Using Ultrasonic Guided Waves in Evaluation of Pipes

Saeed Izadpanah 1, Gholam Reza Rashed 2, Sina Sodagar 3
1- Petroleum University of Technology, Abadan, Iran
2- Petroleum University of Technology, Ahvaz, Iran
3- University of Toronto, Toronto, Canada

First Author’s E-mail: saeed.izadpanah@gmail.com

Abstract:
Nowadays, using the relatively long tubular structures, such as transmission pipeline and drilling strings, are common in many industries such as oil, petrochemicals and power plants. In regards to the sensitivity of these structures, they need proper inspection method for ensuring the reliability and lack of defects. But Inspection of these structures with ordinary non destructive test are expensive, difficult and in some cases impossible due to excessive length ,inaccessibility to the entire structures and also dependency on exact evaluation of defects. In light of above mentioned difficulties, using guided waves for inspection of structure have been considered by many researchers due to possibility of using various waves with different properties. Therefore, this article outlines principles, characteristic, advantageous, disadvantageous and limitation of non destructive method for inspection of tubular structures such as pipes by means of guided waves. Also propagation of the waves in the longitudinal direction of cylindrical waveguide will be investigated.

Keywords: Ultrasonic, Guided waves, tubular structure, dispersion curve

Introduction:
Testing large structures using conventional bulk ultrasonic wave techniques is slow because the test region is limited to the area immediately surrounding the transducer. Therefore, scanning is required if the entire structure is to be tested. Also A high proportion of these industrial pipelines is insulated, so that even external corrosion cannot readily be detected without the removal of the insulation which in most cases is prohibitively expensive. There is therefore an urgent need for the development of a quick, reliable method for the detection of corrosion under insulation.

Ultrasonic guided waves provide an attractive alternative solution to this problem because they can be excited at one location on the structure and propagate over a long distance under the insulation. By analyzing the characteristics of the guided waves such as the returning echoes, change of dispersion relationships, etc., the presence of flaws may be detected. However, because of the multimode nature of guided waves, ultrasonic tests using guided waves are more complicated.

A number of authors have worked on the use of Lamb waves for the inspection of pipes and tubes [1-7]. Much of this has addressed the requirements for inspection of heat exchanger tubing which is typically 1 in. in diameter and is therefore somewhat smaller than the chemical plant piping. However, studies have included the inspection of larger diameter gas pipelines using circumferentially travelling waves [6,7]. Relevant studies have also been reported previously and elsewhere on the interaction of Lamb waves with defects in plate and pipe structures [8-11]. Regarding the present project, publications have reported the development of the dry-coupled piezoelectric transducers for the excitation and detection of the guided waves [12], studies of the reflection and mode conversion behavior of the guided waves [13-16], studies of the influence of features such as flanges and pipe supports [17], and the results of field trials [18].
Application, Advantageous And Limitation:

In recent years advancement in NDT Technology has taken place in a very great pace. Among all NDT methods, Ultrasonic testing has undergone many developments and is evolving with more methodologies using sophisticated equipments. Meanwhile Guided Wave ultrasonic test is one of the pioneer method. Guided wave inspection named by many end users is technically a," long range inspection". The guided wave inspection is a volumetric inspection used mainly to determine the pipe integrity as a rapid screening tool for corrosion. “Guided Waves” are ultrasonic waves guided by the geometry of the object in which they propagate. Due to very less attenuation loss these waves transmit along the whole circumferential of the pipe propagating in the planer direction. These wave travel across the straight stretches of pipe to several meters. Bends supports, welds, type of insulation and coating adds to attenuation loss.

Initial Nondestructive Testing methods (Ultrasonic Testing (UT), Radiographic Testing (RT), Eddy Current Testing (ECT), Magnetic Flux Leakage (MFL) can be point by point inspection. It has the problem of time restriction and expense. To overcome these problems, the develop of effective testing method has been needed. Ultrasonic guided waves follows the geometric structure and it propagates with length direction. It consist of a longitudinal wave and a transverse wave.[19]

Guided wave inspection is employed basically as a fast screening tool for volumetric inspection. The major application are for Pipe under insulation, Under Ground Piping, Road Crossing Piping, Internal tube piping and Adhesive Bond inspection.

