]).

The L(0,2) wave mode has predominantly axial displacement and the L(0,1) wave mode has radial displacement and low axial displacement. Commercially available ring of UGW transducers (axially aligned) can be used to excite the L(0,1). However, commercial UGW transducers excite both wave modes, due to the axial displacement of L(0,2) and L(0,1) wave modes, which means an additional ring of transducers are required to suppress the spurious wave mode. These additional rings of transducers increase the cost and weight of commercial tooling.

FE model was performed to study the waveforms generated by current commercially available UGW transducers by applying in-plane shear vibration longitudinally. Then another FE model was performed to study the waveform generated by applying compression vibration (out-of-plane). For this specific example, a 40kHz, 10-cycle Hann-windowed pulse was excited at transmitting points 0.5m away from the pipe edge. The generated waveforms in both FE models were monitored 1.5m away from the transmitting points (Fig. 3(a)). Excitation was applied using equally spaced 24 points around the circumference to suppress flexural modes and transmit only axisymmetric modes in the UGW frequency region.

Fig. 3(b) and (c) illustrates the predicted time-domain data from the FE models and displacement caused by each transducer arrangement (in-plane shear vibration and out-of-plane vibration, respectively). Predicted waveforms are labelled based on the time-of-flights information extracted from dispersion curves (Fig. 1). Fig. 3(b), illustrates the waveforms generated by longitudinally aligned UGW transducers. Both the L(0,1) and the L(0,2) wave modes were generated due to the axial displacement in both modes. Furthermore, it is evident from the Fig. 3(b) that the L(0,2) has mostly axial displacement. Therefore compression (out-of-plane) transduction suppresses the L(0,2) wave mode and transmit the L(0,1) in relative isolation (Fig. 3(c)). Based on this study, there will be no need of additional rings transducers to suppress the L(0,2) and the data interpretation will be easier due to the mode purity.

3. Empirical validation

Compression transducers (out-of-plane vibration) are designed for the same dimensions as the current commercial UGW thickness-shear transducers to be used with the existing UGW hardware. Laboratory experiments have been performed on an 8-inch schedule 40 steel pipe (outer diameter: 219.1mm and wall thickness: 8.18mm). To validate

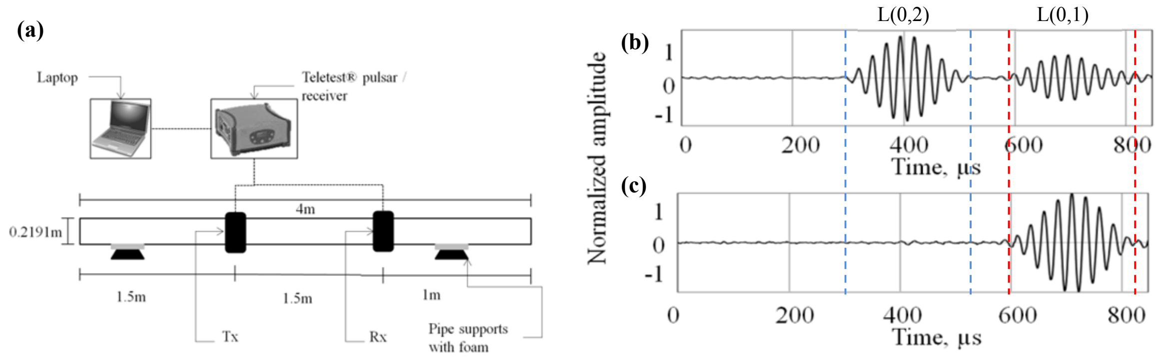

Figure 4: (a) experimental setup and monitored waveforms generated by (b) in-plane shear longitudinal vibration and (c) out-of-plane (compression) vibration

the FEA results in Section 2, a ten cycle Hann-windowed 40kHz pulse has been applied using 24 evenly spaced commercial UGW transducer (longitudinally aligned) and compression transducers. Generated waveforms are captured 1.5m away from the excitation. The layout of the experiment and the results are illustrated in Fig. 4.

There is a good agreement with the predicted FE results in Section 2 and experimental results in Section 3. Based on these results, the most adequate way to excite the L(0,1) in isolation for UGW inspection is using transduction with compression vibration and the L(0,2) is suppressed due to the out-of-plane vibration. Therefore, there is no need of additional rings of transducers to suppress L(0,2) wave mode. This reduces the cost and weight of UGW inspection tools. Furthermore, it will make the data interpretation less complicated.

