Ultrasonics 65 (2016) 228–241

Contents lists available at ScienceDirect

Ultrasonics

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

On the scattering of elastic waves from a non-axisymmetric defect in a coated pipe

Wenbo Duan [a],*, Ray Kirby [b], Peter Mudge [c]

[a] Brunel Innovation Centre, Brunel University, Uxbridge, Middlesex UB8 3PH, UK
[b] School of Engineering and Design, Brunel University, Uxbridge, Middlesex UB8 3PH, UK
[c] NDT Technology Group, TWI Ltd, Cambridge CB21 6AL, UK

ARTICLE INFO

Article history:
Received 6 July 2015
Received in revised form 2 September 2015
Accepted 24 September 2015
Available online 1 October 2015

Keywords:
Guided wave
Non-axisymmetric defect
Hybrid finite element method
Dispersion and scattering analysis

ABSTRACT

Viscoelastic coatings are often used to protect pipelines in the oil and gas industry. However, over time defects and areas of corrosion often form in these pipelines and so it is desirable to monitor the structural integrity of these coated pipes using techniques similar to those used on uncoated pipelines. A common approach is to use ultrasonic guided waves that work on the pulse-echo principle; however, the energy in the guided waves can be heavily attenuated by the coating and so significantly reduce the effective range of these techniques. Accordingly, it is desirable to develop a better understanding of how these waves propagate in coated pipes with a view to optimising test methodologies, and so this article uses a hybrid SAFE-finite element approach to model scattering from non-axisymmetric defects in coated pipes. Predictions are generated in the time and frequency domain and it is shown that the longitudinal family of modes is likely to have a longer range in coated pipes when compared to torsional modes. Moreover, it is observed that the energy velocity of modes in a coated pipe is very similar to the group velocity of equivalent modes in uncoated pipes. It is also observed that the coating does not induce any additional mode conversion over and above that seen for an uncoated pipe when an incident wave is scattered by a defect. Accordingly, it is shown that when studying coated pipes one need account only for the attenuation imparted by the coating so that one may normally neglect the effect of coating on modal dispersion and scattering.

1. Introduction

Viscoelastic materials are often used as coatings on the outer surface of pipelines in order to protect the pipe from external damage and corrosion. However, over time it is possible for these coatings to degrade and for regions of corrosion or other defects to form within the pipe substrate. Accordingly, it is desirable to monitor the integrity of the pipe and a fast and efficient way to do this is through the use of non-destructive testing (NDT) techniques such as long range ultrasonic testing (LRUT) [1,2]. The application of LRUT to coated pipes involves sending a guided wave along the pipe wall, but this technique is less successful for coated pipes because the viscoelastic coating attenuates the ultrasonic wave as it travels along the pipe wall. This has the effect of significantly reducing the range over which LRUT can be successfully used in the location of defects such as corrosion. This presents a significant problem because LRUT is an important tool for interrogating pipelines and the use of viscoelastic coatings is relatively widespread. It is desirable, therefore, to try and develop a better understanding of the way in which a coating attenuates an ultrasonic wave, as well as how it affects the scattering of waves from defects. One approach to achieving a better understanding is through the development of theoretical models, however there are very few articles in the literature that use theoretical models to analyse scattering from defects in a pipeline coated with a viscoelastic material. Accordingly, this article utilises a three dimensional model that is suitable for analysing scattering from defects of arbitrary shape in a pipe of arbitrary length coated with a viscoelastic material. In doing so this model moves away from relying on dispersion curves in order to analyse a scattering problem that is more representative of problems found in the field.

A typical pipeline consists of a long and uniform pipe in which the defect, or region of corrosion, forms only over a short section of the pipe. LRUT works by sending an incident pulse down the pipe and then recording the reflected pulse scattered by the defect. The energy contained within the incident and reflected pulse travels as a series of eigenmodes and so one must be careful to excite the appropriate mode, or modes, as well as to retain some understanding of the characteristics of each mode when interpreting the returning pulse, and here a knowledge of group velocity is

---

* Corresponding author.

http://dx.doi.org/10.1016/j.ultras.2015.09.019
0041-624X/© 2015 The Authors. Published by Elsevier B.V.

