Inspection of pipe networks containing bends using long range guided waves

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Abstract
Guided wave inspection has the advantage of providing full volumetric coverage of tens of metres of pipe from a single test location. However, guided wave behaviour is complex. There are many factors to consider such as the numerous possible vibrational modes, dispersion and multiple reflections. The guided wave inspection technique is potentially immensely valuable for unpiggable sections of pipeline such as at cased road crossings. However, in situations such as this, there are often bends in the pipe. The presence of the bend is known to distort the received signals, particularly in tight bends. In order to address this issue, a study has been carried out that uses finite element analysis to understand the behaviour of guided waves in a relatively tight pipe bend example.

1. Introduction

With the ability that guided waves offer to inspect the whole volume of tens of metres of pipeline, comes complexity. Each feature such as a weld, corrosion flaw, pipe branch or pipe bend will cause a disturbance to the propagation of the waves. Information about the condition of the pipe is contained in the received signals, but extracting that information is challenging. This process becomes more complicated with complex geometries and multiple features. One such complexity is a bend in a pipe.

The most relevant work to this chapter is summarised here. Demma et al calculated dispersion curves and studied the transmission of waves through pipe bends using a combination of finite element analysis and experiments(1). Some authors have investigated the effects experimentally(2), including Rose et al who have used a tuning concept to study the sensitivity of guided waves to the detection of a flaw beyond an elbow (3,4).

Here, finite element analysis has been used to quantify the behaviour of guided wave modes as they propagate around pipe bends. The effects on both the wave modes themselves and the reflected signals from flaws beyond the bend have been considered.

2. Approach

2.1 Nomenclature

Structures which are essentially prismatic and are long relative to the wavelength can act as waveguides. A given 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). Each of these basic axisymmetric wave modes has a set of flexural wave modes which have similar particle displacement characteristics. The naming convention popularised by Silk and Bainton[5] 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.

2.2 Finite Element Analyses

A previously validated finite element modelling method[6] has been used to simulate the behaviour of guided waves when they propagate around bends in pipes. An example is taken of a 10-cycle 20kHz Hann-windowed input signal in a 3” Schedule 40 ferritic steel pipe (88.9mm outer diameter, 5.49mm wall thickness) with a 90° bend and a 133.35mm mean bend radius. Figure 1 shows the layout of the model.

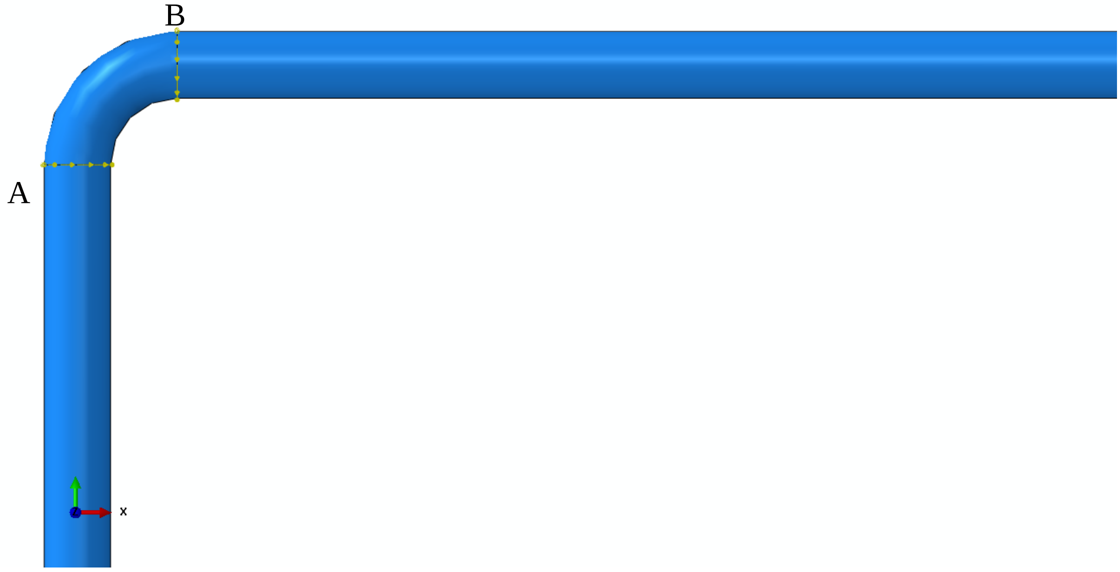


Figure 1. Layout of the finite element model.

