Guided waves scattering by discontinuities near pipe bends

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Guided waves became in recent years a useful tool in nondestructive testing of pipes used in many industrial applications. The torsional and longitudinal waves in pipes are the main choice for integrity inspection. The first step is the computation of the dispersion curves, for straight pipes. Since most pipes have bends, the problem of guided modes in the toroidal segment remains of interest. Various methods have been applied to solve this problem. The most promising numerical method to obtain the dispersion curves for a torus is based on Finite Elements (FE), using a standing waves model. Based on these dispersion curves, transmissions of longitudinal and torsional waves through a bend were also investigated. The present paper presents the scattering process produced by geometrical discontinuities such as circumferential welds before and after a pipe bend. Longitudinal L(0,2) mode is sent along the straight pipe in FE simulations, towards the bend. Reflected and transmitted modal amplitudes are determined for frequencies of interest. The capability of detecting a defect close to one of the two welds is thus assessed. The modes transmitted past the bend are also characterized. Comparisons with results obtained by other researchers are used to validate the method.
INTRODUCTION

The long range nondestructive inspection of pipes has made significant progress in the last decades, using guided waves. The basis for any numerical or experimental investigation is represented by the dispersion curves. Since in pipes can propagate, leaving aside the shear horizontal (SH) waves, three classes of waves: torsional (T), longitudinal (L) and flexural (F), the investigation of these dispersion curves remains a field of research. From the early works of Leo August Pochhammer [1] who established the longitudinal waves equation in a cylindrical rod, many researchers have developed the fundamental aspects of guided wave propagation. The general solution of harmonic longitudinal wave propagation in an infinitely long elastic hollow cylinder has been obtained by Gazis [2] and detailed analysis has been presented in a specialized textbook by Armenakas, et. al. [3]. Numerical solution of the dispersion equations remains a difficult task especially for high values of the thickness-frequency product of the structure. A rigorous asymptotic formulation of the dispersion equations for SH and Lame waves in pipes is presented by Gridin et. al. [4], providing thus an approach which greatly simplifies the numerical solution of the dispersion equations, especially for high frequencies.

The use of longitudinal or torsional guided waves, after many years of researches, was introduced as industrial inspection method which has allowed inspection of pipes over tens of meters. Lowe et al. remark that the “wave propagation properties in pipes are extremely complicated, much more so than in plates” [5]. Indeed for a nominal 3 inch pipe, there are 25 propagating modes for up to 100 kHz, which represents a serious challenge for practical applications. Their selected mode was the longitudinal L(0,2) mode, for several reasons: it is practically non-dispersive over a considerable bandwidth around 70 kHz central frequency, its group velocity is highest among all propagating modes in this frequency range and its mode shape makes it equally sensitive to internal and external defects. Two remarkable experimental optimizations are used, allowing very good results: two ring transducers separated by a wavelength and having a phase lag of π/2, thus enforcing the L(0,2) mode against L(0,1) mode and sending the L(0,2) mode in a chosen direction [5]. More detail on the finite elements method (FEM) applied to circumferential notches and on the experimental setup is given, by the same authors in ref. [6]. Their model was axially symmetric and only half of the pipe cross-section needed to be modeled. By removing rectangular elements from the mesh, starting from the outer surface, a circumferential notch of selected depth could be generated in the wave guide. One important conclusion of these researches is that the reflection coefficient of the L(0,2) mode is linearly dependent on the circumferential extent of a notch of any depth. The flexural F(1,3) is mode converted by the incident L(0,2) mode and can be used also for notch extent estimation, even if the dependency on the circumferential notch length is like a rectified half-sine function. A detailed investigation of the reflection coefficient variation as function of all geometrical characteristics of notches and on wave frequency is presented by Cawley et al. in [7] for 2 – 24 inches pipes. The authors show that for part-thickness notches of a given circumferential extent and minimal axial extent, the reflection coefficient increases monotonically with notch depth at all frequencies, and increases with frequency at a given depth. The axial length of part-thickness notches has a strong influence on the reflection coefficient being a maximum at an axial extent of about 25 per cent of the wavelength and a minimum at 0 and 50 per cent, especially in the high-frequency regime. Li et al. have investigated the possibility to focus non-axially symmetric guided waves, onto selected regions of high radius pipes [8]. Their model uses Lamb waves as modal basis for the numerical simulations.