important when distinguishing modal content. Therefore, understanding the properties of the pipe eigenmodes is very important in the practical application of LRUT and so a common starting point for a theoretical analysis of coated pipes is to find the pipe eigenmodes, or dispersion curves as they are known. This approach is illustrated for coated pipes by Barshinger and Rose [3], who applied a global transfer matrix method to compute the phase and attenuation of axisymmetric longitudinal modes. The global matrix method derives an analytic expression for the governing dispersion relation and so numerical routines are necessary to find the complex roots of this equation. Root finding in the complex plane is often difficult and time consuming, especially at higher frequencies [3] and so it is advantageous to use alternative methods. Accordingly, numerical techniques are becoming increasingly popular and one of the most reliable and efficient methods for obtaining the eigenmodes of a uniform structure is the semi analytic finite element (SAFE) method. This approach substitutes an analytic expression for the displacement in the axial direction into Navier's governing equation and then uses the finite element method to solve the resulting two dimensional eigenequation. Thus, one only needs to mesh the cross section of the structure, and the SAFE method may be applied to structures with an arbitrary cross-section provided they are uniform in the axial direction. A rigorous introduction to the SAFE method is provided by Bartoli et al. [4], who proceed to apply the method to a waveguide of arbitrary cross-section, as well as a viscoelastic plate; for other examples of the application of the SAFE method see [5–9]. Mu and Rose [10] also applied the SAFE method to pipes with a viscoelastic coating, and by using an analytic expansion for the circumferential direction they were able to further reduce the problem to one dimension. Moreover, through the use of an orthogonality relation for the pipe eigenmodes, Mu and Rose were able to sort values for phase velocity and attenuation for a large number of propagating eigenmodes. Further applications of the SAFE method to problems involving energy dissipation include the work of Castaings and Lowe [11], who calculate the eigenmodes for a waveguide of arbitrary cross-section that is surrounded by an absorbing region, and Marzani et al. [12] who examined multi-layered structures and computed the energy velocity for the eigenmodes, which is generally more appropriate than group velocity for structures in which material damping is present [13]. Thus, the SAFE method has now been shown to deliver a reliable and efficient means for finding the eigenmodes in a waveguide containing material damping and so this method is well suited to studying coated pipes. Accordingly, this article will make use of the SAFE method to calculate eigenmodes for uniform regions of a coated pipe and in the section that follows the SAFE method is applied to a two dimensional problem.

The SAFE method is very useful for finding the eigenmodes in an infinitely long structure, however the eigenexpansion assumes that the structure is uniform. If one is also to model the scattering from a defect then this adds considerable additional complexity, especially if one also wishes to study a non-axisymmetric defect. Modelling difficulties are caused by the non-uniformities in the structure and whilst it is possible simply to numerically discretise an entire pipe this likely to require extremely high numbers of degrees of freedom even for modest pipe lengths. Moreover, discretising the entire pipe obviously cannot be achieved if the pipe is infinite, and so this approach normally requires some form of non-reflecting boundary in order to close the problem for an equivalent finite length of pipe. An example of the finite element method was presented by Hua and Rose [14], who studied a short length of coated pipe. Hua and Rose used commercial software and studied the attenuation of guided waves in a uniform pipe where there is no additional mode conversion at the end of the pipe, however this method will quickly generate excessive degrees of freedom if one moves to more representative geometries. Predoi et al. [15] used an absorbing boundary layer method to study scattering from a defect in a two dimensional viscoelastic plate and it is clear that extension to three dimensions is likely to become computationally expensive. It is also possible to reduce computational expenditure by introducing higher order finite elements and Żak [16] demonstrates the application of the spectral element method to wave propagation in a plate. The spectral finite element is now well developed for structural health monitoring and the increase in computational efficiency that this provides means that it is now capable of being applied to relatively large structures [17], however one must still mesh the entire structure and this is not always the most attractive option, especially for structures such as pipelines that are long and slender. Moreover, structures such as pipelines also have a relatively simple geometry and it is possible to take advantage of this when developing a numerical model. This is achieved by using alternative methods for modelling wave propagation in the long uniform sections found in pipe installations, or similar guided wave applications. For example, Galán and Abascal [18] used a hybrid boundary element-finite element approach to study scattering from a defect in a plate coated with a viscoelastic material; this approach then reduces the degrees of freedom required in the uniform section through the use of a boundary element discretisation. An alternative approach that is potentially even more efficient is to use a modal expansion for the uniform section of pipe and to couple this to a numerical discretisation that surrounds only the defect being studied. This will radically reduce the number of degrees of freedom required when compared to a full discretisation and in principle it can be used for any length of pipe without incurring additional computational costs. A relevant example of this approach for uncoated pipes is the method of Zhou et al. [19], who used the wave finite element method to solve the eigenequation in the uniform section, and then coupled this to a finite element discretisation surrounding the defect. Recently Benmeddour et al. [20] used a hybrid SAFE-finite element (FE) method to analyse elastic wave propagation in a solid cylinder, and Duan and Kirby [21] used a similar method to analyse elastic wave propagation in an uncoated pipe. The article by Duan and Kirby contains a more detailed discussion about these and other alternative numerical approaches and so these will not be discussed further here. However, it is noticeable that in the literature the only application of a hybrid SAFE-FE approach to coated pipes was that reported by Kirby et al. [22,23]. The models developed by Kirby et al. were used primarily to deduce the bulk shear and longitudinal properties of the viscoelastic coating, and to do this it was necessary only to study the axisymmetric problem. Therefore, Kirby et al. restricted their analysis to either torsional [22] or longitudinal [23] modes, and so these approaches are not suitable for studying the more general problem of scattering from non-axisymmetric defects.

The aim of this article is to analyse scattering from non-axisymmetric defects in coated pipes using the hybrid SAFE-FE method. Relevant examples of the application of this method to elastic wave propagation in circular geometries include the articles by Benmeddour et al. [20], and Duan and Kirby [21]. Note that Benmeddour et al. use a variational formulation, whilst Duan and Kirby use a weighted residual formulation to derive the final system of equations. Thus, in Section 2 a weighted residual formulation is adopted for the three dimensional problem. In Section 3 predictions generated using a three dimensional model are validated against two dimensional predictions and measurements. In Sections 4 and 5 predictions are generated that quantify scattering from a non-axisymmetric defect representative of corrosion in a coated pipe, and here predictions are presented in the frequency and time domain. Parametric studies are also undertaken and