Determination of modal attenuation due to external and internal fluids in pipes

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Abstract. The ultrasonic nondestructive evaluation of structural integrity of pipes in high risk industries such as chemical or nuclear, represents a domain of highest importance. The inspection of kilometers of piping in rough conditions is a difficult if not an impossible task. Guided ultrasonic waves can propagate however along tens of meters in pipes and bring by the reflected signal, important information concerning the presence of flaws. There are three classes of guided modes in a pipe: longitudinal, torsional and flexural. The longitudinal modes have an axial symmetry of the radial and axial displacements. These waves prove to be most sensitive to partly circumferential flaws. These waves are dispersive, the wave velocity strongly depending on the frequency. The torsional modes are less dispersive, especially the fundamental SH₀ mode. Moreover, the radial displacements are negligible, reducing the interaction with the surrounding fluids and thus reducing the attenuation. The interaction of these waves with axial flaws is more pronounced. The flexural modes are highly dispersive and attenuated. However, if the symmetry of the emitting transducer is not perfect, these modes can propagate in the pipe and their properties must be understood. The presence of fluid inside and in some cases outside the inspected pipe represents a challenging problem of computing the guided modes dispersion curves. The various guided modes velocities and attenuations are determined for several fluids which might be filling and surrounding the common size steel pipes. A dedicated software package developed by our team is used for this purpose. These dispersion curves are used for optimal numerical simulation, using the Finite Elements Method (FEM), in order to verify the attenuation mechanism. The obtained results allow a motivated selection of the least attenuated mode, from the three classes explained before, at a given inspection frequency and for a typical steel pipe, filled with various fluids. The numerical data can be used for comparison with laboratory experiments. The experimental setup is using common ultrasonic transducers in a special geometrical arrangement. The experiments allow the measurement of the numerically predicted modal attenuation. The maximum expected inspection range can be thus determined before the inspection on real industrial piping.

1. Introduction
The inspection of kilometres of piping in chemical or nuclear plants is difficult, time and resources consuming task, even impossible to be done in some locations. Guided ultrasonic waves can propagate along tens of meters in pipes and bring by the reflected signal, important information concerning the
presence of flaws. For this reason, guided waves are considered as possible replacements for the classical non-destructive inspection techniques [1, 2].

There are three classes of guided modes in a pipe: longitudinal, torsional and flexural [3, 4]. The longitudinal modes have an axial symmetry of the radial and axial displacements. These waves prove to be most sensitive to partly circumferential flaws, but are in general dispersive, meaning that the wave velocity depends on the frequency. The torsional modes are less dispersive, especially the fundamental SH0 mode. Moreover, the radial displacements are negligible, reducing the interaction with the surrounding fluids and thus reducing the attenuation. The interaction of these waves with axial flaws is more pronounced. The flexural modes are highly dispersive and attenuated. However, if the symmetry of the emitting transducer is not perfect, these modes will propagate in the pipe and their properties must be understood.

The presence of fluid inside and in some cases outside the inspected pipe represents a challenging problem of computing the guided modes dispersion curves [5, 6, 7]. In the present paper, the various guided modes velocities and attenuations are determined for several fluids which might be filling and surrounding the common size steel pipes. An efficient method, based on the Finite Elements Method (FEM) has been recently developed, with extended capabilities in solving dispersion equations for multi-layered anisotropic tubes [8] A user-friendly dedicated software package developed for this purpose has been also developed [9]. These dispersion curves are used for optimal numerical simulation, using the (FEM), in order to verify the attenuation mechanism [10, 11]. The obtained results allow a motivated selection of the least attenuated mode, from the three classes explained before, at a given inspection frequency and for a typical steel pipe, filled with various fluids. The numerical data can be compared with laboratory experiments. The experimental setup is using common ultrasonic transducers. The experiments will allow the measurement of the numerically predicted modal attenuation. The maximum expected inspection range can be accurately determined before the inspection on real industrial piping.

2. Dispersion Curves

The material used for the industrial piping is homogeneous steel, assumed to have mass density $\rho=7800$ kg/m$^3$. Young modulus $E=210$ GPa and Poisson coefficient $\nu=0.3$. The fluid filling the pipe is gasoline or Kerosene, of mass density $\rho_f=800$ kg/m$^3$ and bulk modulus $K=1.3$ GPa. A common type of pipe is considered, of outer diameter $D=60$ mm and wall thickness $h=3$ mm. The displacement field is defined by radial, tangential and axial displacements respectively [8]:

$$
\begin{align*}
  u_r(r, \theta, z, t) &= U(r) \cos(m\theta) \exp\left[i(kz - \omega t)\right] \\
  u_\theta(r, \theta, z, t) &= V(r) \sin(m\theta) \exp\left[i(kz - \omega t)\right] \\
  u_z(r, \theta, z, t) &= W(r) \cos(m\theta) \exp\left[i(kz - \omega t)\right]
\end{align*}
$$