One major difficulty in pipe inspection, especially for industrial applications, is represented by the pipe bends. Even for high radius to wall thickness, the modal basis for a bend differs considerably from that of the pipe having the same radius and wall thickness. Aristégui et al. [9] have investigated the reflection and mode conversion at a 3-inch pipe bends. The FEM used by the authors involves a membrane elements model. Benefiting from the existence of a symmetry plane, only half of the real geometry needs to be modeled. The amplitudes of the transmitted L(0,2) mode and of the converted modes F(1,3) and F(2,3) are determined for a wide range of bend radiuses. A surprising maximum transmission coefficient was obtained for \( R_m/D=3 \), in which \( R_m \) is the bend mean radius and \( D \) is the pipe mean diameter, whereas a monotonic increase would be expected since the pipe tends to become straight as the mentioned ratio increases. Demma et al. [10] have made an attempt to determine the dispersion curves for a torus, using the method of Wilcox [11]. The method has serious limitations, but in the absence of a better solution, their dispersion curves for a 2 inch and 40 inch pipes represent a good starting point for further investigations. They provide insight for the doubling of the dispersion curves of the corresponding straight pipe, which significantly complicates the practical use of these dispersion curves for modal analysis. The L(0,2) mode transmission coefficient over several \( R_m/D \) values was determined. The evolution is not monotonic, e.g. for \( R_m/D=10 \), the transmission coefficient decreases with increasing frequency, but at higher \( R_m/D \) the transmission coefficient is again close to 1.
In the present work, a 90 degree bent in a 2 inch pipe is considered for all numerical simulations. The longitudinal L(0,2) mode is propagated at several frequencies. Reflection and transmission coefficients are determined. Two circumferential welds are then considered between the bent and the two straight pipes. Their influence on the transmission coefficients is determined. Then, a welding defect is simulated as a partial circumferential notch. The notch detectability is investigated.

LONGITUDINAL GUIDED WAVES

It is well known that guided waves are scattered by discontinuities in wave guides. The incident wave energy is spread among some or all the propagating modes at the frequency spectrum of the incident wave, depending on the discontinuity geometry, symmetric or not with respect to planes or axes. In the particular case of pipes, a continuous research effort has been made to understand the scattering for various types of incident waves and types of discontinuities and this effort continues. The starting point is to determine the dispersion curves. There are a finite number of propagating guided modes in a pipe and an infinite number of non-propagating (evanescent) modes. The first ones correspond to real solutions of the dispersion curves for the wavenumbers and the last ones are indicated by purely imaginary or complex valued wavenumbers. Solving for each class of propagating modes requires numerical methods to determine the zeros of specific determinants, for each type of modes. Another option is to use the FEM approach of Gavrić [12], applied to pipes.

In the following is considered a pipe of nominal 2 inch diameter (outer radius 30mm, wall thickness 4mm) made of steel (Young modulus 200 GPa, Poisson coefficient 0.33, mass density 7850 kg/m³). Using the FEM method [12], was obtained the full set of propagating modes in the free pipe, as wavenumbers or phase velocity vs. frequency (Fig.1) for frequencies from 10 to 400 kHz in steps of 2 kHz. The longitudinal, torsional and flexural modes are obtained together at each frequency, and almost 8 hours on a 2.7 GHz dual processor laptop were needed for the whole set of dispersion points. Identification of modal nature and numbering are a post-processing task, by inspecting the deformed shape of the cross-section of the pipe. Only a few modes were marked on this plot, but more information can be obtained from a similar plot of Lowe (Fig.2 [5]).

![Figure 1](https://via.placeholder.com/150)

**FIGURE 1.** Dispersion curves for a nominal 2 inch steel pipe. The phase velocity vs. frequency for the longitudinal, torsional and flexural modes are superposed. First two L and three F modes as well as the first T mode are labeled on the figure.
For the reader unacquainted with the modal displacements, on figure 2 are presented the displacements for the cross-section of the investigated pipe, for the modes which are marked on figure 1. Red arrows indicate the displacements in the plane of the cross-section, whereas the longitudinal displacements are shown as colored surfaces having shapes given by the local longitudinal displacement.

**FIGURE 2.** Modal displacements for a 2 inch steel pipe at 100 kHz: T(0,1)-(a), L(0,1)-(b), F(1,2)-(c), L(0,2)-(d), F(1,3)-(e), F(2,3)-(f). Red arrows indicate in-plane displacements and color surfaces correspond to longitudinal displacements.

