The effect of pipe bend radii on guided wave propagation in small diameter pipes

Ruth Sanderson, Jianxin Gao
TWI
Granta Park, Great Abington, Cambridge, CB21 6AL, UK
01223 899000
ruth.sanderson@twi.co.uk

Abstract

Guided waves are an exciting and relatively new non-destructive testing technique used for screening pipes for corrosion. The technique works well in straight lengths of pipe and can be used to provide information about corrosion severity. However, pipe bends are known to distort the signal. This could result in false identification of flaws that are not actually there (so called ‘false positives’) or missing flaws that are present (‘false negatives’). Additionally, newly developed flaw sizing techniques rely on accurate amplitudes of reflected wave modes and would therefore become inaccurate if the propagation though a pipe bend altered these. Work has been carried out to quantify the effects of pipe bends on guided wave propagation using finite element analysis procedures. Based on an understanding of how the bends affect the signals, methods for distortion removal are discussed.

1. Introduction

Guided waves are an exciting and relatively new non-destructive testing technique used for screening pipes for corrosion. The technique works well in straight lengths of pipe and can be used to provide information about corrosion severity. However, pipe bends are known to distort the signal. This could result in false identification of flaws that are not actually there or missing flaws that are present. Additionally, the flaw sizing techniques developed [1,2] rely on accurate measurement of the amplitudes of reflected wave modes and would therefore become inaccurate if the propagation though a pipe bend altered these.

This paper contributes to the knowledge on the effects of pipe bends by calculating behaviour of guided waves in range of pipe bend radii in a small diameter pipe (where the effect of pipe bends are known to be most prevalent). An understanding of the behaviour will lead to the ability to interpret inspection data beyond pipe bends more effectively.

2. Approach

2.1 Previous work

The earliest known research on curved waveguides was when Lord Rayleigh(3) discussed the phenomenon of a gallery beneath a dome or vault or enclosed in a circular or elliptical area in which whispers can be heard clearly in other parts of the building.

More recently, Liu and Qu(4,5) investigated wave propagation in curved plates using the exact formulation of the dispersion relation. Similar work was carried out by Wilcox(6) and the mode shapes for curved plates were published by Beard(7). However, the theoretical approach taken by these authors for plates is not applicable to the more complicated geometry of pipes(8).

Some experimental research has been carried out into focusing of sound energy in and around bends. A natural flexural mode tuning technique for inspection within a pipe bend has been presented(9). This can be achieved by either a staggered spacing of angle beam transducers around the pipe or by circumferential time delay profiles applied to the multi-element angle beam transducer or segmented comb elements mounted in the plane around the circumference of the pipe. In this work relatively high frequencies were used (between 400 and 750kHz) which is well out of the operating range of commercial long range ultrasonic inspection equipment. Further studies were carried out on focusing energy via partial circumferential loading. Experimental work was carried out to investigate the reflections from a 16mm diameter hole 0.36m beyond a 90° pipe bend in a 4in Schedule 40 steel pipe. The best focus conditions for flaw detection were derived experimentally and it was shown that the hole could be detected using these techniques. However, since this technique is derived experimentally, it is only applicable to a specific case.

Finite element analysis has been used to calculate the behaviour of guided waves in and beyond bends. A simplified finite element model was used to calculate the effects of a 90° bend on the axially symmetric mode L(0,2)(10). An assumption of constant axial motion through the thickness of the pipe wall was made so that membrane elements could be used. The mode conversions caused by the bend and the effect of bend radius were reported. Additionally, the effect of frequency on the transmission of the L(0,2) mode was both predicted using the model and measured. Good agreement was achieved.

Similar studies were carried out using a 2D axisymmetric finite element modelling approach which has limitations for tight bend radii(8). The dispersion characteristics of wave modes that can propagate within pipe bends were calculated. It was reported that the phase velocity for pipe bends of the same bend radius is the same for a given frequency diameter product, providing ratio of the pipe wall thickness to the pipe diameter is the same.

In 2005, Hayashi et al presented a semi-analytical finite element approach(11). This was used to calculate transmission amplitudes of the axisymmetric modes L(0,1) and L(0,2) for a range of frequencies in a 4in Schedule 40 steel pipe. The paper points out that more detailed studies are required.

In summary, the potential for inspection in and beyond bends has been demonstrated. There is some information available in the literature quantifying the effects of pipe bends on guided waves for a limited number of cases. These have mainly concentrated on analysis of the effect of frequency and bend radius. However, the published trends demonstrate the complex behaviour of guided waves across pipe bends and to date, no technique for reconstructing the signal or removing the effects of bends has been published.