Guided wave is a fast screening tool, and covering a large length of inspection. About 40Meters of coverage is possible under favorable conditions, in addition Defects of more than 5% volumetric size of the pipe can be detected ,also its fast result and Portability makes it easy for field application.

The major disadvantageous or limitation of guided wave is that Small volume defects, like localized pitting cannot be detected also it operates Poor on heavily corroded pipes and Bitumen and concert coated piping. its sizing capabilities is limited and it need UT and VT to follow up and pinpoint and Requires very experienced technicians.[20]

Application of The Guided Waves In The Longitudinal Direction:

Pipes are extensively used for transporting chemicals, water, and other necessities. A nation’s civil and chemical infrastructure depends to a large extent on the integrity of thousands of miles of pipes. Nondestructive inspection and monitoring of pipes are critical to these industries. Ultrasonic techniques have been used extensively for this purpose. One of the examples of this application is using smart pig for locating the corrosion [21]

Another examples include detecting broken rail with guided waves [22], Determining the Poisson’s ratio in wires [23]. And measuring fluid viscosity by using guided waves in a rod immersed in the fluid being measured [24]

Application of Guided Waves In The Circumferential Direction:

Fatigue cracks have been found to initiate and grow in the radial direction in many of the annular shaped components in aging helicopters. These include some of the most critical components such as the rotor hub, connecting links and pitch shaft, etc. At the present time, detection of such radial fatigue cracks relies mostly on visual inspection. More systematic, automated, and efficient methods to detect these cracks are needed.

Conventional ultrasonic imaging techniques can be used to detect such radial cracks. However, these techniques are impractical for real-time, integrated diagnosis. Nagy et al. proposed that guided ultrasonic waves that propagate in the circumferential direction may be used for the detection of radial fatigue cracks in annular components.[25] Because of its potentials in nondestructive evaluation of annular components, extensive studies have been conducted to understand the generation and propagation of guided circumferential waves. Recently, a number of papers have been devoted to the study of the various properties of guided circumferential waves and their applications in nondestructive evaluation [26-33]

Generation of Guided Waves In The Cylindrical Waveguide:

The guided wave is generated by placing the probe ring or can term as an array of probes generating sound on both side of the pipe. Usually it is placed by removing the heavy coating or insulation on that particular location. These transmitted waves reflect back from the anomalies thereby generating signals and giving information about the distance from the ring and as well the loss of energy. typically inspection is based on a single carefully selected guided mode, however in some cases, a multimode approach is adapted, for example , by using a linear array comb transducer.
Generating desired wave modes in the cylindrical waveguide is the first task for nondestructive testing. There are many ways of generating guided waves in cylindrical waveguides. Typically, an angle beam transducer is used for generating waves in a pipe, whereby refraction into the test pipe produces multiple reflection and transmission of ultrasonic energy and numerous mode conversions. A very short distance away from the transducer, clearly formed wave packets of ultrasonic energy are produced that can propagate along the pipe. Another common technique is to make use of a comb type transducer whereby ultrasonic energy is pumped into the structure at some particular spacing of the comb transducer where guided waves are generated in both directions [34]. Guided waves can also be produced in a pipe by electromagnetic acoustic and magnetostrictive transducers [35].

Guided Mode Properties:
Various wave modes are used in inspection for full coverage and reliability requirements. Among many waves, torsional and longitudinal waves have found to have more adaptability basically using two mode of operation i.e. Symmetric Mode or Ant symmetric Mode.

Many guided wave mode exists in a particular component. Certain modes are sensitive to particular flaws. It is very important to select the mode to fulfill the inspection objectives. In many cases multi modes are used to cover the full thickness coverage and for identification of particular flaws.

The modes include a family of axially symmetric longitudinal, flexural and torsional motion of the pipe wall, as would be expected from an understanding of Lamb and Love modes if the pipe was considered simply as a curved plate. However, in addition to the axially symmetric (zero-order) modes, there are modes which have harmonic variation of displacements and stresses around the circumference. The order 1 modes have one cycle of variation around the circumference, order 2 have two, and so on. For each of this infinite series of orders there is a family of modes. The modes in the figures are labeled after the convention of Silk and Bainton [1], the first integer of the integer pair in each mode label gives the harmonic order of circumferential variation; thus the axially symmetric modes have zero as their first integer. The letters L, F and T denote longitudinal, flexural and torsional modes, respectively.