In the following, focus is made on the longitudinal waves. Group velocities have been determined (Figure 3) using a numerical solver of the dispersion equation, for this particular type of waves.

**FIGURE 3.** Group velocities of the longitudinal waves for a 2 inch steel pipe. Only the longitudinal modes are plotted.

In the frequency range at which L(0,2) mode is almost non-dispersive, are selected central frequencies of 100, 200 and 300 kHz.
FINITE ELEMENTS MODEL

After testing a full 3D model, then a full shell model, comparisons have shown that \( L(0,2) \) mode propagation can be accurately modeled by only half of the real structure, cutting it along the symmetry plane, as in ref. [9].

![Figure 4](image)

**FIGURE 4.** Geometry of the models: (1) no welds, (2) two seam welds (blue) (3) HAZ with a 4mm through thickness notch

Three models were used and implemented in the COMSOL Multiphysics FEM package [13] as time dependent solutions. In all three, a nominal 2 inch pipe is modeled as a shell of mean diameter \( D=56 \) mm and \( h=4 \) mm wall thickness, 300 mm long for each of the two parts. The bent is a standard 90°, \( R_m=76 \) mm (\( R_m/D=0.74 \)) made of the same structural steel and wall thickness. The first model is a continuous bend pipe (gray parts on Figure 4). The second model includes two weld seams of 4 mm wide and thickness. Material for the weld was chosen 316L [14]. The third model represents the Heat Affected Zone (HAZ) near one weld seam as a 4 mm wide strip. A 4 mm rectangular punch, centered at the symmetry plane is considered (see Figure 4 notch detail). At one end, a harmonic signal of 3 periods, modulated by a Hanning window, is applied as longitudinal displacement, separately at each of the three selected central frequencies. As seen on Figure 2, the \( L(0,2) \) mode is very close to the uniform longitudinal displacement and is thus expected to be a pure incident mode. The other open end is free as well as the notch boundaries. The rest of the boundaries are imposed symmetry plane conditions. Two displacements monitoring half-circles are placed at 150 mm from both ends and two others are at the two weld seams. Symmetric modes displacements are obtained as integrals of the longitudinal displacements along these half-circles. The time marching solution spans 400 \( \mu \)s, which allows slower modes to arrive at the monitoring section (1), but in next figures 300 \( \mu \)s will cover all useful aspects. The mesh was adapted to the longitudinal shortest wavelength at each of the three frequencies, providing element sizes 10 times smaller than the corresponding wavelength. Computations duration was between 4 and 9 hours on an I7-2.7 GHz with 8 Gb RAM computer.

### NUMERICAL RESULTS

The numerical results concern the wave pattern in the bent, the amplitudes of the symmetric \( L(0,2) \) mode at the monitoring sections. Due to the imposed displacements at one end of the pipe, the incident and reflected waves are monitored at section (1). Based on the axial symmetry of the \( L(0,2) \) mode, the amplitudes of this mode at each section are proportional to the integral of the longitudinal displacements along the corresponding circle, which is in fact a hemi-circle in this model. The higher order flexural modes, having at least one nodal diameter, the integral along the monitoring path should cancel these modes in the monitored amplitudes [8].

In all cases, the \( L(0,2) \) mode was sent towards the bent and the plane wave front was strongly affected by the bent. On Figure 5 are shown computed total displacements at four moments. It can be seen that the wave front is not following the torus bent as plane waves (a). Modal conversions take place and displacement maxima occur along the...
outer bend radius (b), which can thus be better examined. The notch strongly scatters the high amplitude wave pack (c). The reflected wave by the notch is a strong signal at 300 kHz (d).

![Numerical simulations snapshots at 300kHz:](image)

**FIGURE 5.** Numerical simulations snapshots at 300kHz: (a) 75 μs, (b) 85 μs, (c) 95 μs, (d) 105 μs.

This focalization of the incident wave in a particular small area of the bent can be better followed on position-time diagram (Figure 6) in the case of 300 kHz incident wave. The total displacements on a logarithmic scale are plotted for 0 < t < 20 μs along the longest line parallel to the piping model central axis. On Figure 5, this line is nearest to the arrow indicating the incident mode, and includes the quarter circle of largest radius of the bent. The notch is also on this path, which is formed by model boundaries.