The excitation was torsional so the T(0,1) family of wave modes will be preferentially excited. For these conditions, three main wave modes are possible: T(0,1), F(1,2) and F(2,2). Figure 2 shows the dispersion curves for a 3” Schedule 40 ferritic steel pipe calculated using Disperse[7].

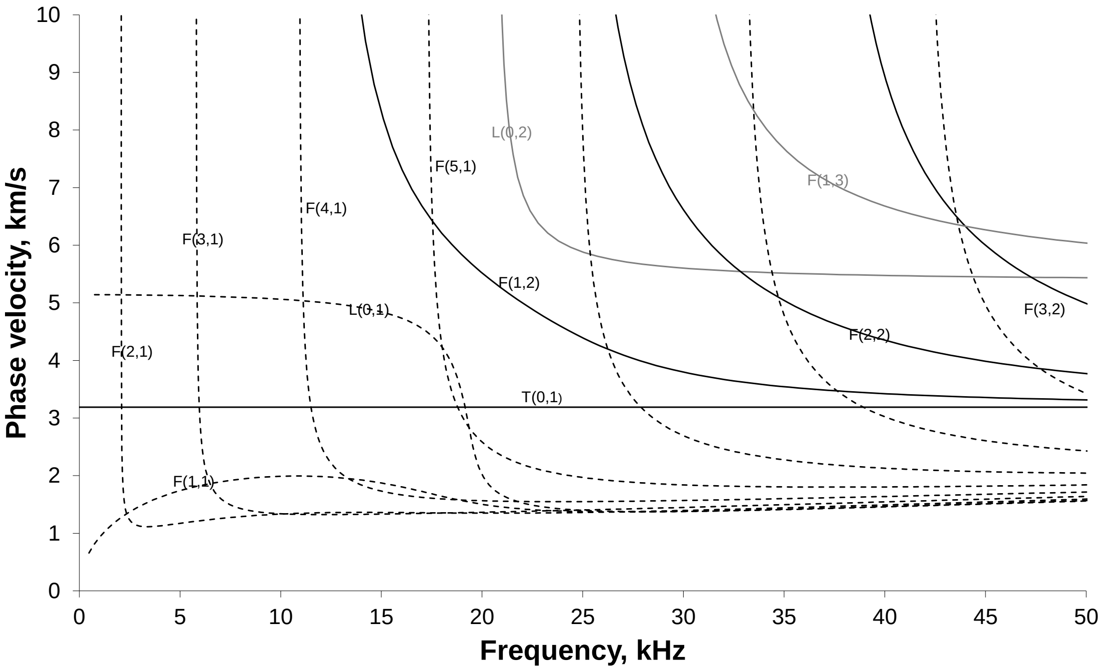


Figure 2. Phase velocity dispersion curves for a 3" Schedule 40 steel pipe.

The model was generated and processed using the commercially available finite element code, ABAQUS version 6.10. The model was three-dimensional and used linear brick elements with reduced integration (ABAQUS element type C3D8R). The following material properties were used:

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

A structured mesh was used with elements of 2.5mm along the length, approximately 3mm around the circumference and four elements were used through the thickness. In the bend, the element lengths ranged from around 1.7mm on the intrados to 3.3mm on the extrados. This level of mesh refinement was used so that there were enough elements to adequately represent the smallest wavelength of interest in the system.

An excitation of a 10-cycle 25kHz Hann-windowed pulse was applied to twelve evenly spaced points around the circumference, just before the bend at point A. The signals were recorded at twelve evenly spaced points around the circumference, just after the bend at point B. Firstly, the T(0,1) mode was excited, then the amplitude of the excitation was varied around the circumference in order to excite the flexural wave mode F(1,2). The F(1,2) wave mode was excited at six different circumferential orientations from 0° to 150° in 30° increments. Due to symmetry, this was enough to represent all possible orientations in 30° increments. The formula used to calculate the amplitude of the input pulse was as follows(8):

$A=\cos[n\,(\theta-\alpha)]$,…………………………………………………………………… (1)

where A is the amplitude of the input pulse, n is the order of the mode to be excited, θ is the circumferential location of the exciter and α is the desired orientation of the flexural wave mode. The convention adopted for the angles was the intrados as 0°, top dead centre as 90° and the extrados as 180°.

