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Interaction of low-frequency axisymmetric ultrasonic guided waves with bends in pipes of arbitrary bend angle and general bend radius

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ABSTRACT

The use of ultrasonic guided waves for the inspection of pipes with elbow and U-type bends has received much attention in recent years, but studies for more general bend angles which may also occur commonly, for example in cross-country pipes, are limited. Here, we address this topic considering a general bend angle φ, a more general mean bend radius R in terms of the wavelength of the mode studied and pipe thickness b. We use 3D Finite Element (FE) simulation to understand the propagation of fundamental axisymmetric L(0,2) mode across bends of different angles φ. The effect of the ratio of the mean bend radius to the wavelength of the mode studied, on the transmission and reflection of incident wave is also considered. The studies show that as the bend angle is reduced, a progressively larger extent of mode-conversion affects the transmission and velocity characteristics of the L(0,2) mode. However the overall message on the potential of guided waves for inspection and monitoring of bent pipes remains positive, as bends seem to impact mode transmission only to the extent of 20% even at low bend angles. The conclusions seem to be valid for different typical pipe thicknesses b and bend radii. The modeling approach is validated by experiments and discussed in light of physics of guided waves.

1. Introduction

Ever since Gazis [1] proposed the solution to the general problem of the harmonic wave propagation in hollow cylinders, the use of ultrasonic guided waves for the inspection of pipe structures has received considerable research interest. Although early work already considered methods for practical inspection of tubes and piping [2–5], the field saw a spurt of interest in the nineties, driven by applications in the oil and gas industry [6–13]. This research effort is well summarized in excellent review articles [14,15], while articles [16–18] discuss more recent developments. The propagation of guided ultrasonic waves in straight pipes is now well understood [19] and guided waves are today widely applied for the inspection of straight pipes and pipe sections in several industries [20–22]. Numerical solution procedures such as Finite Elements, Finite Differences, Boundary Elements, and Finite Integration are very effective for guided wave problems because of their complex, multimodal nature and especially when dealing with complex geometries [23–30].

In the last few decades, the interaction of guided waves with features such as notches, cracks, and corrosion patches in straight pipes have been studied by many researchers [31–42]. However, the propagation of guided waves across features such as bends in the pipe network is still not well understood and has been a topic for much recent research. It is often thought that bends can themselves scatter guided waves and thus mask any signatures of defects present in the bend region. Thus an understanding of the influence of bends is vital for the success of practical guided wave inspection tools. In recent years, a number of studies have been carried out on the topic of propagation of guided waves across elbow (90°) and U-bends [43–51]. A comprehensive study of the influence of pipe elbows on low-frequency Longitudinal and torsional guided waves using Finite Element (FE) models and experiments is presented in [43]. A new flexural mode tuning technique was introduced in [44] to study the testing of pipe elbow to find the defects in the elbow region. The application of ultrasonic guided waves in bent pipes in a wide frequency domain range was reported in [46] using a wide band laser ultrasonic system together with time–frequency analysis. Also, a semi-analytical approach was used to develop a calculation technique for the generation of guided waves in pipes and rails [47,48] and accuracy of this technique is verified experimentally. A similar approach was used to verify a flaw detection method by understanding the influence of elbow curvature on mode configuration and propagating velocity [51]. A numerical time-domain scheme based on the electrodynamics finite integration technique (EFIT) for modeling elastic wave propagation in pipe-like structures and pipe bends was proposed in [49].

The main drawback of most of the previous studies is that they are mostly limited only to cases involving an elbow bend (with the exception of perhaps [49] where complex combinations of elbow

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and U-bends are considered) with a large mean-bend radius. Recent research based on wave finite elements [52] and FE-modal decomposition hybrid models [53] offers more generic frameworks, however results are again presented only for the elbow case. Studies for other more general bend angles, which may also occur commonly (for example in cross-country pipes), are limited. Moreover, none of the previous studies is based on the wavelength of the mode used for inspection and this is a very important property when dealing with wave propagation problems.

The objective of the present paper is to understand the propagation of low-frequency axisymmetric Longitudinal L(0,2) mode [9] in pipes with axial bends of more general bend angle φ, mean bend radius R and different typical pipe thicknesses b. The knowledge so gained will be helpful to differentiate the effects of bends from those due to possible defects in the bend region. Such understanding is also important for the success of improved imaging and monitoring of bends using techniques such as ultrasonic tomography [54]. We consider several bend angles in the range from $\varphi = 0^\circ$ (no bend) to $\varphi = 180^\circ$ (U-bend). When dealing with wave propagation across bends, we believe, that the ratio of the bend radius R to the operating wavelength λ constitutes a characteristic ratio that affects the physics. This aspect has not been considered in previous studies, as borne out by our survey of literature in this area. Hence we considered three regimes: sharp bend ($R/\lambda < 1$), moderate bend ($R/\lambda \approx 1$) and shallow bend ($R/\lambda \gg 1$). We found that very sharp bends are not generally preferred, due to manufacturing and practical constraints and hence we chose to study the moderate ($R \approx \lambda$) and shallow ($R \approx 10\lambda$) bend regimes. Most previous work [43–51] has been carried out in the shallow bend regime. Typical pipe dimensions and thicknesses of interest to the industry are also considered.