(1)

in which the modal displacements $U(r), V(r), W(r)$ are shown on Figure1, $k$ is the wavenumber, $\omega$ the angular frequency and $m = 0, 1, 2, \ldots$ the modal circumferential order and $i = \sqrt{-1}$ .
The corresponding stress field, leaving aside the propagating factor \( \exp(i\omega t - \omega_0 t) \), is:

\[
S_{rr} = \left[ C_{11}U' + C_{12}\left(\frac{m}{r}V + \frac{U}{r}\right) + i k C_{12} W \right] \cos(m\theta);
S_{\theta\theta} = \left[ C_{12}U' + C_{11}\left(\frac{m}{r}V + \frac{U}{r}\right) + i k C_{11} W \right] \cos(m\theta);
S_{zz} = \left[ C_{66}U' + \frac{m}{r}V + \frac{U}{r}\right] \cos(m\theta); \quad S_{\phi\phi} = C_{66}\left[V' - \frac{m}{r}U - \frac{V}{r}\right] \sin(m\theta)
\]

The elastic constants \( C_{11}, C_{12} \) and \( C_{66} \) can be easily obtained [3] from the given material data.

3. **Longitudinal axially symmetric L(0,n) waves for a pipe**

The differential equations of motion in this case (\( m=0 \)) can be expressed as [8]:

\[
\frac{\partial}{\partial r} \left[ r C_{11}U' + C_{12} \left( \frac{m}{r}V + \frac{U}{r} \right) - ir C_{12} k W \right] - \left( C_{11}U' - ir C_{12} k W \right) - \left( \frac{C_{11}}{r} U + i C_{12} k W \right) - k^2 r C_{66} U = -r \rho \omega^2 U
\]

\[
\frac{\partial}{\partial r} \left[ r C_{66} W' + ir C_{66} k U \right] + ir C_{12} k U' + i C_{12} k W - k^2 r C_{11} W = -r \rho \omega^2 W
\]

This set of equations represents the differential form of the dispersion equation. The associated eigenvalue problem can be solved using the algorithm shown in [8] which can be implemented in a commercial available FEM software [12] the \( L(0,n) \) “pipe modes” are the modes corresponding to the empty pipe. The first five such modes are shown on figure 2a.

![Figure 1](image1.png)  
**Figure 1.** Displacement field on the pipe wall.

![Figure 2a](image2a.png)  
**Figure 1.** Wavenumbers of the \( L(0,n) \) pipe modes (a); Group velocities for the pipe modes (b).

Several practical aspects will be remarked. The shorter wavelengths \( \lambda = 2\pi/k \) are preferred for their higher sensitivity to smaller defects. This means higher wavenumbers, encountered at higher frequencies. For frequencies above 1 MHz, the shortest wavelength is about 3 mm, for the \( L(0,1) \) mode and close to it, for the \( L(0,2) \) mode. Another aspect is the group velocity \( c_g \), representing the
velocity of the short signal propagating in the inspected pipe. For this pipe, the group velocities are shown on Figure 2b. In the frequency range $1 \rightarrow 1.8 \text{ MHz}$, the L(0,4) mode will reach first the receiving transducer, followed by the rest of modes L(0,1), L(0,2) and L(0,3). For this reason, the L(0,4) mode would be a good candidate for pipe inspection, if other reasons do not intervene.

4. **Longitudinal axially symmetric L(0,n) waves for the fluid filled pipe**

It would be very useful if the inspection could take place with pipe filled with the conveyed fluid (kerosene in this case). The fluid inside the pipe is represented by the same equations, but using the bulk modulus ($C_{11}=C_{12}=K; \ C_{66}=0$). This method is faster implementable, but it requires more computing resources, than by using specific fluid wave equations and coupling boundary conditions. The large number of “fluid modes” representing the guided modes of the fluid inside a rigid pipe is posing a difficult task to the FEM solver. For a reasonable computation time (less than 4 hours on a quad-core I7 – 8 GB RAM computer), the search of eigenvalues was limited to 24 per frequency step (2 kHz in this case).

