A Modelling Approach for Guided Wave Propagation in Coated and Buried Pipes

Wenbo DUAN¹, Anurag DHUTTI¹, Abbas MOHIMI¹, Peter MUDGE²,
Cem SELCUK¹, Tat-Hean GAN¹,²
¹ Department of Mechanical, Aerospace and Civil Engineering, Brunel University
London, Uxbridge, Middlesex, UK, UB8 3PH
² Integrity Management Group, TWI Ltd, Cambridge, UK, CB21 6AL

Contact e-mail: wenbo.duan@brunel.ac.uk; tat-hean.gan@brunel.ac.uk

Abstract. Ultrasonic guided waves are routinely used for non-destructive testing of defects in pipelines, since guided waves have an advantage of inspecting long range of uncoated pipes, compared to bulk waves. Nuclear power plants have extensive piping systems, some of which are buried and generally carry cooling water. The environment beneath the surface of earth can cause corrosion. These pipes are therefore protected by coating of some corrosion resistant materials. With the presence of coating, sound energy is heavily absorbed by the viscoelastic material, and the scanning distance of guided waves is significantly reduced. Furthermore, for buried pipes, the sound energy will radiate into the surrounding soil. To obtain an optimum ultrasonic inspection regime for these pipes, it is important that the properties of guided waves in coated and buried pipes are well understood. In this paper, a semi-analytical finite element (SAFE) method is used to study wave propagation characteristics in coated pipes. For buried pipes, the surrounding medium is assumed to be infinite, and a perfect matched layer (PML) is proposed to model wave propagation in the surrounding medium. The SAFE model in the waveguide is coupled to the PML technique in the surrounding medium, and leaky modes are presented. Dispersion properties are presented for both coated and buried pipes. These properties can indicate the most suitable mode to be used for a particular problem.

1. Introduction

Ultrasonic guided waves have been used for defect detection in pipelines for a few decades [1,2]. It normally works on the pulse-echo principle where a short duration pulse is transmitted to and propagates through the pipe wall. The pulse will be scattered by any defect inside the pipe wall. The time of flight between the incident and reflected pulses can then be used to calculate the position of the defect [3]. Ultrasonic guided waves can scan dozens of meters of pipeline from a single test location for an uncoated and unburied pipe. However, under certain conditions pipelines have to be coated to prevent corrosion. The scanning distance of ultrasonic waves is then significantly reduced because the coating materials are generally viscoelastic and absorb sound energy [4-6].

In nuclear power plants, pipelines are widely used to transfer fluids such as cooling water. The safety of the power plant pipelines is especially important, as pipeline failures may produce catastrophic consequences. Furthermore, access to these pipelines is often limited, and it is desirable to have a non-destructive inspection method to ensure their...
structural integrity. It is also common to see that these pipes are coated and/or buried in nuclear power plants. Under such conditions, long range ultrasonic testing method is especially appealing as a non-destructive tool as it only requires limited access to the pipe. However, when a pipe is buried underground, the scanning distance of guided waves is reduced because sound energy leaks into the surrounding medium [7, 8]. Furthermore, a pipe buried in soil is more susceptible to corrosion problems, and it is often necessary to coat the pipe before it is buried. In this case, sound absorption and sound leakage may work simultaneously. It is thus important to understand the acoustic characteristics of guided waves in these complicated conditions in order to achieve best inspection regime.

In this paper, a modelling approach is used to study guided wave propagation characteristics in coated and buried pipes. A SAFE method is adopted so that a three dimensional wave propagation problem is transformed into a two dimensional eigensolution problem. Furthermore, for pipes and rods, the waveguide is axisymmetric, so that harmonic solutions can be assumed for wave motion around the circumference of the pipe. This allows a two dimensional eigen problem to be reduced to a one dimensional problem [9]. For buried pipes, the PML technique is used to represent the infinite medium surrounding the pipe so that the computation domain is closed. The coordinates in the PML layer are stretched in the radial direction only, and wave motion in the circumferential and axial direction of the pipe remains unchanged. This allows a one dimensional eigen problem to be formulated for a buried pipe as well [9]. The structure of the paper is as follows. In section 2, the theory for the SAFE and the PML technique is briefly introduced. In section 3, predictions are given for a coated pipe, a buried pipe, and a pipe that is both coated and buried. Comparisons are made between these cases, and some useful conclusions are drawn in section 4.