Finally, the model was used to simulate notch-like flaws beyond the pipe bend. The T(0,1) wave mode was impinged on a set of flaws of different circumferential extents and the reflected signals were allowed to propagate through the bend. Figure 3 shows the layout of the model.

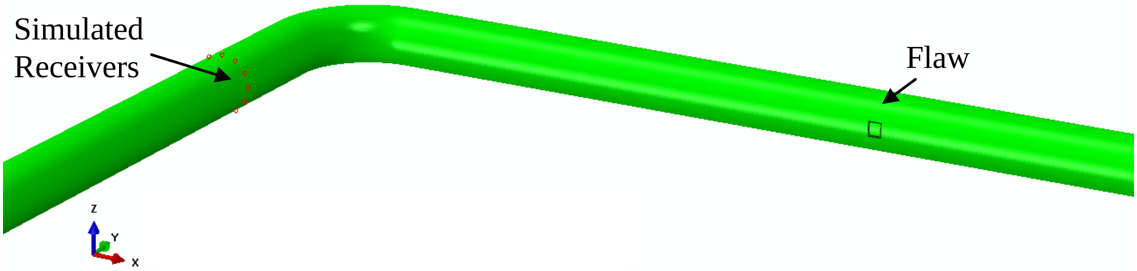


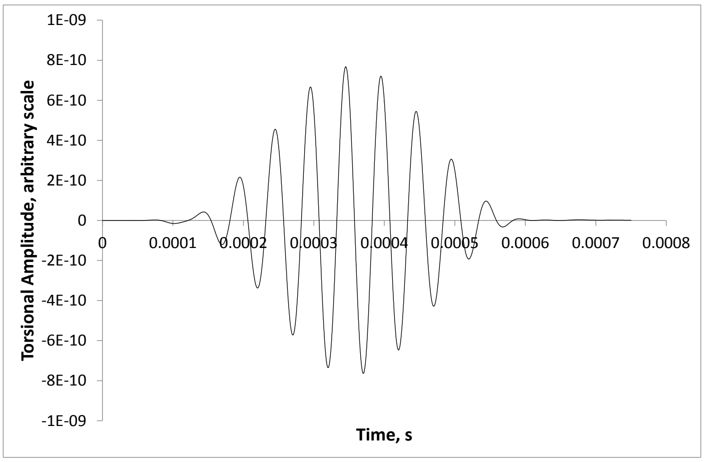
Figure 3. Layout of the model used to assess the effect of the pipe bend on the reflected signals from flaws. Example of a flaw with a circumferential extent of 30° shown.

All of the received signals were processed using a wave mode filtering technique. This involves reapplying the excitation amplitudes to the signal at each point and then summing all twelve signals[8]. The filtering technique allowed the individual wave modes to be examined separately.