The dispersion curves are shown on Figure 3. It is interesting to notice the large number of fluid modes which are interacting with the “pipe modes”, which are superposed as continuous lines for easier comparison. The wavenumbers of the fluid modes increase very fast with frequency (almost vertical lines in the f-k space). The wavenumber of any fluid mode increases rapidly from its cut-off frequency (frequency beyond which the mode can propagate) until reaching a pipe mode. The interaction between the two types of modes can be seen as superposing (along a short frequency range) the fluid modes and the pipe modes, after which the fluid modes continue to rapidly increase in wavenumber (and lower the phase velocity). These fluid modes are very close, so that the pipe modes can be recognized as a succession of short segments.

5. **FEM simulation of the wave propagation in a pipe with fluid inside**

The signal central frequency of 1.25 MHz is a good compromise between too many propagating modes and a short wavelength. For this reason, a FEM model simulating a pulse propagating at this frequency can determine the most sensitive mode, for an indiscriminate piston-like axial stress applied on one end of the pipe. The pipe is filled with kerosene, keeping the same mechanical parameters. The simulation covers 40 μs of propagation along 200 mm of pipe. The time marching solution required 4 computation hours.

The dispersion curves are shown on Figure 3. It is interesting to notice the large number of fluid modes which are interacting with the “pipe modes”, which are superposed as continuous lines for easier comparison. The wavenumbers of the fluid modes increase very fast with frequency (almost vertical lines in the f-k space). The wavenumber of any fluid mode increases rapidly from its cut-off frequency (frequency beyond which the mode can propagate) until reaching a pipe mode. The interaction between the two types of modes can be seen as superposing (along a short frequency range) the fluid modes and the pipe modes, after which the fluid modes continue to rapidly increase in wavenumber (and lower the phase velocity). These fluid modes are very close, so that the pipe modes can be recognized as a succession of short segments.

![Figure 2](image1.jpg)

**Figure 2.** Total displacements after 10 μs (left), 20 μs (middle), 30 μs (right).
The propagating pulse can be seen on Figure 4. Being produced by a piston-like excitation, the pulse is made of up to 5 modes, each with different group velocity. For this reason, the highly dispersive behaviour of the ultrasonic pulse is clearly visible. The first pack can be assumed to be L(0,4), having the highest group velocity.

The pressure wave in the fluid inside is propagating as seen on Figure 5. The pressure wave velocity in kerosene is 1275 m/s, considerably less than the group velocities in steel. For this reason, the wave front is conical in the fluid. One aspect which is not discussed by other authors is the interference of the conical wave fronts as they reach the axis of the pipe, which can reduce/amplify the pressure wave.

**Figure 3.** Pressure wave in the fluid filling the pipe, at 10μs (left), 20μs (right).

In this simulation, after 20 μs, the wave front reaching the centre of the pipe, can no longer be followed, due to very low pressure amplitudes.

FEM simulation of the wave propagation in a pipe with fluid outside

The FEM simulation uses the same pipe and input signal. The pipe is empty, but surrounded by fluid (kerosene). The fluid domain is in perfect contact with the pipe wall and non-reflecting condition on the other boundaries, which is a possibility to simulate an infinite fluid domain.

It is known, that in this case, the radial stress on the pipe outer surface, produces pressure waves in the infinite fluid. By this mechanism, wave energy is radiated and the propagating modes are attenuated even if the solid and fluid materials are ideal (lossless).

The total displacements after 10, 20 and respectively 30μs are shown on figure 6. At 10μs, the signal resembles the equivalent one on figure 4, but the similarities do not continue in the next two moments, due to different interactions with the fluid.

The pressure wave in the fluid however, follows the expected behaviour (figure 7). The propagation is producing conical wave fronts, having angles depending on the wave's velocities in the two domains. However, since the ultrasonic pulse is made of several modes with different group velocities in the pipe, the wave pattern in the fluid domain has several interfering pressure wave cones, as can be seen on figure 7 (bottom).

**Figure 4.** Total displacements after 10μs (left), 20μs (middle), 30μs (right).

**Figure 5.** Pressure wave in the fluid surrounding the pipe, at 10μs (left), 20μs (middle), 30μs (right).
These signals can be processed by double FFT in frequency and position, in order to identify the propagating modes. The experiments require reading signals along a generatrix, following the wave propagation. These signals are proportional to the radial velocity and consequently to the radial displacements at a given frequency. Signal processing provides wavenumbers and modal attenuation. Experimental results confirm the mode propagation and attenuation, and will be developed in next period.

6. Conclusions
The FEM simulations of wave pulse propagation in a kerosene filled and kerosene surrounded pipe have indicated the wave attenuation in both cases. This practical aspect, for the pipe filled with an inviscid fluid, is not mentioned in the literature, because for an infinite duration signal, in an infinite pipe, without material dissipation, the modes should propagate without attenuation. The maximum expected inspection range can be determined with good accuracy, before the inspection on real industrial piping.

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