Mathematical Formulation:
If $\Phi$ is a scalar function and $A$ is a vector function, then any displacement field $u$ can be expressed in the following manner:

$$ u = \nabla \phi + \nabla \times A \tag{1} $$

the displacement equations of motion in a cylindrical coordinate system can be written as:

$$ \nabla^2 u_r = \frac{u}{r^2} - \frac{2}{r^2} \frac{\partial u_\theta}{\partial \theta} + \frac{1}{1 - 2\nu} \frac{\partial U_r}{\partial r} = \frac{1}{c_r^2} \frac{\partial^2 U_r}{\partial t^2} \tag{2} $$

$$ \nabla^2 u_\theta = \frac{u_\theta}{r^2} + \frac{2}{r^2} \frac{\partial u_r}{\partial \theta} + \frac{1}{1 - 2\nu} \frac{\partial U_\theta}{\partial r} = \frac{1}{c_r^2} \frac{\partial^2 U_\theta}{\partial t^2} \tag{3} $$

$$ \nabla^2 u_z = \frac{1}{1 - 2\nu} \frac{\partial U_z}{\partial z} = \frac{1}{c_z^2} \frac{\partial^2 U_z}{\partial t^2} \tag{4} $$

where $\nabla^2$ is the Laplacian operator:

$$ \nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2 \sin \theta} \frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial z^2} \tag{5} $$

and the symbol $\Delta$ represents the dilatation.
The corresponding stresses are given in terms of the displacements.

It can be shown by direct substitution that the displacement equations of motion, Equation 2 through Equation 4, are identically satisfied if the potentials satisfy the following equations:

\[ \nabla^2 \varphi = \frac{1}{c_I^2} \frac{\partial^2 \varphi}{\partial t^2} \tag{15} \]

\[ \nabla^2 \psi_r = \frac{\psi_r}{r^2} - \frac{2}{r^2} \frac{\psi_\theta}{\partial \theta} = \frac{1}{c_I^2} \frac{\partial^2 \psi_r}{\partial t^2} \tag{16} \]

\[ \nabla^2 \psi_\theta = \frac{\psi_\theta}{r^2} + \frac{2}{r^2} \frac{\psi_r}{\partial \theta} = \frac{1}{c_I^2} \frac{\partial^2 \psi_\theta}{\partial t^2} \tag{17} \]

\[ \nabla^2 \psi_z = \frac{1}{c_I^2} \frac{\partial^2 \psi_z}{\partial t^2} \tag{18} \]

The stresses can be written in terms of the displacement potentials by substituting Equation 12 through Equation 14 into Equation 6 through Equation 11:

\[ \sigma_{rr} = \lambda \nabla^2 \varphi + 2\mu \left( \frac{\partial^2 \varphi}{\partial r^2} + \frac{\partial^2 \varphi}{\partial \theta^2} - \frac{1}{r} \frac{\partial \varphi}{\partial \theta} - \frac{1}{r^2} \frac{\partial^2 \varphi}{\partial \theta^2} + \frac{1}{r} \frac{\partial \psi_r}{\partial \theta} - \frac{1}{r^2} \frac{\partial^2 \psi_r}{\partial \theta^2} \right) \tag{19} \]

\[ \sigma_{r\theta} = \lambda \nabla^2 \varphi + 2\mu \left( \frac{1}{r} \frac{\partial \varphi}{\partial \theta} + \frac{1}{r^2} \frac{\partial^2 \varphi}{\partial \theta^2} + \frac{1}{r} \frac{\partial \psi_r}{\partial \theta} - \frac{1}{r^2} \frac{\partial^2 \psi_r}{\partial \theta^2} - \frac{1}{r} \frac{\partial \psi_\theta}{\partial \theta} + \frac{1}{r^2} \frac{\partial^2 \psi_\theta}{\partial \theta^2} - \frac{1}{r} \frac{\partial \psi_z}{\partial \theta} \right) \tag{20} \]

\[ \sigma_{r\theta} \tag{20} \]

