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ULTRASONIC GUIDED WAVES INSPECTION OF PIPES FROM ONE END TO THE FIRST BENT

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Abstract. *Non-destructive inspection of long pipes can be time consuming and some localized defects might remain undetected. A new technique based on guided waves was developed in the last decade. High risk industries such as chemical or nuclear, require a reliable method covering if possible the whole length of the piping. Guided ultrasonic waves can propagate along several meters and up to tens of meters in pipes. The reflected signal, which is usually made of some of the propagating modes, brings information concerning the presence of defects and in some conditions on their location and size. There are three classes of guided modes which can propagate in a pipe: longitudinal, torsional and flexural modes. Even if many authors have investigated the guided waves in pipes, in the present research we are focusing on generating a high energy ultrasonic pulse, capable to produce detectable signals from small defects. Moreover we discuss the probability of detectability of defects near and especially on pipe bends. Using our in-house specialized software package to determine the dispersion curves and displacements fields, we determine the incident modes sent in a pipe from its free end, as in heat exchangers. These results are used for optimal numerical simulation, using the Finite Elements Method (FEM), in order to determine the defect detectability. The numerical data are compared with results obtained in laboratory experiments standard equipment for ultrasonic NDT.*

1 INTRODUCTION

Non-destructive inspection of long pipes, as is the case for the petro-chemical industry, can be time consuming and moreover, some localized small but dangerous defects might remain undetected. A new technique based on guided waves was developed in the last decade, as can be remarked in the works of Ditri [1], Cawley et al. [2] Lowe at al. [3], Li and Rose [4], just to mention a few of the most relevant. Guided ultrasonic waves can propagate along several meters for liquid filled or coated pipes and up to tens of meters in hollow uncoated pipes. The defect reflected signal, which is usually made of several propagating modes, brings information concerning the presence of defects and in some favorable conditions, on their location and size.

Guided waves have special propagation characteristics, as shown in classical textbooks of Auld [5], Miklowitz [6], Achenbach [7], Graff [8] or Rose [9]. There are three classes of guided modes which can propagate in a pipe: longitudinal, torsional and flexural modes as shown by Gazis theoretically in [10] and numerically in [11].

The longitudinal modes are axially symmetric and have dominant radial and axial displacements. These waves prove to be most sensitive to partly circumferential flaws. The waves are dispersive, meaning the wave phase and group velocities are strongly depending on the frequency. The torsional modes are also axially symmetric and less dispersive, especially the fundamental SH_0 mode which is non-dispersive at least on the straight part of a pipe. Since the radial displacements are negligible, the interaction with the surrounding various media is weak, thus reducing the wave attenuation. The interaction of these waves with dominantly axially oriented defects is more pronounced. The flexural modes which are no longer axially symmetric are in general highly dispersive and more attenuated, but these modes can also propagate in a pipe and must be taken into account.

Guided waves in pipes have been numerically investigated using several methods, for the two main aspects: dispersion curves and propagation-scattering simulation.

The dispersion equations can be solved using numerical root finding algorithms, limited to real solutions like Gazis [11] or Predoi et al. [12] or determining the complex solutions as done by the team of Lowe [13]. A better approach, providing the full spectrum of complex solutions, is to take advantage of the axial symmetry or circumferential periodicity and use the so-called Semi-Analytical Finite Elements Method (SAFEM). This method requires a finite elements mesh only along a radial segment limited by the pipe walls, as done by Predoi [14]. Another possibility is to mesh the entire cross-section of the waveguide, which can thus be used for any shape of the cross-section as shown by Hayashi at al. [15].

The propagation of acoustic ultrasonic waves can be numerically simulated by direct time marching solutions using finite differences as Gsell et al. [16], or by using the Finite Elements Method (FEM) for either the time-marching solution or the frequency domain equivalent problem. The time-marching solutions are resources consuming and thus limited to small frequency and propagation length. The frequency domain approach can be used for higher frequencies.

In the present research we are focusing on generating a high energy ultrasonic pulse, capable to produce detectable signals from small defects, at relatively high frequency (1MHz). Moreover we discuss the probability of detectability of defects near and especially on pipe bends, continuing previous researches concerning bents [17], by using FEM simulations [18] and optimal selection of modes [19].

