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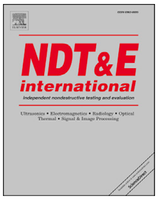

# Reflection of torsional T(0,1) guided waves from defects in pipe bends

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ABSTRACT

This paper investigates the reflection of the torsional T(0,1) mode from defects in pipe bends. The effect of varying circumferential and angular position along the pipe bend, as well as the influence of the bend radius, is investigated via 3D finite element simulations. The results show that the reflection expected from a small defect varies significantly with position, the minimum reflection coefficient being about 10% of that from a comparable defect in a straight pipe, while maxima of around four times the straight pipe value are seen. The areas of low detectability are mainly found on the bend intrados and those of high detectability close to its extrados; similar effects are seen in bends with radii varying from one to twenty pipe diameters. It is shown that the reflection from a defect at a given location is roughly proportional to the square of the von Mises stress produced by the transmitted wave at that position. This holds for defects such as circumferential cracks, the detailed subject of this investigation, and is also expected to be valid for corrosion patches; it will not hold for axial cracks. The results explain the low reflection seen from a simulated corrosion defect at a bend in a previous investigation.

## 1. Introduction

Guided wave inspection has been in use commercially for over a decade for the detection of corrosion and other defects in pipework in a range of industries including oil and gas [1,2]. In the most common implementation, a non-dispersive torsional T(0,1) signal is introduced into a pipe using a ring of piezoelectric transducers [3]; alternatively a system with magnetostrictive transducers can be used [4,5]. The walls of the pipe act as a one dimensional waveguide, allowing the signal to travel tens of meters in each direction from the measurement location [3]. Unlike traditional ultrasonic inspections this enables the measurement to cover large volumes of pipework from a single inspection position. Defects, such as corrosion or cracks, will cause a part of the input wave pulse to be reflected; the amplitude of this reflected signal increases with the cross sectional area loss of the pipe caused by the defect [6,7]. The defect signal is recorded by the same transducer ring as used for transmission, allowing for the location of the defect to be determined using the travel time of the wave pulse. During a conventional guided wave inspection the time trace recorded by the transducer ring will be evaluated manually by the operator. The minimum defect size to be found with this methodology in practical applications corresponds to approximately 5% cross sectional area loss of the pipe wall [8]. This value can vary significantly depending on the position of the defect, the general condition of the inspected pipe and the presence of other pipe features [9]. Pipe bends pose further difficulties as they introduce mode conversion such that signals from beyond bend are more complex thus making interpretation more challenging, thereby reducing detection sensitivity [10].

There is an increasing interest in permanently installed guided wave structural health monitoring (SHM) systems [11]; these have been in use commercially in pipe monitoring applications [12]. A blind trial of such a system (gPIMS produced by Guided Ultrasonics Ltd) was conducted by ESR technology [13]. The monitoring was performed on an 8 inch diameter schedule 40 carbon steel pipe containing a 90° 1.5D bend section as seen in Fig. 1 (a). A number of defects were introduced into the setup and incrementally increased in size such that the sensitivity and validity of the new SHM method could be investigated. A total of five defects in the straight pipe sections before as well as past the bend could be identified. These defects were first detected at a cross sectional area loss of between approximately 0.5 and 1.5%. A sixth defect, unlike the rest, was placed on the pipe bend roughly at the 12 o'clock position i.e. on top of the bend. An image of this defect can be seen in Fig. 1 (b). It was only possible to identify this defect after it had been grown to a cross sectional area loss of 3.5% i.e. substantially more severe than the other defects. Even after the conclusion of this trial with the knowledge of the defect size and position it was not possible to identify the defect retrospectively from earlier measurements. This suggested that the reduced

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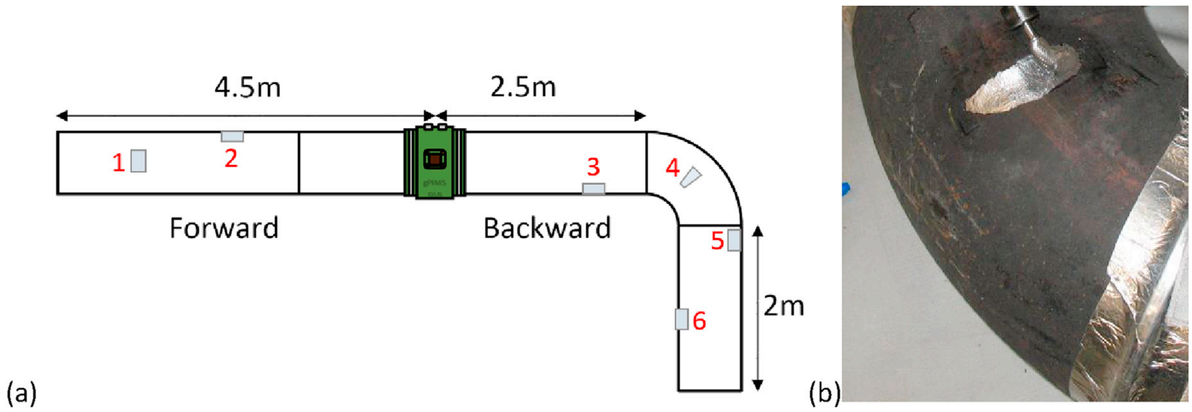

**Fig. 1.** (a) Setup of the 8 inch pipe with a 1.5D bend section used in the blind trial [13]. The transducer ring is shown in green. Defects are highlighted in grey. (b) Example defect located on the pipe bend at the 12 o'clock position.

detectability of the bend defect is not related to a shortcoming of the SHM methodology but rather limited by the geometry of the pipe setup and the particular location of the defect.