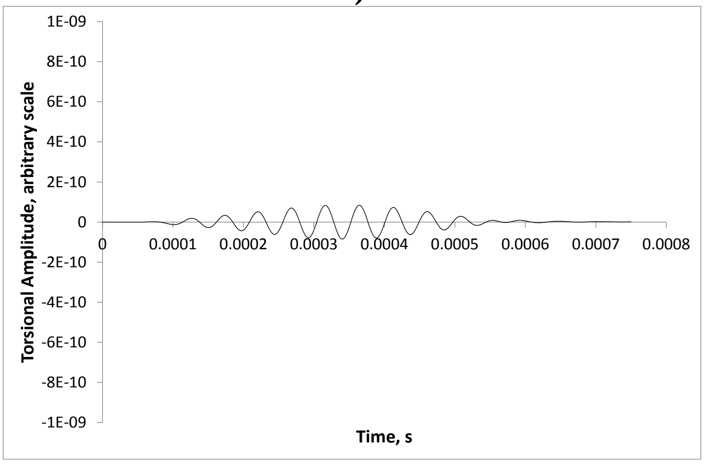
3. Results and Discussion

3.1 Excitation of T(0,1) before the bend

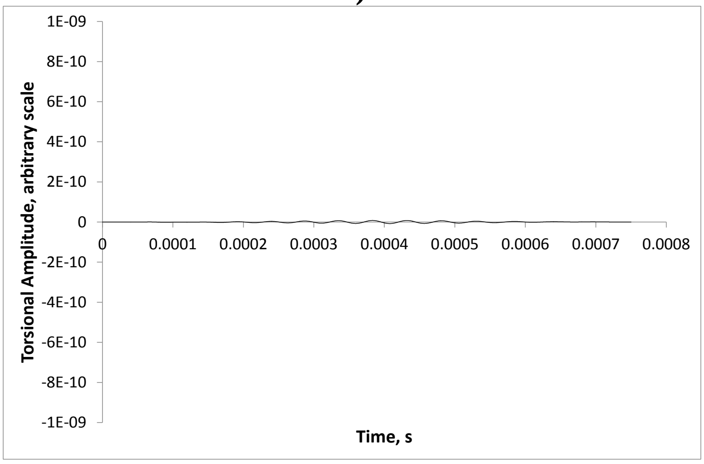
Figure 4 shows the received signals after the bend for an excitation of T(0,1) before the bend. It can be seen that all three torsional family wave modes are present in the received signal. The strongest signal is the T(0,1) wave mode with the second strongest excitation being the F(1,2) which is around 11% of the amplitude of the T(0,1) signal. Generation of the F(2,2) wave mode is minimal. The flexural wave modes are both aligned at 0°. This indicates that there would be more sensitivity to flaws aligned with the extrados or intrados of the bend and less sensitivity to flaws at other orientations. The predicted amplitude of the T(0,1) signal received after propagation through the bend divided by the amplitude of the incident T(0,1) signal was 0.85. There is therefore some signal amplitude loss which could cause difficulty in the inspection of a pipe network with a number of bends.



a)



b)

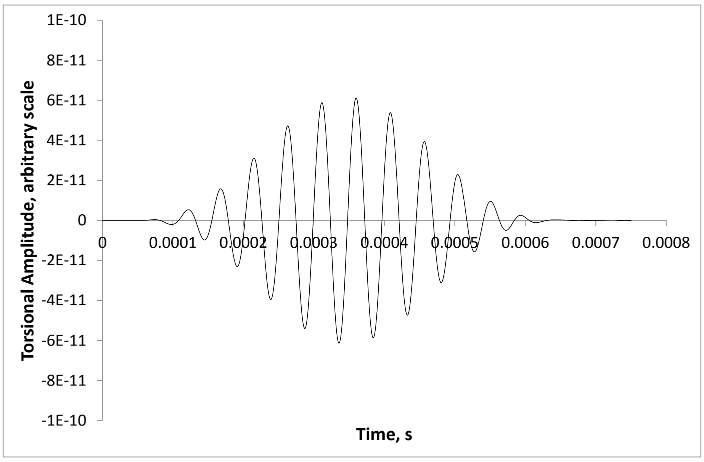


c)

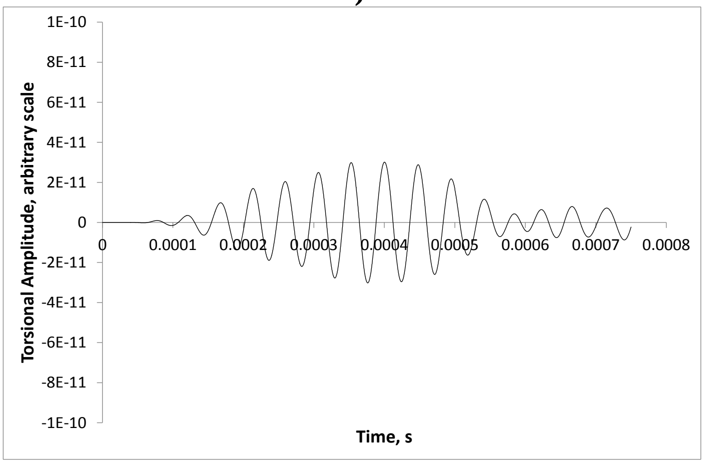
Figure 4. Received signals after propagation of T(0,1) through the bend:
a) T(0,1);
b) F(1,2);
c) F(2,2).

3.2 Excitation of F(1,2) before the bend

The effect of the orientation of incident F(1,2) wave mode was studied by varying the orientation around the circumference in 30° intervals (as described in more detail above). For excitation of the flexural wave modes before the bend, all three wave modes were generated to varying degrees in most cases. Figure 5 shows the predicted waveforms for the first two wave modes for the 60° F(1,2) case as an example.



a)



b)

Figure 5. Received signals after propagation of F(1,2) at 60° through the bend:
a) T(0,1);
b) F(1,2).