Using our in-house specialized software packages “Tubewave” [12] for real wavenumbers and especially the SAFEM [14] for complex valued wavenumbers, we determine the dispersion curves and displacements fields, in a pipe. These results are used for optimal numerical simulation, using the Finite Elements Method (FEM), in order to determine the defect detectability.

2 PROPAGATING LONGITUDINAL GUIDED WAVES

The detection of small localized defects can be done by using guided waves of short wavelengths, which implies high frequency. On the other hand, high energy flux is necessary in order to receive a detectable echo. For these reasons, in the following we focus on longitudinal axially symmetric guided waves, produced by longitudinal wave ultrasonic transducer, with central frequency of 1 MHz.

2.1 Dispersion curves

The geometry and displacement field notations are shown on Figure 1.

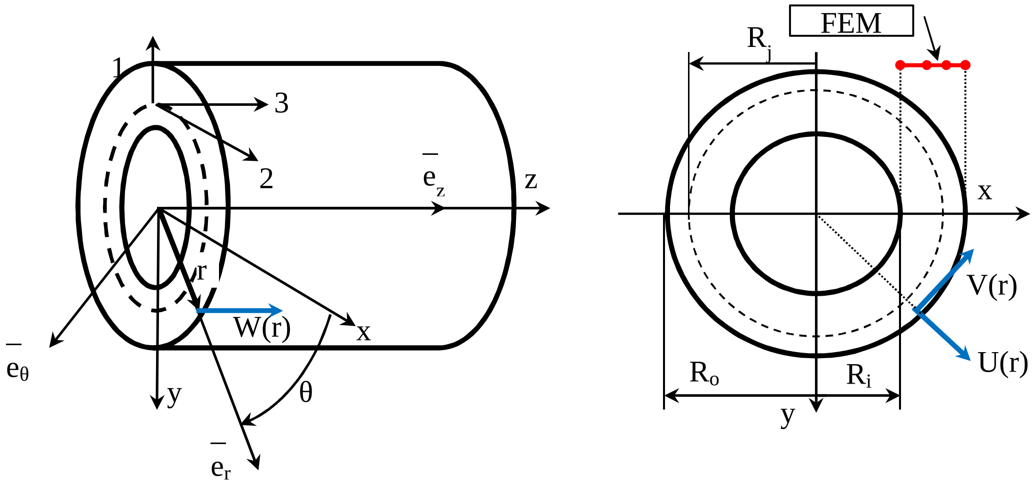

Figure 1 Pipe geometry and displacements field

Plane wave harmonic displacement field is assumed for the longitudinal waves, with k (1/m) the wavenumber and ω (rad/s) the angular frequency:

$$\begin{aligned} u_r(r,{}^{-},z,t) &= U(r)\exp\left[i(kz-\mu t)\right] \\ u_{-}(r,{}^{-},z,t) &= 0 \\ u_z(r,{}^{-},z,t) &= W(r)\exp\left[i(kz-\mu t)\right] \end{aligned} \quad (1)$$

The differential equations of longitudinal plane wave propagation can be written as [14]:

$$\begin{aligned} &\frac{\partial}{\partial r}\left[rC_{11}U' + C_{12}(U+irkW)\right] - (C_{12}U' - irC_{66}kW') - \left(\frac{C_{11}}{r}U + iC_{12}kW\right) - k^2 rC_{66}U = -r^{\circ}\mu^2 U \\ &C_{66}\frac{\partial}{\partial r}(rW' + irkU) + ikC_{12}(rU'+U) - k^2 rC_{11}W = -r^{\circ}\mu^2 W \end{aligned} \quad (2)$$

in which an isotropic homogeneous material is assumed ($C_{12} = C_{11} - 2C_{66}$), with C_{11} and C_{66} the Lame elasticity constants of the material, which can be also expressed in terms of Young's elasticity constant and Poisson's ratio. The pipe used in this example is a brass made pipe,

R_o=9mm, R_i=7.8 mm, mass density ρ=8400 kg/m^3; bulk longitudinal wave velocity c_L=4400 m/s and bulk transverse velocity c_T=2200 m/s, from which the Lame's constants can be easily obtained. The dispersion curves have been obtained using the algorithm detailed in [14], implemented in a FEM commercial package [20]. The variation of the wavenumbers k (labeled Re(kx)) on Figure 2 corresponds to known results, with a special remark for the L(0,5) mode which can propagate above 1650 kHz as "retro-propagative mode" up to 1800 kHz, beyond which it is propagating normally. A "retro-propagative mode" has phase and group velocities in opposite directions, which is a peculiar feature.