In an initial finite element investigation, the reflections from a number of through thickness slits of different circumferential extent located at the 12 o'clock position and an angular position of $\theta = 45^\circ$ along a 1.5D bend were compared to those obtained from defects of the same size positioned in a straight pipe section. It was found that the amplitude of the reflections from the defects located on the bend was reduced to 30–40% of that from defects on the straight pipe; these values correspond with the results obtained in the blind trial [13]. This suggested that a more comprehensive study of the influence of defect position in a bend on the reflection obtained would be valuable.

There has been little work published on the reflection from defects in pipe bends and on the influence of the precise position of the defect in the bend. The propagation of the L(0,2) mode [14] as well as its reflection from defects at various positions on pipe bends has been investigated more than the T(0,1) mode [15,16]. It was found that the reflection from a crack at the bend intrados was significantly lower than that from a crack of the same size at the extrados of the bend. Qi et al. [17] studied T(0,1) mode reflections from axial defects at three different locations on a pipe bend, observing varying detectability with position. Jack et al. [35] investigated the reflections of L(0,2) and T(0,1) waves from circumferential defects at bend welds. Rose et al. [18] used flexural mode tuning to improve the detectability of defects on a pipe bend and investigated the reflection from defects located past the bend [19], while the scattering of the T(0,1) mode from junctions of straight pipe sections and bends was investigated by El Bakkali et al. [20]. The nature of modes in a bend [21–23] and mode conversion of guided waves traveling through bends have been studied extensively in the past decade using experimental as well as finite element approaches [10,24–27]. To the authors knowledge there has not been a systematic study of the sensitivity to defects as a function of their position along and around a pipe bend for the T(0,1) incident mode.

This paper studies the spatial variations in the sensitivity of guided wave inspections as a function of defect position around a bend and as a function of the bend radius. The original motivation was to find an explanation for the results of the blind trial [13], but it will also be a valuable tool in understanding the ability of guided wave inspections to detect defects on pipe bends. To obtain a sensitivity map of a 1D pipe bend the torsional T(0,1) wave reflections from small defects located on the bend with varying circumferential and angular position were studied. The results were obtained from a numerical finite element model of a pipe section similar to that employed in the blind trial as shown in Fig. 1.

Section 2 specifies the properties of the finite element bend models used. This is followed by a description of the defects introduced into the model and the stress and displacement outputs generated by the analysis. In Section 3 the results from the crack study are presented and compared to the stress distribution in a bend of the same size. The correlation between the two is discussed and the stress distributions in 2D, 3D, 5D, 7D and 20D bends are presented. Next, in Section 3, the expected reflections from defects at specific areas of interest in bends of different radii are compared and discussed. Section 4 presents the conclusions of the investigation.

## 2. Methodology

A 3D Finite Element (FE) model was constructed to investigate the behaviour of a torsional ultrasonic guided wave propagating through a bend and reflecting from defects located on the pipe bend. The mesh was generated using Abaqus CAE [28] and subsequently solved with Abaqus Explicit. Defects, source nodes as well as monitoring nodes and elements were introduced via a MATLAB [29] code; post processing of the model was also carried out in MATLAB.

For the investigation of the problem encountered in the blind trial as presented in Section 1 a model of an 8 inch diameter schedule 40 carbon steel pipe (wall thickness 8.2, mm inner radius 101.4 mm and outer radius 109.5 mm) containing a 90° bend section was created. The model consisted of 3 distinct components; firstly a 2 m long straight section into which the input signal would later be introduced, secondly a 90° bend was connected to the previous section with a bend radius of either 1, 2, 3, 5, 7 or 20 times the outer diameter of the pipe and finally a further 1 m length of straight pipe. The simplified geometry of the setup can be seen in Fig. 2. Shown here is a 1D bend with a radius of $R = 0.2191$ m.

The geometry was meshed with 300 8-node linear brick elements (C3D8R) around the circumference of the pipe and 4 elements through its thickness. The number of elements in axial direction of the bend is dependent on the bends radius. A ring of 1500 source nodes was located at the beginning of the first straight pipe section i.e. at a distance of 2 m from the start of the bend. The excitation signal was a 2 cycle Hanning windowed tone burst, with a centre frequency of 25.5 $kHz$. The signal was applied as circumferential displacements of the same amplitude to all source nodes around the pipe, therefore exciting a pure torsional T(0,1) mode since the excitation frequency was well below the T(0,2) mode cut off frequency. The model was set to a total run time of 2 ms allowing the signal to propagate throughout the full length of the bend.

The position of elements on the bend are denoted as seen in Fig. 3. The intrados of the bend lies at $\phi = 0^\circ, 360^\circ$, while the extrados of the pipe is at with $\phi = 180^\circ$. The top and bottom of the pipe are located at the circumferential position of $\phi = 90^\circ$ and $\phi = 270^\circ$, respectively.

In order to investigate the relative reflection amplitudes from defects located at different positions on the bend, circumferential through thickness cracks were introduced in the finite element model by disconnecting a small number of nodes. The cracks had a circumferential