The models were then used to study the relationship between the orientation of the flexural wave mode before the bend and the orientation of the transmitted F(1,2) wave mode after the bend. It was found that the orientation was actually preserved for this example. The orientation of the flexural wave modes is used to determine the circumferential location of flaws. Therefore, the presence of this type of bend would not affect this calculation.

The amplitude of the transmitted/generated wave modes for different F(1,2) excitations was also studied. Figure 6 shows the amplitude of the T(0,1) and F(1,2) wave modes received after the bend versus the orientation of the F(1,2) excitation. There is a significant variation of the amplitude of the T(0,1) wave mode. For an excitation of

F(1,2) at 90° there is no generation of T(0,1) whereas the amplitude of the transmitted F(1,2) wave mode is relatively unaffected by the excitation orientation before the bend. Variation such as this should be taken into account when examining flaws which lie beyond a pipe bend.

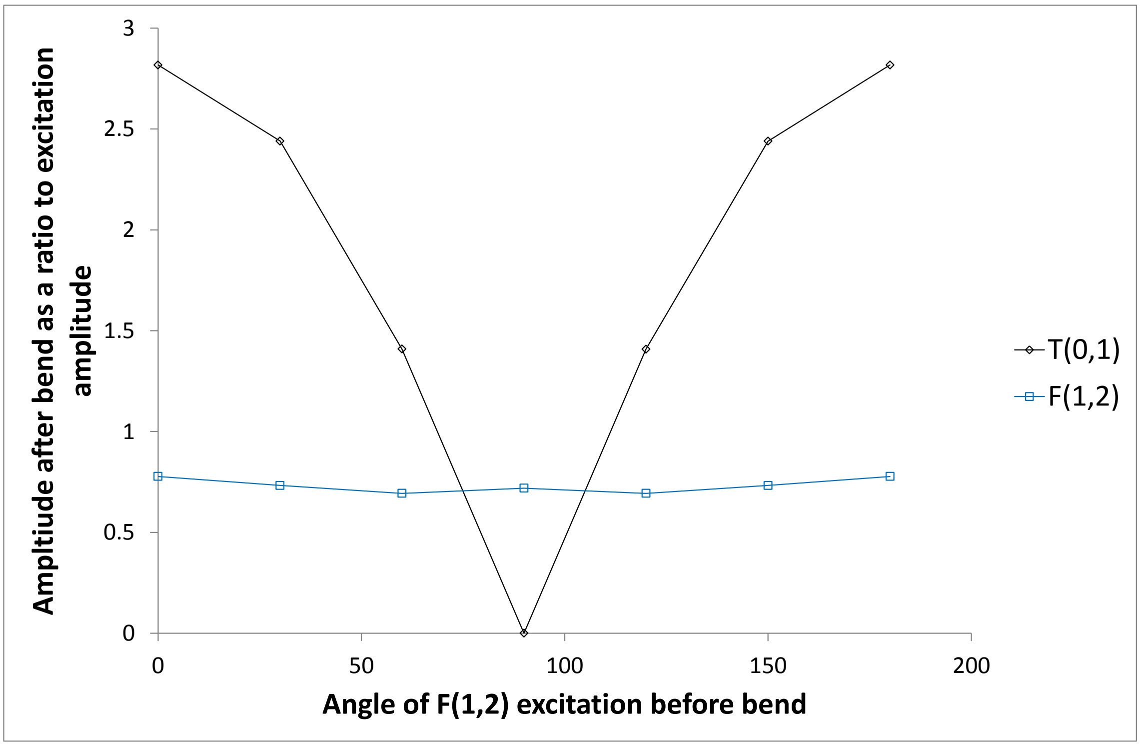


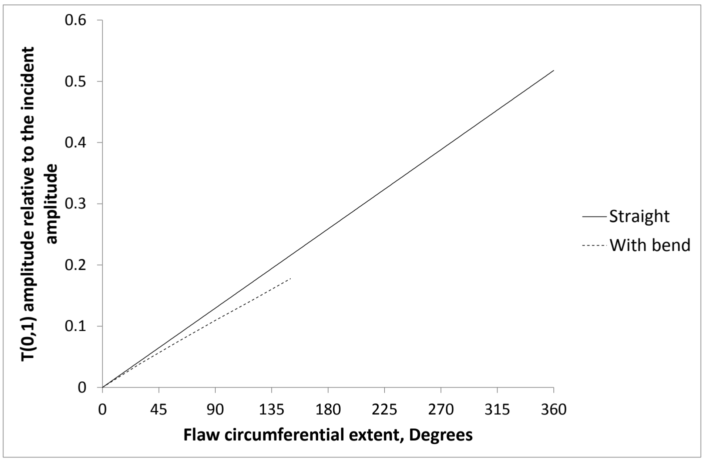
Figure 6. Amplitude of wave modes received after the bend against the orientation of the excited F(1,2) wave mode before the bend.

The proximity of the excitation location to the bend may have an effect on the signals that are excited in the pipe. The excitability of wave modes and dispersion could cause differences in the results presented here. Further work is needed to investigate this.

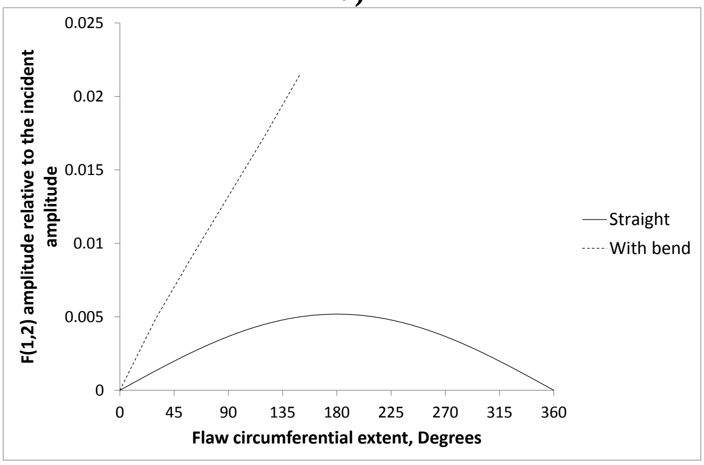
3.3 Reflections from flaws beyond the bend

Finally, the model was modified to simulate a flaw beyond the pipe bend. The flaw was notch-like and was centred on the symmetry plane. The through wall extent of the flaw was 50% of the pipe wall thickness (2.745mm) and the axial extent of the flaw was 20mm. This was selected so that it was approximately a quarter of the wavelength, where the maximum possible reflection amplitude is obtained. The circumferential extent of the flaw was varied in 30° increments from 30° to 150°. The T(0,1) wave mode was impinged on the flaw and then the reflected signals were allowed to propagate