In order to gain a more in depth understanding of the propagation of guided waves in pipe bends, the present study has been carried out using full 3D finite element analysis to calculate velocity versus frequency for pipe bend wave modes for a range of different bend radii in a small diameter pipe (3” Schedule 40).

2.2 Nomenclature

Prismatic structures act as waveguides. A given prismatic structure will have a number of wave modes (ways in which it vibrates depending on the excitation arrangement and input waveform). A pipe has three main ‘families’ of wave modes named after the three basic axisymmetric wave modes that exist at low frequency: L(0,1), L(0,2) and T(0,1). The Silk and Bainton[(12)] naming convention is used throughout this paper. The letters L, F or T stand for longitudinal, flexural or torsional respectively and relate to the main direction of particle displacement of the wave mode. The first number in the brackets is the order of cyclic variation around the circumference of the pipe and the second number in the brackets is a counter index which increases with increasing frequency of a wave mode’s cut off. For example, F(3,2) is the second flexural wave mode to exist with three cycles of particle displacement variation around the circumference.

2.3 Finite Element Analyses

Finite element models of three different bend radii in a 3” Schedule 40 steel pipe (88.9mm outer diameter, 5.49mm wall thickness) were generated using ABAQUS. The models were constrained in the axial direction at each end so that standing waves were simulated. A natural frequency extraction was then performed over a range of frequencies (0-80kHz). The results from these analyses can be converted to velocity versus frequency data (i.e. dispersion curves) by determining the wavelength of each mode and multiplying by the frequency.

The bend radii studied were 3 times, 5 times and 10 times the outer diameter of the pipe. The length of each section of pipe simulated was approximately 1m. Figure 1 shows the finite element mesh used for the 10 times the diameter model. The axial element length was ~2mm, which was sufficient to capture the smallest possible wavelength (~25mm for a straight section of pipe). There were 144 elements around the circumference which, using the generally accepted rule[(13,14)] of 8 elements per wavelength, should be sufficient to capture wave modes with cyclic variations of up to order 18. There were four elements through the thickness. Similar meshes were used in the other cases. The element type used was 8-noded linear bricks (ABAQUS element type C3D8). This level of mesh refinement and element type has been successfully validated against theoretical solutions in previous work[(13)].

The material properties used for the analysis were as follows:

Young's Modulus = 207 GPa
Poisson's ratio = 0.3
Density = 7830 kg/m^3

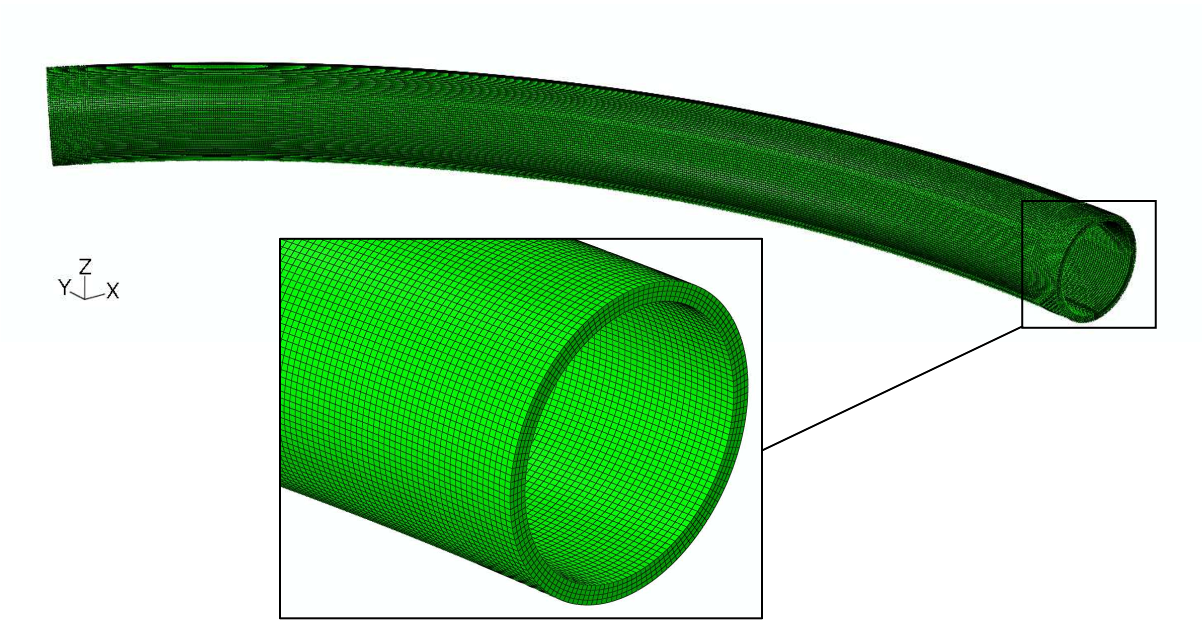


Figure 1 Finite element mesh used for natural frequency extraction model of 10 times diameter radius bend in 3" Schedule 40 steel pipe (88.9mm outer diameter, 5.49mm wall thickness).