4. Conclusion

The aim of the work presented was to study the potential of adopting the L(0,1) wave mode for UGW inspection of pipelines. In the literature, less attention has been given to the UGW inspection using the L(0,1) guided wave mode due to its dispersive and attenuative properties. However, dispersion could be minimised by selecting an appropriate frequency and/or dispersion compensation techniques [5] could be used. Attenuation also differs in different frequency regions so it is possible to create the test with low attenuation [11]. Therefore, a combination of careful frequency selection and application of appropriate signal processing procedures make inspection with the L(0,1) a viable prospect. Having higher number of flexural modes will enhance the capability of flaw sizing techniques and UGW focusing methods. Suitable transduction technique has been investigated for exciting the L(0,1) in isolation. It was validated that the compression transducers are capable of exciting the L(0,1) in isolation for UGW inspection of pipelines. This eliminates the need of having additional rings of transducers to suppress spurious wave modes. This reduces the cost and weight of UGW inspection tooling.

Further work will be performed to study the UGW inspection using the L(0,1) wave mode for flaw sizing and UGW focusing. Furthermore, the UGW inspection of coated and buried pipelines using the L(0,1) need to be investigated.

Acknowledgements

The authors gratefully acknowledge TWI Ltd and the Centre for Electronic System Research (CESR) of Brunel University for funding that made this study possible.

References

[1] A. H. Meitzler, "Mode Coupling Occurring in the Propagation of Elastic Pulses in Wires," *Journal of Acoustical Society of America,* vol. 33, no. 4, pp. 435-445, 1961.

[2] M. G. Silk and K. F. Bainton, "The propagation in metal tubing of ultrasonic wave modes equivalent to lamb waves," *Ultrasonics,* vol. 17, no. 1, pp. 11-19, 1979.

[3] J. L. Rose, "An introduction to ultrasonic guided waves," in *4th Middle east NDT conference and exhibition*, Kingdom of Bahrain, 2007.

[4] J. L. Rose, "Standing on the shoulders of giants : An example of guided wave inspection," *Materials Evaluation,* vol. 60, pp. 53-59, 2002.

[5] P. D. Wilcox , "A Rapid Signal Processing Technique to Remove the Effect of Dispersion from Guided Wave Signals," *IEEE Transaction on Ultrasonics, Ferroelectrics and Frequency Control,* vol. 50, no. 4, pp. 419-427, 2003.

[6] P. D. Wilcox, M. J. S. Lowe, and P. Cawley, "Mode and trasnducer selection of long range lamb wave inspection," *Journal of Intelligent Material Systems and Structures,* vol. 12, pp. 553-565, 2001.

[7] S. Fateri, N. V. Boulgouris, A. Wilkinson, W. Balachandran, T-H. Gan, "Frequency-Sweep Examination for Wave Mode Identification in Multimodal Ultrasonic Guided Wave Signal," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* vol. 61, no. 9, pp. 1515-24, 2014.

[8] R. Sanderson, "A closed form solution method for rapid calculation of guided wave dispersion curves for pipes," *Wave Motion,* vol. 53, pp. 40-50, 2014.

[9] R. M. Sanderson, "Long range ultrasonic guided wave focusing in pipe with application to defect sizing," in *International Congress on Ultrasonics*, Vienna, 2007.

[10] T. Hayashi, K. Kawashima, Z. Sun, and J. L. Rose, "Analysis of flexural mode focusing by a semianalytical finite element method," *Journal of Acoustical Society of America,* vol. 113, no. 3, pp. 1241-1248, 2002.

[11] W. B. Na and H. S. Yoon, "Wave-attenuation estimation in fluid-filled steal pipes: the first longitudinal guided wave mode," *Russian Journal of Nondestrcutive Testing,* vol. 43, no. 8, pp. 549-554, 2007.

[12] ABAQUS, "ABAQUS Version 6.13 user's manual," Simulia, 2013.

[13] D. N. Alleyne, M. J. S. Lowe, and P. Cawley, "The reflection of guided waves from circumferential notches in the pipe," *ASME Journal,* vol. 65, pp. 635-641, 1998.

[14] P. S. Lowe, S. Fateri, R. Sanderson, and N. V. Boulgouris, "Finite Element Modelling of the Interaction of Ultrasonic Guided Waves with Coupled Piezoelectric Transducers," *Insight - The journal of the British institute of non-destructive testing,* vol. 56, no. 9, pp. 505-508, 2014.

[15] S. Fateri, P. S. Lowe, B. Engineer, and N. V. Boulgouris, "Investigation of Ultrasonic Guided Waves Interacting with Piezoelectric Transducers," *IEEE Sensors Journal,* p. DOI 10.1109/JSEN.2015.2414874, 2015.