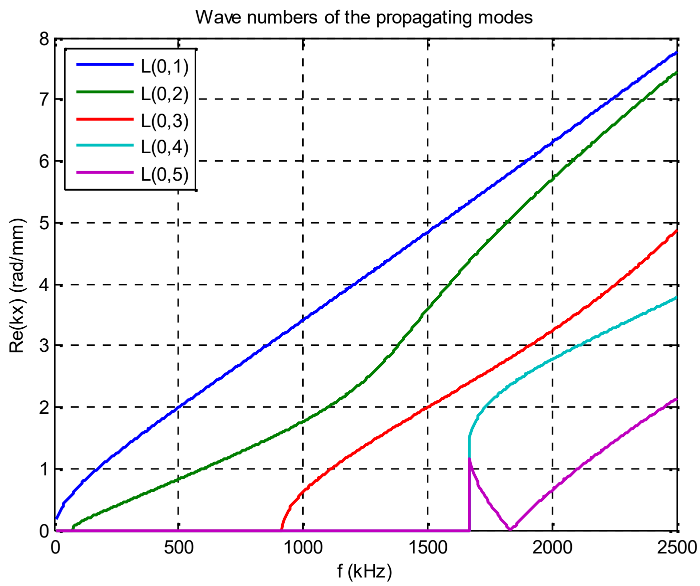

Figure 2 Dispersion curves: wavenumbers k vs. frequency for the first five propagating modes

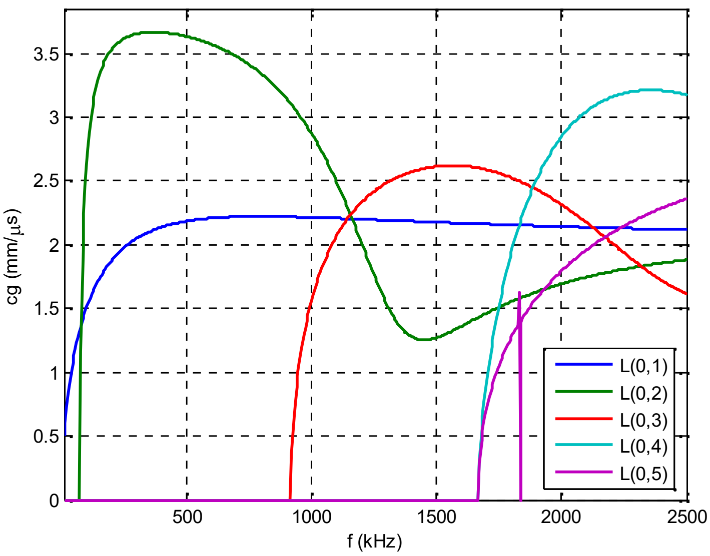

Figure 3 Dispersion curves: group velocities c_g vs. frequency for the first five propagating modes

For experimental and FEM simulations purposes, it is more useful to plot the group velocities, with which travel the short acoustic pulses in the pipe (Figure 3).

2.2 Displacement fields

Frequency ranges for which there is a large variation of group velocity are not recommended, since the incident pulse energy will be spread into a long chirp, beginning with the fastest and ending with the slowest moving part of the mode. The effect is a long measured signal with low amplitude, which is difficult or even impossible to analyze. For this reason, most authors prefer to use lower frequencies (e.g. lower than 900 kHz in this case) for which L(0,2) mode is practically non-dispersive and the L(0,1) mode has a much higher group velocity and can be thus easily separated in the received signals. We suggest in this paper to use the frequency of 1200 kHz (or using a 1 MHz commercial transducer) because:

- higher frequency increases the defect detectability
- at this particular frequency all three propagating modes have almost the same group velocity, concentrating the acoustic energy in a single signal burst
- defect sensitivity is increased near the free inner and outer surfaces, where higher displacements amplitudes exist and higher energy flux is concentrated.