2.4 Results and Discussion

2.4.1 Dispersion curves

The dispersion curves obtained were compared to those for a straight section of 3" Schedule 40 pipe (88.9mm outer diameter, 5.49mm wall thickness) calculated using the dispersion curve calculation software, Disperse(15). Figures 2-4 present the comparison of the dispersion curves for straight pipe to those for the tightest bend radius studied (3xOD). The order of variation around the circumference is colour coded (i.e. order 0 is grey, order 1 is black, order 2 is blue etc.). The three 'families' of wave modes are presented separately. Figures 5 and 6 present the dispersion curve comparison for the other two bend radii studied (5xOD and 10xOD respectively). Here, all three 'families' of wave modes are presented on the same graph and the colour code used is the same as for Figures 2-4.

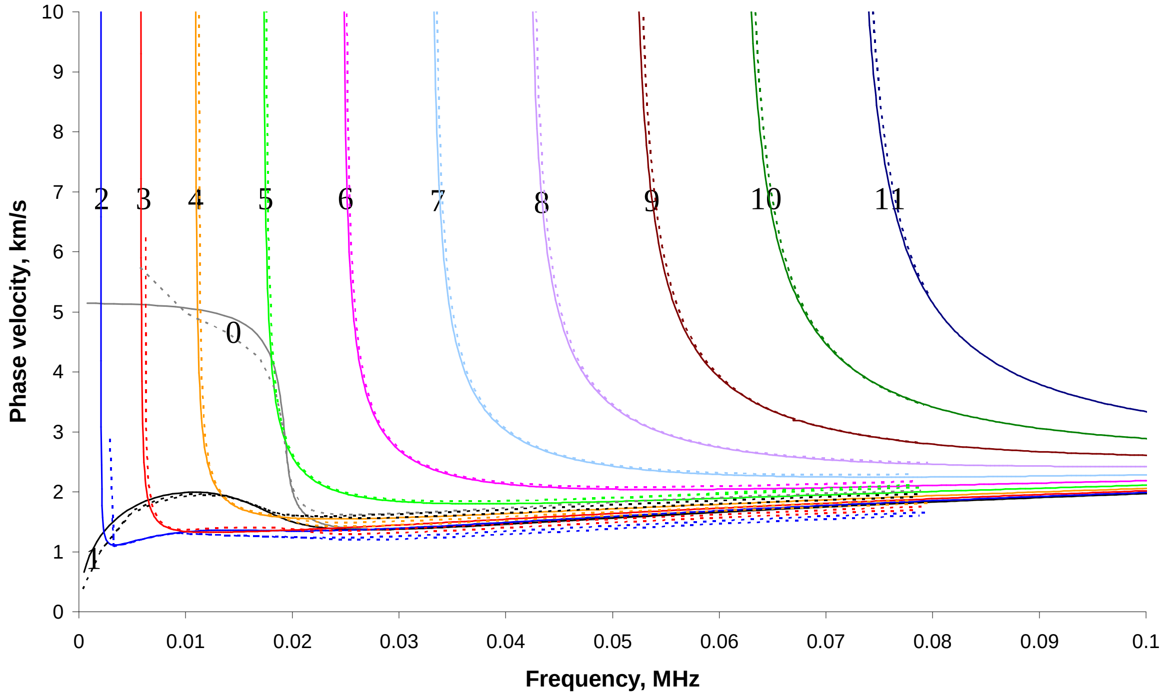


Figure 2 Straight pipe dispersion curves for L(0,1) 'family' in 3" Schedule 40 steel pipe (continuous lines) compared with pipe bend dispersion curves for bend radius of 3 times the outer diameter of the pipe (dotted lines). The circumferential order of the wave mode is indicated for each curve.