\[ \sigma_{rr} = \lambda \nabla^2 \varphi + 2\mu \left( \frac{\partial^2 \varphi}{\partial r^2} + \frac{\partial^2 \varphi}{\partial \theta^2} - \frac{1}{r} \frac{\partial \varphi}{\partial \theta} - \frac{1}{r^2} \frac{\partial^2 \varphi}{\partial \theta^2} + \frac{1}{r} \frac{\partial \psi_r}{\partial \theta} - \frac{1}{r^2} \frac{\partial^2 \psi_r}{\partial \theta^2} - \frac{1}{r} \frac{\partial \psi_\theta}{\partial \theta} + \frac{1}{r^2} \frac{\partial^2 \psi_\theta}{\partial \theta^2} - \frac{1}{r} \frac{\partial \psi_z}{\partial \theta} \right) \tag{21} \]

\[ \sigma_{r\theta} = \mu \left( \frac{2}{r} \frac{\partial \varphi}{\partial \theta} - \frac{2}{r^2} \frac{\partial \varphi}{\partial \theta} + \frac{1}{r^2} \frac{\partial \psi_r}{\partial \theta} + \frac{1}{r^2} \frac{\partial \psi_\theta}{\partial \theta} + \frac{1}{r^2} \frac{\partial \psi_z}{\partial \theta} - \frac{1}{r^2} \frac{\partial^2 \psi_z}{\partial \theta^2} - \frac{1}{r^2} \frac{\partial \psi_z}{\partial \theta} \right) \tag{22} \]

\[ \sigma_{r\theta} \tag{22} \]

\[ \sigma_{r\theta} = \mu \left( \frac{\partial \psi_r}{\partial \theta} + \frac{1}{r} \frac{\partial \psi_\theta}{\partial \theta} + \frac{2}{r^2} \frac{\partial \varphi}{\partial \theta} - \frac{1}{r^2} \frac{\partial \psi_\theta}{\partial \theta} - \frac{1}{r^2} \frac{\partial \psi_z}{\partial \theta} + \frac{1}{r^2} \frac{\partial^2 \psi_z}{\partial \theta^2} + \frac{1}{r^2} \frac{\partial \psi_z}{\partial \theta} \right) \tag{23} \]

\[ \sigma_{r\theta} \tag{23} \]

\[ \sigma_{r\theta} = \mu \left( \frac{1}{r^2} \frac{\partial \psi_\theta}{\partial \theta} + \frac{1}{r} \frac{\partial \psi_\theta}{\partial \theta} + \frac{1}{r^2} \frac{\partial \psi_\theta}{\partial \theta} + \frac{1}{r^2} \frac{\partial \psi_z}{\partial \theta} + 2 \frac{\partial \psi_\theta}{\partial \theta} - \frac{1}{r^2} \frac{\partial^2 \psi_z}{\partial \theta^2} + \frac{1}{r^2} \frac{\partial \psi_z}{\partial \theta} + \frac{1}{r^2} \frac{\partial \psi_z}{\partial \theta} \right) \tag{24} \]

\[ \sigma_{r\theta} \tag{24} \]

**Propagation Θ_ in the Axial Direction:**

For time-harmonic waves propagating in the axial (the z-axis) direction of the cylindrical waveguide of circular cross section as shown in Figure 1, the displacement potentials can be written in the following form.
\[ \varphi = \phi(r) \cos(m \theta + \theta_0) \exp[i(k_z z - wt)] \] (25)

\[ \psi_r = \psi_r(r) \sin(m \theta + \theta_0) \exp[i(k_z z - wt)] \] (26)

\[ \psi_\theta = \psi_\theta(r) \cos(m \theta + \theta_0) \exp[i(k_z z - wt)] \] (27)

\[ \psi_z = \psi_z(r) \sin(m \theta + \theta_0) \exp[i(k_z z - wt)] \] (28)

where \( \theta_0 \) is an arbitrary constant, while \( m \) can only be either zero or integers, because the functions must be periodic in the circumferential direction for waves propagating in the axial direction.