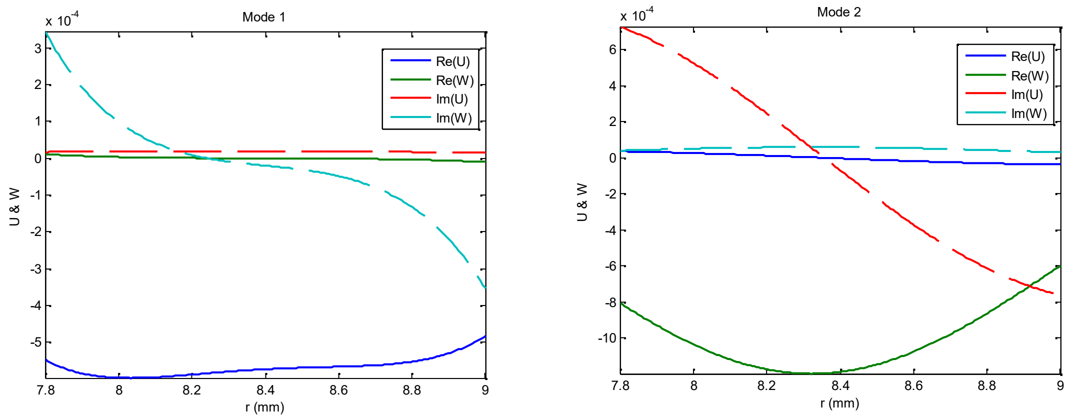

Figure 4 Displacement fields for the first two modes L(0,1) and L(0,2)

At 1MHz, the displacement fields for the first two modes L(0,1) having k=3410.8 rad/m and L(0,2) having 1764.6 rad/s are plotted on Figure 4. The existence of real and imaginary parts of the displacements is related to the phase of these displacements. The L(0,2) mode has a dominant real radial negative displacement (U) almost constant along the cross-section, with a very small imaginary part. The axial displacement (W) has an imaginary part of large values at the free surfaces and of opposite signs on these surfaces. Here, the phase lag between the radial and axial displacement is $\pi/2$, indicated by the real/imaginary significant components. The L(0,2) mode has a constant sign (negative on this plot) for the real part of the axial displacement (Re(W)), but the radial displacement changes sign along the cross-section (Im(U)) and is phase lagged by $\pi/2$. The L(0,3) mode of k=616.24 rad/s, is not shown here, being less important in the next analysis.

3 FEM MODEL

Since the investigation is done for multimode high frequency, the frequency domain analysis was selected. Even so, the 32 GB RAM memory (100 GB virtual memory) imposed limitations on the number of hexahedral elements 99456, which correspond to the requirement of 10 elements per shortest wavelength and a minimum number of 3 elements per pipe thickness in case of slowly radial varying displacements fields. The last condition is not correctly fulfilled since the displacements fields have rapid variations along the radius (Figure 4), but a compromise had to be made. A mesh detail is shown on Figure 5 for a 90° bent.