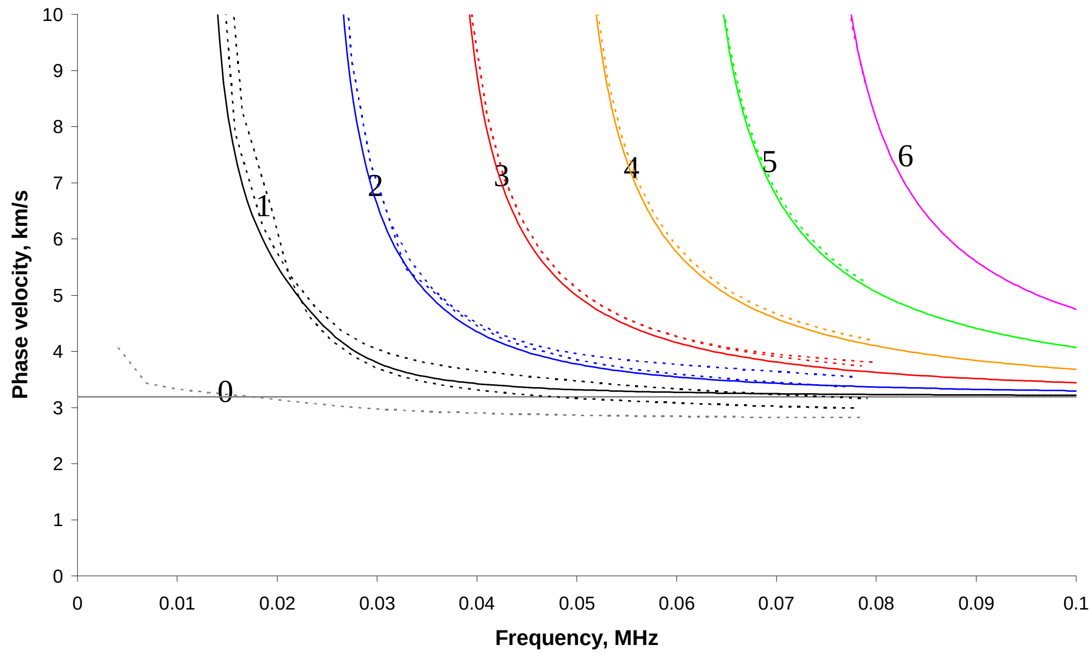


Figure 3 Straight pipe dispersion curves for T(0,1) 'family' in 3" Schedule 40 steel pipe (continuous lines) compared with pipe bend dispersion curves for bend radius of 3 times the outer diameter of the pipe (dotted lines). The circumferential order of the wave mode is indicated for each curve.

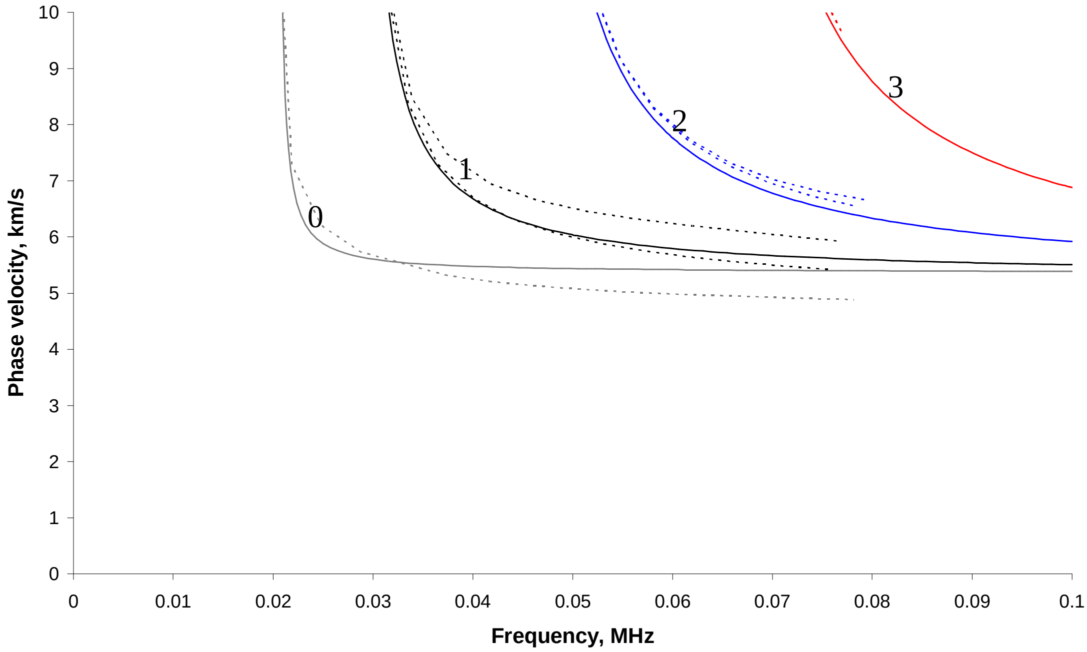


Figure 4 Straight pipe dispersion curves for L(0,2) 'family' in 3" Schedule 40 steel pipe (continuous lines) compared with pipe bend dispersion curves for bend radius of 3 times the outer diameter of the pipe (dotted lines). The circumferential order of the wave mode is indicated for each curve.