2. Theory

The governing equation for the pipe and the coating is given by Navier’s equation [9]. For the infinite medium surrounding the pipe or coating a PML method is used. Coordinate stretching is applied to the radial dimension only, so that the radial coordinate \( r \) is replaced by a stretched coordinate \( \tilde{r} \) as:

\[
\tilde{r} = \int_0^{\tilde{r}} \xi_r(s) \, ds
\]

where \( \xi_r \) is a no-where zero, continuous, complex-valued coordinate stretching function.

The governing equations in the bounded PML region can thus be defined as:

\[
\rho_m \frac{\partial^2 u_r}{\partial t^2} = \frac{1}{\xi_r} \frac{\partial}{\partial r} \left( \frac{\partial \sigma_{rr}}{\partial r} + \frac{1}{\tilde{r}} \frac{\partial \sigma_{r\theta}}{\partial \theta} + \frac{\partial \sigma_{rz}}{\partial z} + \frac{1}{\tilde{r}} (\sigma_{rr} - \sigma_{r\theta}) \right)
\]

\[
\rho_m \frac{\partial^2 u_\theta}{\partial t^2} = \frac{1}{\xi_r} \frac{\partial}{\partial r} \left( \frac{\partial \sigma_{r\theta}}{\partial r} + \frac{1}{\tilde{r}} \frac{\partial \sigma_{r\theta}}{\partial \theta} + \frac{\partial \sigma_{\theta\theta}}{\partial z} + \frac{2}{\tilde{r}} \sigma_{r\theta} \right)
\]

\[
\rho_m \frac{\partial^2 u_z}{\partial t^2} = \frac{1}{\xi_r} \frac{\partial}{\partial r} \left( \frac{\partial \sigma_{zz}}{\partial r} + \frac{1}{\tilde{r}} \frac{\partial \sigma_{z\theta}}{\partial \theta} + \frac{\partial \sigma_{zz}}{\partial z} + \frac{1}{\tilde{r}} \sigma_{rz} \right)
\]

where \( \rho_m \) is density of the surrounding medium.

The stress-strain relationships in the PML region are now given as:
\[
\sigma'_{rr} = \lambda_m \left( \frac{1}{\xi_r} \frac{\partial u'_r}{\partial r} + \frac{u'_r}{r} + \frac{1}{\xi_r} \frac{\partial u'_\theta}{\partial \theta} + \frac{\partial u'_z}{\partial z} \right) + 2\mu_m \frac{1}{\xi_r} \frac{\partial u'_r}{\partial r} \tag{3a}
\]
\[
\sigma'_{\theta\theta} = \lambda_m \left( \frac{1}{\xi_r} \frac{\partial u'_r}{\partial r} + \frac{u'_r}{r} + \frac{1}{\xi_r} \frac{\partial u'_\theta}{\partial \theta} + \frac{\partial u'_z}{\partial z} \right) + 2\mu_m \left( \frac{u'_r}{r} + \frac{1}{\xi_r} \frac{\partial u'_\theta}{\partial \theta} \right) \tag{3b}
\]
\[
\sigma'_{zz} = \lambda_m \left( \frac{1}{\xi_r} \frac{\partial u'_r}{\partial r} + \frac{u'_r}{r} + \frac{1}{\xi_r} \frac{\partial u'_\theta}{\partial \theta} + \frac{\partial u'_z}{\partial z} \right) + 2\mu_m \frac{\partial u'_z}{\partial z} \tag{3c}
\]
\[
\sigma'_{r\theta} = \mu_m \left( \frac{1}{\xi_r} \frac{\partial u'_\theta}{\partial r} - \frac{u'_\theta}{r} + \frac{1}{\xi_r} \frac{\partial u'_r}{\partial \theta} \right) \tag{3d}
\]
\[
\sigma'_{\theta z} = \mu_m \left( \frac{1}{\xi_r} \frac{\partial u'_z}{\partial \theta} + \frac{\partial u'_\theta}{\partial z} \right) \tag{3e}
\]
\[
\sigma'_{z\theta} = \mu_m \left( \frac{\partial u'_r}{\partial z} + \frac{1}{\xi_r} \frac{\partial u'_r}{\partial r} \right) \tag{3f}
\]

where \(\lambda_m\) and \(\mu_m\) are the Lamé coefficients of the surrounding medium.