through the pipe bend. The received signals were collected 0.2m from the pipe bend. Figure 7 compares the reflection amplitude trends for each of the two torsional family wave modes to the expected trends in straight pipe. It can be seen that the presence of the bend causes a slight decrease in the amplitude of the T(0,1) wave mode. This has potential implications in underestimating the severity of a flaw beyond the bend (Figure 7a). The amplitude of the reflected F(1,2) wave mode is strongly affected by the presence of the bend. The amplitude is much larger and the shape of the trend is completely different (Figure 7b). This would significantly affect flaw characterisation methods which rely on the relative amplitudes of wave modes.

The reflections reported here are from a single trip through the pipe bend. This was done to develop an incremental understanding of the effects a pipe bend has on the signals. In standard inspections, the incident wave mode would first travel through the bend and then reflect from flaws beyond the bend.



a)



b)

Figure 7. Reflection amplitude of wave mode versus circumferential extent with and without the presence of a pipe bend for a 3” Schedule 40 steel pipe example:
a) T(0,1);
b) F(1,2).

4. Conclusions

Finite element modelling has been used to understand the behaviour of torsional family guided waves in pipe bends for a tight bend radius in a 3” Schedule 40 steel pipe (88.9mm outer diameter, 5.49mm wall thickness). The orientation and amplitudes of the wave modes received after the bend were quantified for a range of possible input excitation scenarios. In most cases, both torsional and flexural wave modes were excited beyond the bend to some degree. This indicates that standard guided wave inspection would be inaccurate for inspection beyond pipe bends and there would be greater potential for false calls.

Moreover, the models were used to examine the effect of the bend on reflected signals from a flaw. It was found that the amplitudes of the reflections were significantly affected. This would have implications for flaw characterisation techniques based on signal amplitude.

Acknowledgements

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