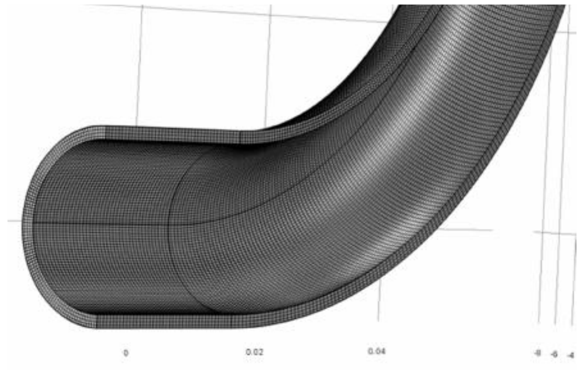

Figure 5 Mesh used for the 90° bent

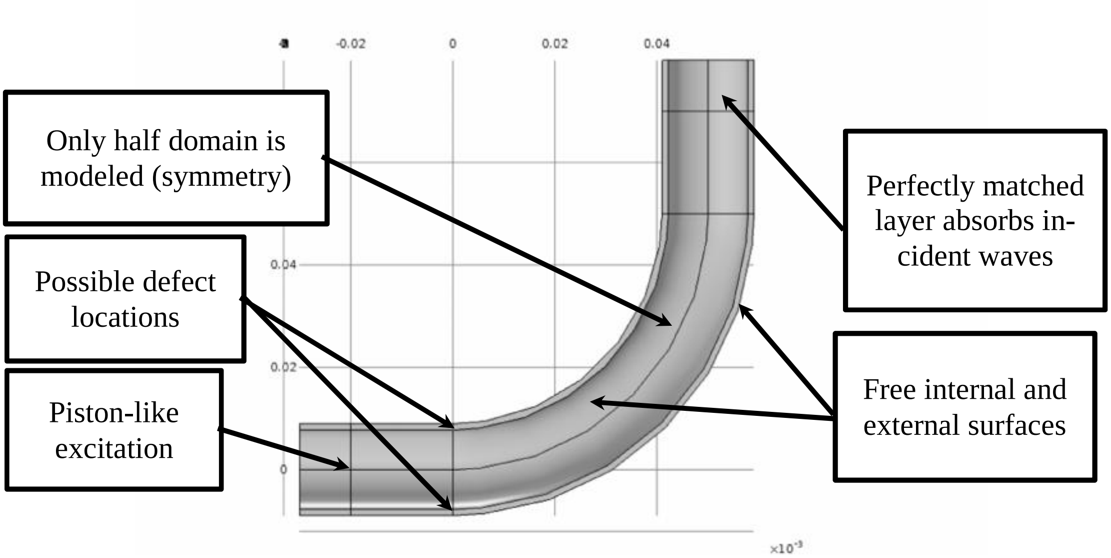

Figure 6 FEM domain and boundary conditions

The boundary conditions require special attention in frequency domain simulations. The equivalent in the time domain is a permanent harmonic excitation a single frequency. For this reason, spurious reflections from FEM domain boundaries have to be eliminated. The FEM software used in this case [20], offers two options: radiation condition and Perfectly Matched Layer (PML). The radiation condition is perfect if the incident wave is perpendicular on the radiating surface, but this not the case in the bent pipe. Consequently, two PML domains have been attached at the two ends of the pipe FEM model. Even so, the PML is not a perfect solution since several modes can propagate in the pipe and each of them has to be absorbed in the PML. A very rapid attenuation represents a rapid variation in acoustic impedance, so reflections still occur. This is particularly important for waves of large wavelengths, for which the PML must cover more than a wavelength. Again a compromise had to be made, since these PML mean a supplementary number of finite elements, to the already large number of elements in the domain of wave propagation. The optimal parameters for the PML have been selected from a simpler model of a short straight pipe, for which the solution time is less than 2 min. The displacement field attenuation to negligible values at the exit from the PML was the selection criterion.

The excitation is done by a piston-like source placed between the first PML and the FEM physical domain, at a frequency of 1 MHz of pressure intensity 10 kPa. The rest of the surfaces are stress-free. Three simulations have been selected for the analysis: the 90° bent without defects, and with half-through flat bottomed holes on the pipe exterior, one on the inside (Figure 7a) and the other on the outside of the bent (Figure 7b), respecting the cross-section plane symmetry.