The weak forms of these equations and the final global matrix for the multi-layered waveguide are given in Ref. [9], and won’t be repeated here for the sake of space.

3. Results and analysis

3.1 Coated pipe

An 8 inch schedule 40 pipe is studied here. This pipe has an outer radius \(b_1 = 109.54\) mm, and an inner radius \(a_1 = 101.36\) mm, with \(c_{T_2} = 3260\) m/s, \(c_{L_1} = 5960\) m/s, and \(\rho_1 = 7932\) kg/m³. The coating is 1.5mm bitumen. Material properties of bitumen has been reported by Kirby et al [4,5]. In this paper, the same coating material properties used in Ref. [4,5] are used here. The properties of a viscoelastic coating are defined here as \(c_{T_2} = 1/[(1/\tilde{c}_T - i\tilde{\alpha}_T)]\) and \(c_{L_2} = 1/[(1/\tilde{c}_L - i\tilde{\alpha}_L)\), where \(\tilde{c}_T\) and \(\tilde{c}_L\) denote shear and longitudinal phase velocities, respectively, and \(\tilde{\alpha}_T\) and \(\tilde{\alpha}_L\) represent the shear and longitudinal attenuation in the coating. Following Kirby et al. [4,5], bitumen coating with a thickness of 1.5 mm is analysed here, so that \(\tilde{c}_T = 750\) m/s, \(\tilde{c}_L = 1860\) m/s, \(\tilde{\alpha}_T = 3.9 \times 10^{-3}\) s/m, \(\tilde{\alpha}_L = 0.023 \times 10^{-3}\) s/m, and \(\rho_2 = 1200\) kg/m³.

The numerical model is executed on a laptop with a 2.4 GHz Intel Core™ CPU and 8 GB of RAM. Three noded line elements are used in the pipe and the coating region. Ten elements are used in the pipe and the coating region respectively, which corresponds to a minimum of 66 nodes per wavelength for the shortest bulk shear wave in the long range ultrasonic testing frequency range from 10kHz to 120kHz. Even with such a fine element density, it only takes about 0.2s to compute for each frequency, including the time spent sorting the modes.

The full energy velocity and attenuation dispersion curves are presented in Figs. 1 and 2 respectively. It can be seen that a large number of modes are present, with the largest circumferential mode number to be 33. Note that the energy velocity of modes in a coated pipe is very similar to the group velocity of the equivalent modes in an uncoated pipe [6]. The attenuation is shown in the range of 0-3.5 dB/m. Generally speaking, the modes in the same family have very similar attenuation, expect near the cutting-on frequency of a particular mode in a corresponding uncoated pipe. The attenuation of each mode increases with increase in frequency, and approaches a relatively flat region. In the frequency range from 20-120kHz, L(0,2) is relatively non-dispersive. T(0,1) is non-dispersive in the entire frequency range. However, Fig.2 shows that the attenuation of both L(0,2) and L(0,1)
increases quickly from 20kHz to 50kHz. \( L(0,2) \) and \( T(0,1) \) can thus scan a much longer distance in the frequency range below 50kHz.

Fig. 1. Energy velocity for the 8inch coated pipe. (a) \( L(0,2) \) family modes; (b) \( T(0,1) \) family modes; (c) \( L(0,1) \) family modes.

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3.2 Buried pipe

In this section, the dispersion characteristics of the same 8 inch schedule 40 pipe buried in dry sand are studied. The properties of the pipe have been reported in the previous section. The properties for dry sand are \( c_{T_m} = 105 \text{ m/s} \), \( c_{L_m} = 800 \text{ m/s} \), and \( \rho_m = 1620 \text{ kg/m}^3 \) [7].