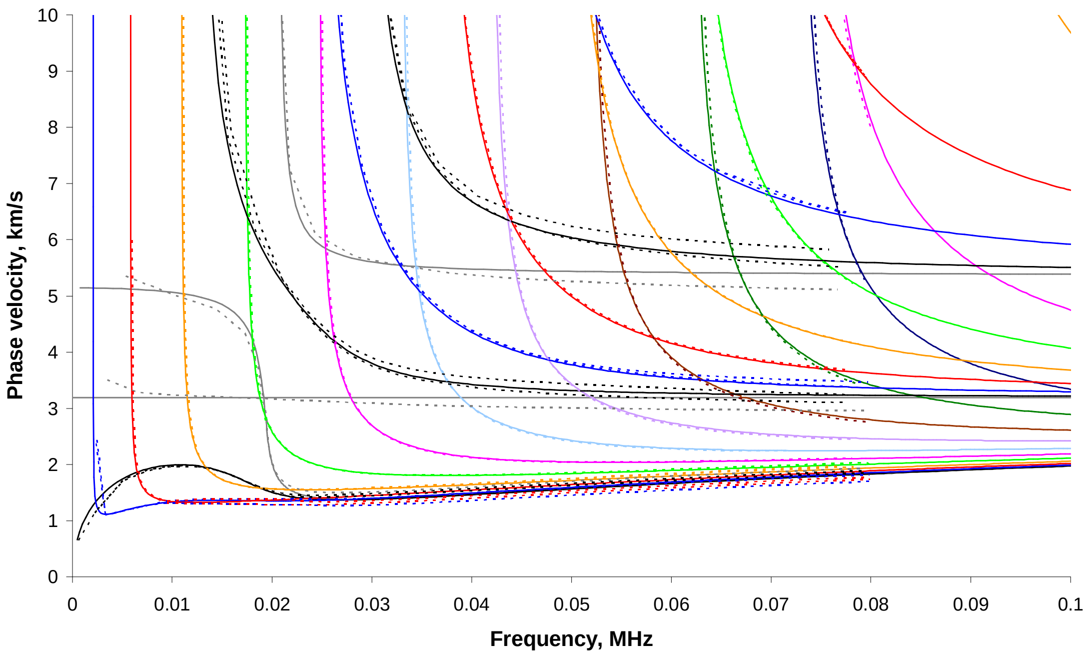


Figure 5 Straight pipe dispersion curves for 3" Schedule 40 steel pipe (continuous lines) compared with pipe bend dispersion curves for bend radius of 5 times the outer diameter of the pipe (dotted lines).