![Total displacements on the longest model boundary](image)

**FIGURE 6.** Total displacements on the longest model boundary as position (arc-length on abscissa) vs. time on a dB scale of colors (blue is lowest level and red the highest) for the 300 kHz signal. The welded pipe (a) and the welded pipe with a notch (b).

The incident L(0,2) mode is scattered by the firstly encountered weld seam and the reflected and transmitted waves are clearly visible. The transmitted signal appears to have a higher group velocity than the L(0,2) mode, but this surprising aspect remains to be confirmed by further studies. After the bent, the L(0,2) wave can be seen as doubled. There is a “first mode” followed by the main transmitted L(0,2) mode. This aspect can be explained following Figure 5, by the non-planar wave which “reflects” from the bent at the smaller torus radius into an advanced L(0,2) as “first mode”. The second weld seam produces a reflected wave (Figure 6a) and a very strong reflected signal due to the notch (Figure 6b). The strongly reflected wave from the notch suffers the same
“reflection” inside the bent, generating a weak “first mode” arriving at the monitoring section before the main notch signal.

Practical information can be obtained as from a measuring system, by plotting integrated longitudinal displacements at the four mentioned stations along the piping system. The L(0,2) mode amplitudes at the four monitoring sections are indicated on Figure 6 for 100 kHz central frequency. The presence of the notch in the third monitoring semicircle, explains the distortion giving a higher amplitude, marked U(3) on Figure 7 (b).

FIGURE 7. L(0,2) monitored signals for 100 kHz central frequency in a pipe with welded bent (a) and with a notch near the second weld (b).

Otherwise, the transmission coefficient over the 90° bent and the two weld seams is 0.56 at 100 kHz and 0.43 at 300 kHz (Figure 8). A distinct signal is recorded after the bent as U(3) and U(4), arriving sooner than the main L(0,2) mode and on the average 6 times weaker. The same “first mode” signal has been found in the ideal bend case simulations, proving that the bent and not the weld or the notch represent the cause of it.

FIGURE 8. L(0,2) monitored signals at positions U(1)…U(4) for 300 kHz central frequency in a pipe with welded bent (a) and with a notch near the second weld seam (b).

It was determined, as shown on Figure 6, that this is also a L(0,2) mode, caused by the bent, propagating in the second pipe after the first “reflection” of the wave front leaving the bent, as can be seen on Figure 5b. However, this finding remains to be explained by further studies, not being a real reflection, but in any case this weak signal is not typical to a defect (notch). The question of notch detectability can be answered by subtracting the U(1) signals from the two simulations (Figure 9) at section U(1). In this way, the incident wave is eliminated as well as other common waves. Since the remaining signals are weaker, the amplitude scale is increased by a factor of five. In order to minimize numerical artifacts, the simulations were done with the same elements sizes and meshing method, using in all simulations the same solver precision.
FIGURE 9. Differences in the L(0,2) monitored signals at section (1) are due to the notch only, for 100 kHz (a) and for 300 kHz (b). Amplitude scale is 5 times larger than on previous figures.

On both plots, the direct recorded signal from the notch at section (1) is followed by the same signal reflected by the pipe end which produced the excitation, after which its displacements are set to zero. This explains the phase opposition of the reflected signal. The last arriving pack comes from the reflection at the opposite free end of the piping system. On Figure 9b can also be seen the weak signal of the “first mode”, arriving before the notch main signal. This signal can be seen also on Figure 6b taking place in the bent, like the first L(0,2) mode on Figure 7, but induced by the notch scattered wave.

CONCLUSIONS

The industrial piping network usually includes 90° welded bends. The investigated pipes are of 2 inch nominal diameter. The real welds are approximated by perfect circular ribbons of 4 mm width, made of a material with slightly different mechanical properties than the steel used for pipes. A 4 by 4 mm notch is considered in one heat affected zone of the farthest weld from the inspection location. A particular symmetric position was selected for the notch. From the three selected frequencies, the results for only the smallest (100 kHz) and the largest (300 kHz) frequencies are presented in this paper. As new results, are presented the curved wave front, a wave which is faster than the L(0,2) mode, wave generated by the firstly encountered weld. Then, a “first mode” which is in fact a weaker L(0,2) mode, which is exiting from the bent before the main L(0,2) wave.

From a practical point of view, the chosen notch is clearly detectable at all selected frequencies. Typical signals have been presented. The detectability limit remains to be established by further researches.

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REFERENCES