The energy dispersion curves of the leaky modes are approximately the same as those shown in Fig. 1, and are not shown here for the sake of space. This shows that dry sand adds little stiffness and mass to the pipe. Note that a large number of radiation modes are present in this case, which have been filtered because they have little value from practical non-destructive testing point of view.

The full attenuation dispersion curves of all the leaky modes are shown in Fig. 3. Compared to the coated pipe, it can be seen that the sand buried pipe has much larger attenuation for all the modes. The coated pipe has very low attenuation in the frequency range from 20 kHz to 50 kHz for both L(0,2) and T(0,1). However, for the buried pipe, the attenuation of these two modes has increased significantly in the low frequency range. The attenuation doesn’t simply increases as frequency increases. The reason is that in the low frequency range, the radial wavelength of L(0,2) and T(0,1) is very long, thus these modes can penetrate deep into the sand [9]. This consequently means that significant amount of energy is leaked into the sand even in the low frequency range.

It is interesting to see that the most significant difference between a coated pipe and a buried pipe comes from the attenuation of the L(0,1) family modes. For a 1.5mm bitumen coated pipe, the L(0,1) modes have dominant radial displacement. These radial displacement can travel through the coating and reaches the external surface of the coating with a little displacement drop [6]. Sound energy will then be reflected back into the pipe and thus attenuation is low. However, for a buried pipe, the radial displacement can travel very long
into the sand [9]. Because the sand surrounding the pipe is considered to be infinite, sound energy is lost into the sand. This explains why the \( L(0,1) \) family modes in a buried pipe have very large attenuation compared to other modes.

Fig. 3. Attenuation for the 8inch buried pipe. (a) \( L(0,2) \) family modes; (b) \( T(0,1) \) family modes; (c) \( L(0,1) \) family modes.

3.3 Coated and buried pipe

In this section, dispersion properties are presented for the 8 inch schedule 40 pipe that is both coated and buried. The coating is 1.5mm bitumen, and the surrounding medium is dry sand. The properties of the pipe, bitumen coating and dry sand are reported in the previous two sections. The energy velocity is not changed by the presence of the coating and the surrounding sand. This shows that both bitumen and dry sand add little stiffness and mass to the pipe. The energy velocity dispersion curves are not shown here for the sake of space.

However, Fig. 4 shows that the attenuation of a leaky mode in a coated and buried pipe is lower than that of the same mode in a buried pipe. The reason is that bitumen coating
absorbs sound energy, so that modal displacement at the external surface of the coating is reduced, consequently the amount of energy that can be leaked into the surrounding medium is also reduced. Thus, viscoelastic coating material can ‘isolate’ sound energy and reduce attenuation of guided waves in buried waveguides [8,9]. Note that the attenuation of the $L(0,1)$ family modes is only slightly reduced comparing Fig. 4 with Fig. 3. This is because the sound energy of the $L(0,1)$ family modes are only slightly absorbed by bitumen, and it is the properties of the surrounding medium that determines the attenuation of the $L(0,1)$ family modes.

Fig. 4. Attenuation for the 8inch coated and buried pipe. (a) $L(0,2)$ family modes; (b) $T(0,1)$ family modes; (c) $L(0,1)$ family modes.
4. Conclusions

In this paper, a one-dimensional numerical model is proposed to study dispersion characteristics of guided waves in pipes that may be coated and/or buried. A semi-analytical finite element method is used to reduce a three-dimensional wave propagation problem to a one-dimensional eigenvalue problem. Furthermore, the perfectly matched layer method is used to close the infinite medium surrounding the pipe.

Dispersion properties of a coated pipe, a buried pipe, a coated and buried pipe are presented and compared here. It is shown that both coating and sand add little stiffness and mass to the pipe. Attenuation is strongest in the buried pipe, while weakest in the coated pipe. Attenuation properties of the L(0,2) and T(0,1) family modes in the coated and buried pipe is largely determined by the coating material, while attenuation properties of the L(0,1) family modes in the coated and buried pipe are largely determined by the infinite surrounding medium.

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References