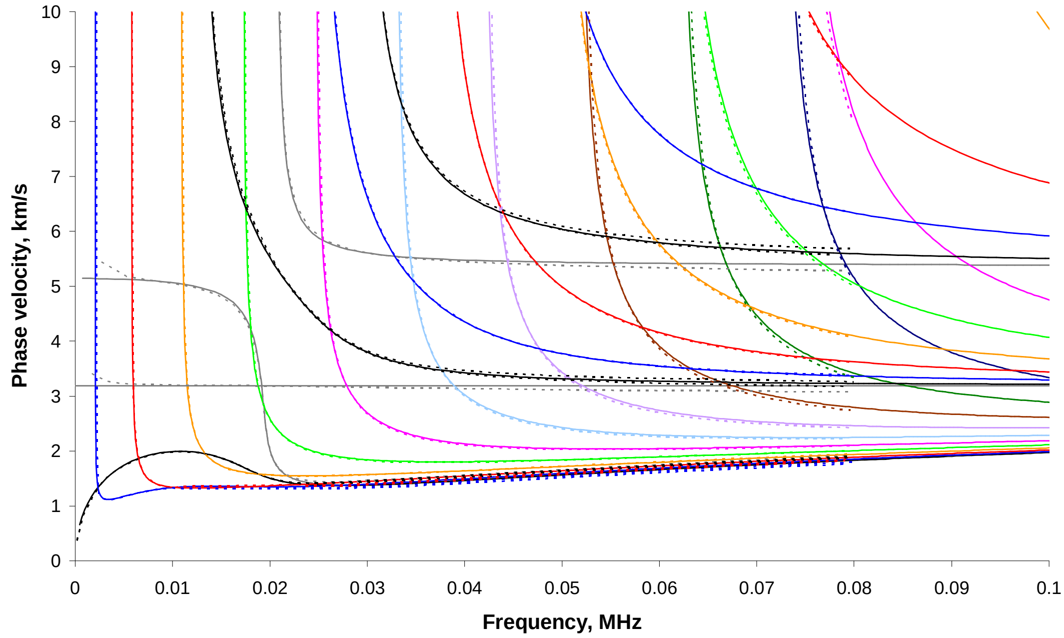
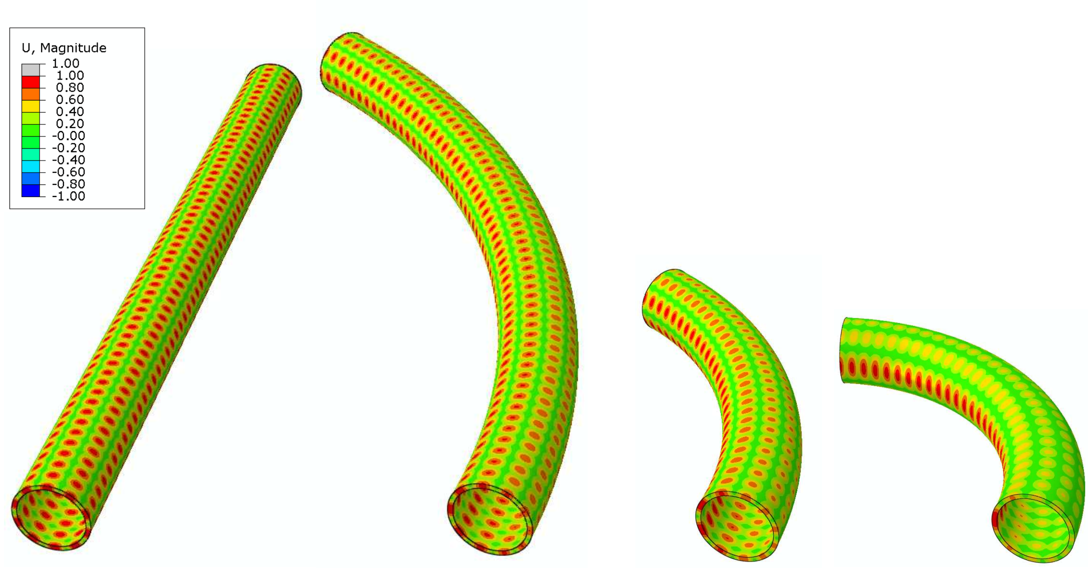


Figure 6 Straight pipe dispersion curves for 3" Schedule 40 steel pipe (continuous lines) compared with pipe bend dispersion curves for bend radius of 10 times the outer diameter of the pipe (dotted lines).

2.4.2 Effect of pipe bend radius on flexural wave modes

For flexural wave modes, there is a split into two distinct wave modes in the bend (symmetric and asymmetric) and there is also some distortion of the wave mode shape, the magnitude of which appears to generally reduce with increasing order of variation around the circumference.

There is little distortion of the shape observed for flexural wave modes in the L(0,1) 'family'. For example, Figure 7 shows the wave mode F(5,1) (from the L(0,1) 'family'). The particle displacement is relatively unchanged in all cases except for the tightest bend radius case (3xOD) where the energy appears to partially migrate to the intrados of the pipe bend, see Figure 7(d).



a) b) c) d)

Figure 7 Changes in displacement magnitude distribution of mode shape for F(5,1) wave mode at 50kHz in pipe bends of different radii
a) Straight pipe
b) Bend radius of 10 times the outer diameter
c) Bend radius of 5 times the outer diameter
d) Bend radius of 3 times the outer diameter

2.4.3 Effect of pipe bend radius on torsional wave modes

The dispersion curves for the fundamental torsional wave mode, T(0,1) are shown in Figure 8. It can be seen that the wave mode in the pipe bend has some level of dispersion compared with no dispersion in straight pipe. This is particularly significant for low frequencies (<20kHz for a 3xOD pipe bend radius).

Figure 9 shows the mode shapes for each of the four cases (straight pipe, 3xOD, 5xOD and 10xOD bend radii). There is a noticeable difference in the wave mode shape. In all three of the pipe bend cases the sound energy (related to the magnitude of particle displacement) is concentrated on the extrados of the pipe bend whereas it is the same at all points around the circumference in a straight pipe. The migration of the sound energy to the extrados appears to get more significant for tighter bend radii. This could mean that there is a reduced chance of detecting flaws or corrosion on the intrados of the pipe bend using standard guided wave inspection techniques. However, there are other pipe bend wave modes which propagate with energy on the intrados and these may be excited via mode conversion from the incident wave mode in straight pipe. Moreover, it would be possible to design a test where energy is concentrated on the intrados. One possible way to achieve this optimisation would be to transmit with a specific, non-uniform loading pattern around the circumference of the pipe, instead of the standard equally distributed excitation.