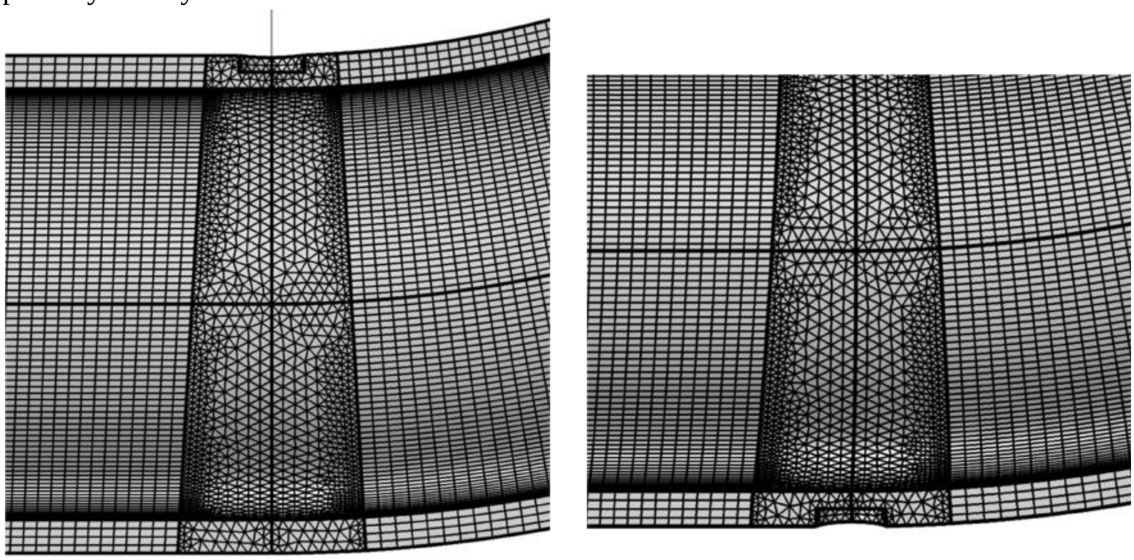

Figure 7 FEM mesh detail with flat bottom half through hole : (a) inner side of bent, (b) outer side of bent

4 SIMULATION RESULTS

The reference case is a 90° bent pipe without defects (Figure 8). The total displacement field indicates parallel lines of alternating amplitudes in the incident wave straight part (lower, left on the image), corresponding to plane harmonic waves. A remarkable phenomenon occurs at the passage to the bend. The waves tend to remain plane and parallel to the incident waves from the straight part and do not become perpendicular on the torus axis as some authors predict. Moreover there is a wave focalization on the outer side of the bent, near its middle. This peculiarities have been emphasized for the first time by Predoi and Petre [17], to our knowledge. A decomposition of the plane incident wave into specific toroidal plane waves seems to be not physical. For this reason we do not try to project the reflected or transmitted acoustic field on the modal basis of the torus and even on the modal basis of the straight pipe.

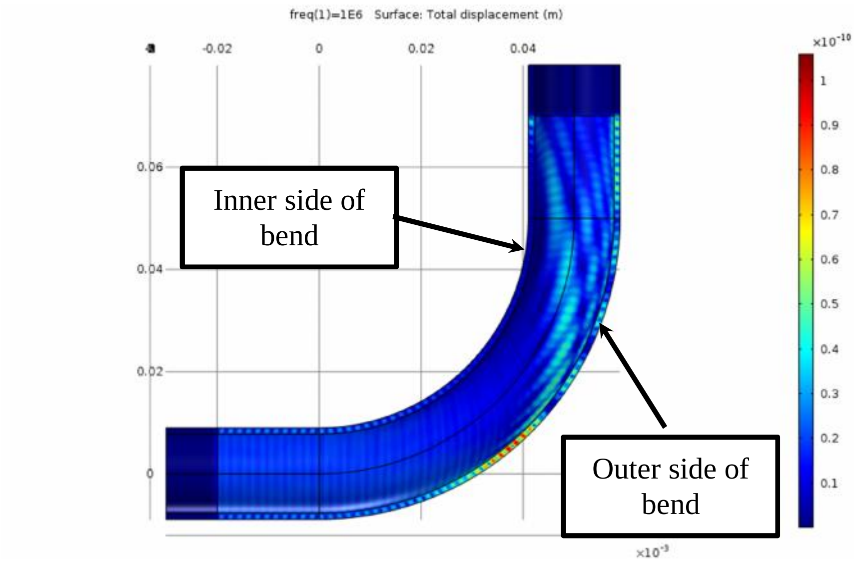

Figure 8 Total displacements for the 90° bent pipe without defects

One can easily associate the irregular pattern of maxima and minima after the middle of the bend as nonplanar partial waves which will impinge on the exit straight part a series of circumferential localized waves. A modal decomposition will be extremely complicated and mostly useless. For this reason we prefer to compare the reflected displacement field of this reference case with the fields of bents with standard defects.