Our studies are performed using FE analysis in three dimensions (3D), implemented in a commercial code [55]. The FE modeling procedure is validated by experiments using novel MsS Transducers [56] bonded to the pipe to achieve repeatable results and demonstrate practical health monitoring of bends. Also, a key advantage of this technique is the ability to produce an almost pure L(0,2) mode in the pipe, as opposed to crystal based methods which are applied at discrete circumferential locations. We must point out though, that this advantage is somewhat balanced by some noise in the measured signals and also by the fact that we are currently mainly able to pick up in-plane displacements by this technique. Finally, our focus in this paper is the possible ability of the L(0,2) mode to monitor defects at the bend. Thus, although as we show below, the L(0,2) mode converts to other non-axisymmetric modes upon interacting with bends, we focus our attention on the transmitted L(0,2) mode, as this gives inspectors a simple and straightforward handle on possible defects at the bend.

This paper is organized as follows. We start with a presentation of the dispersion curves of guided waves in hollow cylinders (pipes) to predict their characteristics and define our problem statement for this set of studies. We then introduce the method used for FE simulations, followed by a description of the experimental procedure used for validation the simulation procedure. Simulation results for the case of ratio of mean bend radius to wavelength of the mode, $R/\lambda \approx 1$ followed by the case of $R/\lambda \approx 10$ are presented and verified by experiments. Results are compared for discussion, after which we conclude with directions for further work.

2. Background

2.1. Problem studied

We consider pipes with dimensions of typical interest to chemical plant and refinery industries, with outer diameter (OD) of 60 mm and thickness of 4.5 mm (allowing for thickness variants of 3–6 mm, this covers 2 in. – Schedule 40/Schedule 80 pipes). Without loss of generality, the pipe is assumed to be made of Mild Steel. Fig. 1 shows the group velocity dispersion curves for 4.5 mm thick and 60 mm OD Mild Steel pipe obtained using DISPERSE [57] software package developed and validated at Imperial College London. As is common with guided wave problems, several wave modes exist at a given frequency, which results in a complex signal. Thus mode selection and selective generation of a single mode are important for practical long range guided wave inspection systems. A low frequency of 50 kHz was chosen for this study and the axially symmetric L(0,2) mode was used for excitation as this mode is very attractive for the practical inspection because of its simple fields and easier excitability. Moreover, this mode is non-dispersive in nature over a range of frequencies, which again is an important feature for signal interpretation in practical inspection.

The pipes studied are bent to various angles as illustrated in Fig. 2. The angle between the two straight segments of the bent pipes is called the bend angle 'φ' and we assume a uniform radius of curvature of the curved pipe segment, with a mean-bend radius 'R'. As discussed in Section 1, we study two bend radius regimes, $R/\lambda \approx 1$ (moderate bend) and $R/\lambda \approx 10$ (shallow bend) where λ is the wavelength of the L(0,2) mode at the chosen center-frequency. In-plane excitation consisting of a 5 cycle Hanning window tone burst pulse is applied through the thickness at several angular positions on one end of the pipe, as suitable to generate the L(0,2) mode. The wave travelling along the pipe is examined by monitoring it at four different positions circumferentially at a point called 'first monitoring position' before the bend, as shown in Fig. 2, in order to understand the reflection behavior of incident signal from bend. In addition, it is also monitored at a point called the 'second monitoring position' after the bend in order to capture the transmitted signal. Both numerical (Finite Element) and experimental studies are carried out and results obtained are analyzed and discussed using the theory on curved pipes reported by Demma et al. [43].

3. Methods

3.1. 3D Finite element simulations

As discussed in Section 1, numerical techniques are often required for studying guided wave propagation and scattering problems [23–42]. In many recent research articles the topic of guided waves in 'straight-curved–straight' type of bent pipes, has been studied through numerical procedures validated by experiments [43,46–48,51,60]. Here, the Finite Element time-marching procedure in three dimensions, provided by ABAQUS/Explicit [30] is used for modeling the propagation of fundamental L(0,2) mode across bends of different angles. A fully three dimensional model is required for accurate analysis of wave propagation in bent pipes.

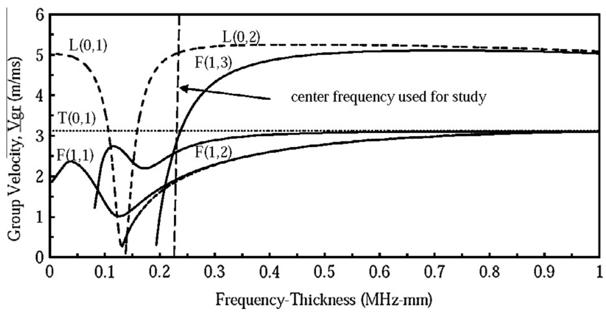

Fig. 1. Group velocity dispersion curves for a 4.5 mm thick and 60 mm OD Mild steel pipe obtained from DISPERSE [57].