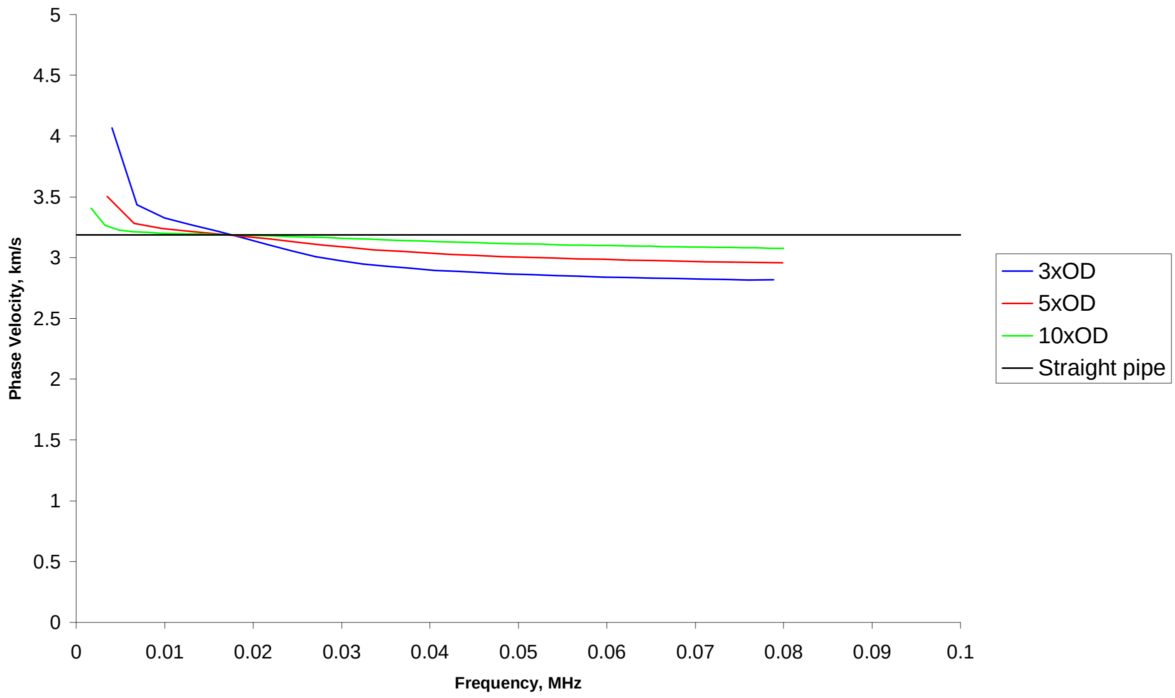


Figure 8 Dispersion curves for the T(0,1) wave mode in pipes of different bend radii. Tighter bends are observed to increase the gradient and therefore level of dispersion of the wave mode.

