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A one dimensional numerical approach for computing the eigenmodes of elastic waves in buried pipelines

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ABSTRACT

Ultrasonic guided waves are often used in the detection of defects in oil and gas pipelines. It is common for these pipelines to be buried underground and this may restrict the length of the pipe that can be successfully tested. This is because acoustic energy travelling along the pipe walls may radiate out into the surrounding medium. Accordingly, it is important to develop a better understanding of the way in which elastic waves propagate along the walls of buried pipes, and so in this article a numerical model is developed that is suitable for computing the eigenmodes for uncoated and coated buried pipes. This is achieved by combining a one dimensional eigensolution based on the semi-analytic finite element (SAFE) method, with a perfectly matched layer (PML) for the infinite medium surrounding the pipe. This article also explores an alternative exponential complex coordinate stretching function for the PML in order to improve solution convergence. It is shown for buried pipelines that accurate solutions may be obtained over the entire frequency range typically used in long range ultrasonic testing (LRUT) using a PML layer with a thickness equal to the pipe wall thickness. This delivers a fast and computationally efficient method and it is shown for pipes buried in sand or soil that relevant eigenmodes can be computed and sorted in less than one second using relatively modest computer hardware. The method is also used to find eigenmodes for a buried pipe coated with the viscoelastic material bitumen. It was recently observed in the literature that a viscoelastic coating may effectively isolate particular eigenmodes so that energy does not radiate from these modes into the surrounding [elastic] medium. A similar effect is also observed in this article and it is shown that this occurs even for a relatively thin layer of bitumen, and when the shear impedance of the coating material is larger than that of the surrounding medium.

1. Introduction

It is common to locate defects or ruptures in pipelines by monitoring the propagation of acoustic energy travelling along the walls of the pipe. For example, in non-destructive testing an ultrasonic guided wave is used to interrogate the structural integrity of the pipeline [1,2], whereas at much lower [audio] frequencies one may detect propagating elastic waves generated by pipe ruptures [3,4]. These techniques are well developed and they generally work well for pipeline applications

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where the attenuation of the propagating wave is negligible. However, in many pipeline applications it is common for some form of attenuation to be present. For example, viscoelastic coatings are often present and they attenuate energy as the wave travels along the pipe wall. This limits the inspection range of non-destructive techniques such as long range ultrasonic testing [5–7]. Furthermore, pipelines are often buried underground and acoustic energy radiates out from the pipe so that the energy remaining in the pipe wall is reduced [4]. This means that it is potentially more difficult to use pulse-echo based techniques to locate defects and ruptures in pipes that are buried and/or coated. Accordingly, this article presents a fast numerical method suitable for obtaining the eigenmodes for a buried pipe, which may then be used to optimise detection techniques.

In long range ultrasonic testing, acoustic energy is generated using transducers attached around the circumference of a pipe. If one assumes that the pipeline of interest is long and slender then the acoustic energy travels along the pipe walls in a discrete set of pipe eigenmodes. Knowledge of the properties of these eigenmodes is essential in order to fully interpret information obtained from a testing regime. A popular approach for obtaining these eigenmodes is through the solution of an analytic expression for the governing dispersion relation. For example, Lowe et al. [8,9] show that by adopting a general matrix method it is possible to obtain eigenmodes for multiple layers, which enables the addition of viscoelastic coatings and/or a surrounding elastic medium such as that encountered by buried pipes [10–12]. Analytic techniques have also been used to study the signals generated by pipe ruptures, for example Muggleton et al. [4] obtained the axisymmetric modes for a buried fluid-filled plastic pipe. The use of analytic techniques to find guided wave properties in buried or embedded structures does however present a number of challenges, and these are mostly associated with finding the roots of an analytic dispersion relation. When one adds complexity to the problem, such as through the addition of a coating and/or a surrounding elastic medium, then root finding becomes ever more problematic. This is because it becomes much harder to track and locate roots in the complex plane and one needs to develop sophisticated algorithms to do this over multiple frequencies. Furthermore, if one wishes to find a large number of eigenmodes then the difficulties with root finding multiply, and it is common to miss modes when attempting to track large numbers of roots through the complex plane. This means that for problems in which complex roots are present, and where one would like to locate a significant number of these roots, root finding can become time consuming and difficult to automate [13]. It is, therefore, not surprising to see that those modes obtained following the solution of an analytic dispersion relation are generally restricted to lower order/axisymmetric modes. For instance, Leinov et al. examine T(0,1) and L(0,2) [12], whereas for imbedded bars Pavlakovic et al. [14] restrict their analysis to [axisymmetric] longitudinal modes and the first flexural mode. Simmons et al. [15] also used an analytic expression to obtain axisymmetric modes for buried bars, or rods, and showed how the argument principle may be used to aid in root finding.

If one wishes to avoid root finding then it is necessary to move towards numerical methods. Whilst this change of approach may be desirable for the analysis of coated pipes and/or more complex multi-layered problems, one may argue that numerical methods are unavoidable when large numbers of eigenmodes are required for use in techniques developed for wave scattering problems [2,16]. A number of different numerical methods are available for finding the eigenmodes for pipes; however, the authors favour the so-called semi-analytic finite element (SAFE) method as it is computationally efficient and it may readily be applied to pipelines with multiple layers, see for example Marzani et al. [17], and for coated pipes see refs. [5–7], as well as Mu and Rose [18]. The extension of the SAFE method to problems involving structures embedded in an infinite medium is, however, less straightforward. The SAFE method requires the solution domain to be closed, which presents a problem for pipes buried in a nominally infinite, or open, medium. This problem was first addressed by Castaings and Lowe [19], who studied a steel rod surrounded by concrete. Castaings and Lowe used a finite element discretisation for the steel rod, and a concentric portion of the surrounding concrete, they then closed the problem with an outer absorbing layer designed to prevent erroneous reflections from the [artificial] boundary of the problem. Castaings and Lowe successfully obtained low order longitudinal and flexural modes, although the accuracy of the method depends on the success of their absorbing layer. Here, Castaings and Lowe note problems with the ability of the layer to absorb longer wavelengths, which was seen in inaccuracies found with the computation of leaky modes with high radiation angles, as well as those modes found at lower ultrasonic frequencies. Moreover, even away from these limiting cases it was found to be necessary to extend the outer boundary of the problem to 16 times the radius of the rod. Thus, the method requires the use of a large number of degrees of freedom, even for a relatively thin rod, and so the absorbing layer proposed by Castaings and Lowe is unlikely to be computationally efficient for problems involving much larger pipework.

An alternative to the use of an absorbing layer was later proposed by Hua et al. [20], who replaced this layer with infinite elements. Hua et al. analysed coated and uncoated pipes buried in soil and they obtained a large number of axisymmetric and flexural modes. The infinite elements used by Hua et al. are popular in the solution of the Helmholtz Equation because they have the potential to be more computationally efficient than absorbing layers. The application of infinite elements requires the discretisation of the exterior domain using elements with an asymptotic or wave based shape function so that one may properly enforce the appropriate radiation boundary condition. However, in regions of high modal scattering it is necessary to increase the radial order of the infinite elements in order to maintain solution accuracy; moreover, infinite elements are also known to suffer from problems with numerical instabilities [21].

Alternative numerical methods for analysing embedded waveguides include a Scaled Boundary Finite Element Method (SBFEM) proposed by Gravenkamp et al. [22,23]. Gravenkamp et al. used the SBFEM in the same way that previous authors had applied the SAFE method, but this time they closed the problem using a numerical dashpot, which was chosen to simulate the appropriate boundary condition. Gravenkamp et al. successfully applied this method to axisymmetric problems