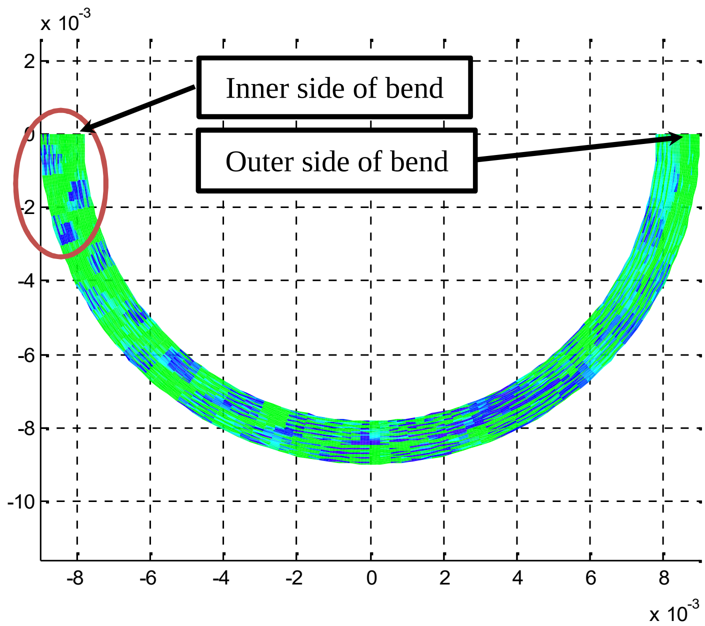

Figure 9 Relative radial displacement with a standard defect on the inner side of the bend

The radial displacement field was extracted by post-processing the FEM results data in all three cases. In order to determine the detectability of defects, the radial displacements fields of the pipes with standard notches were subtracted from the displacement fields of the reference case. All displacements are plotted on a normal cross-section on the straight part of the pipe, 10 mm from the excitation.

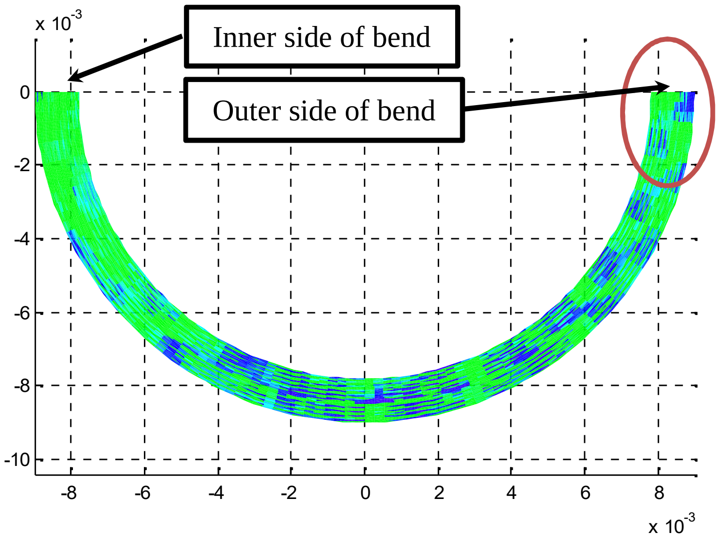

Figure 10 Relative radial displacement with a standard defect on the outer side of the bend

The radial displacements are of higher amplitude on the inner side of the bent when the standard defect is on that side and at the same time, on the outer side of the pipe there is no change in radial signal (Figure 9). If the defect is located on the outer side of the bent, a strong echo can be detected on that side of the pipe and no signal on the opposite side (Figure 10). These results prove the capability of detecting the location of the selected standard defect. The rest of the surface of the pipe is subjected to a complicated pattern of radial displacements and cannot be used for a circumferential receiver transducer.

5 CONCLUSIONS

- Numerical analysis using FEM in the frequency domain was used to investigate the defect presence detectability if such a defect occurs at the junction between the straight and curved part of a pipe. This is a challenge for guided waves techniques, since at this junction occurs modal scattering even in the absence of defects. Modal scattering brings spurious signals on the weak signals due to defects.
- A typical defect on either side of the junction is investigated, keeping the geometrical symmetry of the problem.
- The results are very promising, since the location of an extremely small defect (0.6 mm depth and 2.4 mm diameter) is clearly identified, even if the defect is at the junction between the straight and bent part of the pipe.
- Moreover, we have not used a difficult to obtain, single mode excitation, but a piston like one, at a common frequency of 1MHz.

- The receiver should be however another longitudinal waves transducer, placed perpendicular on the pipe, on either inner or outer generatrix, not too far from the bent.

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