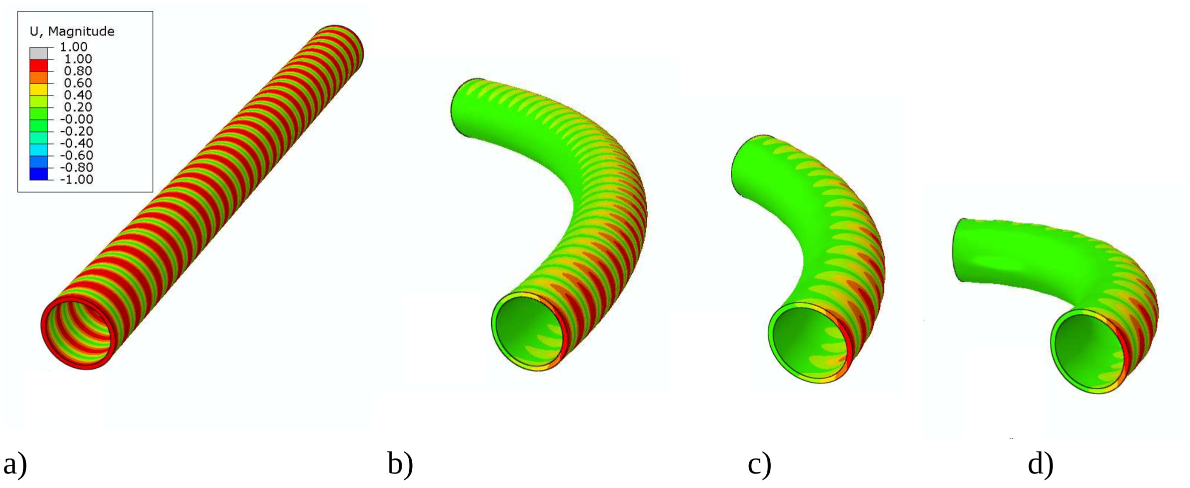
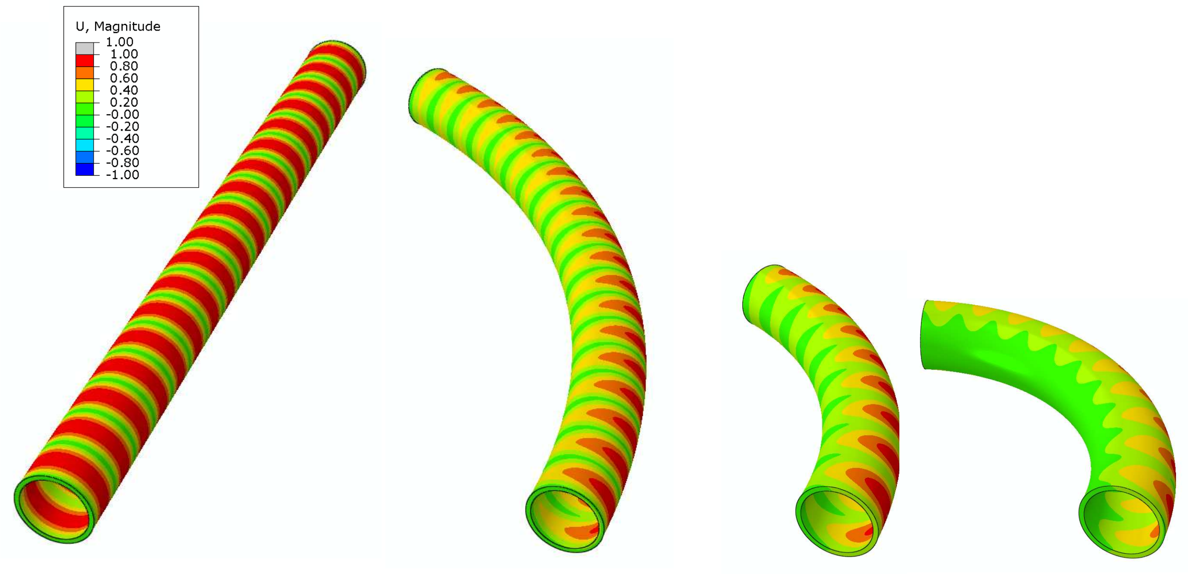


Figure 9 Changes in displacement magnitude distribution of mode shape for T(0,1) wave mode at 50kHz in pipe bends of different radii
a) Straight pipe
b) Bend radius of 10 times the outer diameter
c) Bend radius of 5 times the outer diameter
d) Bend radius of 3 times the outer diameter

2.4.4 Effect of pipe bend radius on longitudinal wave modes

Figure 10 shows mode shapes for the axisymmetric wave mode L(0,2) for each of the four bend radii. It is observed that the sound energy migrates to the extrados in the same way the axisymmetric wave mode T(0,1) did (see Figure 9). However, the change is more gradual and the shallower bend radii have some energy on the intrados of the bend indicating that it would be possible to detect flaws on the intrados using this wave mode in isolation.



a) b) c) d)

Figure 10 Changes in displacement magnitude distribution of mode shape for L(0,2) wave mode at 50kHz in pipe bends of different radii
a) Straight pipe
b) Bend radius of 10 times the outer diameter
c) Bend radius of 5 times the outer diameter
d) Bend radius of 3 times the outer diameter

Additionally, it is observed that there is little effect of the pipe bend on both the dispersion curves and the mode shape for the L(0,1) mode and its family at typical test frequencies (>20kHz). This could mean that a new inspection methodology using the L(0,1) mode could be a straightforward way to overcome the effects of pipe bends.

3. Conclusions

The effects of pipe bend radii on the propagation of guided waves in a 3” Schedule 40 steel pipe have been quantified using finite element analysis. Despite a relatively small shift in the trend of velocity with frequency for the guided wave modes examined in the study, the distribution of energy around the circumference of the pipe is significantly different for even the shallowest bend radii (10 times the outer diameter). In particular, the energy of the axisymmetric wave modes used in standard guided wave inspection concentrates on the extrados of the pipe bend. This indicates that corrosion or flaws on the intrados of the pipe may be more problematic to detect using standard techniques. However, optimised transmission conditions could be used to overcome this.

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