**Axial Waves In Hollow Cylinder:**

Consider a hollow cylinder of inner radius \( a \) and outer radius \( b \) as shown in previous figure. It is assumed that both the inner and outer surfaces are traction free, i.e.,

\[ \sigma_{rr} = 0, \sigma_{r\theta} = 0, \sigma_{rz} = 0 \quad \text{at} \quad r = a, b \]

The general solution to the waves propagating in the axial direction of this hollow cylinder is given by Equation 25 through Equation 28. The Bessel functions of second kind should be retained in this case, because the presence of both incoming (toward the center) and outgoing (away from the center) waves is necessary to satisfy the traction-free boundary conditions on both the inner and outer surfaces. Thus, the corresponding stresses can be computed from Equation 29:

\[
\begin{bmatrix}
\sigma_{rr} \\
\sigma_{r\theta} \\
\sigma_{rz}
\end{bmatrix}
= \mu \begin{bmatrix}
d_{11}^z(m,r) & d_{12}^z(m,r) & d_{13}^z(m,r) & d_{14}^z(m,r) & d_{15}^z(m,r) \\
d_{21}^z(m,r) & d_{22}^z(m,r) & d_{23}^z(m,r) & d_{24}^z(m,r) & d_{25}^z(m,r) \\
d_{31}^z(m,r) & d_{32}^z(m,r) & d_{33}^z(m,r) & d_{34}^z(m,r) & d_{35}^z(m,r)
\end{bmatrix} \mathbf{A}
\]

(29)

Where \( \mathbf{A} = [A_1, B_1, C_1, A_2, B_2, C_2]^T \) and the elements \( d_{aq}^z(m,r) \) are as follows:

\[
d_{11}^z(m,r) = \left[ \frac{2m(m-1)}{r^2} + k_z^2 - q^2 \right] Z_m(pr) + \frac{2p}{r} Z_{m+1}(pr)
\] (30)

\[
d_{12}^z(m,r) = 2ik \left[ qZ_m(qr) - \frac{m+1}{r} Z_{m+1}(qr) \right]
\] (31)

\[
d_{13}^z(m,r) = 2m \left[ \frac{m-1}{r^2} Z_m(qr) - \frac{q}{r} Z_{m+1}(qr) \right]
\] (32)

\[
d_{12}^z(m,r) = 2ik \left[ \frac{m}{r} Z_m(pr) - pZ_{m+1}(pr) \right]
\] (33)

\[
d_{22}^z(m,r) = -\frac{qm}{r} Z_m(qr) + (q^2 - k_z^2) Z_{m+1}(qr)
\] (34)

\[
d_{23}^z(m,r) = \frac{ikm}{r} Z_m(qr)
\] (35)

\[
d_{31}^z(m,r) = -2m \left[ \frac{(m-1)}{r^2} Z_m(pr) - \frac{p}{r} Z_{m+1}(pr) \right]
\] (36)

\[
d_{32}^z(m,r) = ik \left[ qZ_m(qr) - \frac{2(m+1)}{r} Z_{m+1}(qr) \right]
\] (37)
The traction-free condition on both surfaces \( r=a,b \) results in the following eigenvalue problem:

\[
\begin{bmatrix}
& d_{l1}(m,b) & d_{l2}(m,b) & d_{l3}(m,b) & d_{l4}(m,b) & d_{l5}(m,b) & d_{l6}(m,b) & d_{l7}(m,b) & A_1
& d_{s1}(m,b) & d_{s2}(m,b) & d_{s3}(m,b) & A_2
& d_{s1}(m,a) & d_{s2}(m,a) & d_{s3}(m,a) & A_2
& d_{s1}(m,a) & d_{s2}(m,a) & d_{s3}(m,a) & B_1
& d_{s1}(m,a) & d_{s2}(m,a) & d_{s3}(m,a) & C_1
\end{bmatrix} = 0
\]

By setting the determinant to zero, we obtain the dispersion equation for waves propagating in the axial direction of a hollow cylinder of inner radius \( a \) and outer radius \( b \). Let us consider some specific wave motions of practical interest.

**Torsional Motion:**

In a pure torsional motion, \( u_\theta \) should be the only nonzero displacement component. Furthermore, it should be independent of \( \theta \). These conditions are met by setting \( A_n=B_n=m=0 \) and \( \theta_0 = \pi/2 \) in the integral solution. The corresponding dispersion equation is thus deduced from Equation 39:

\[
\begin{bmatrix}
& d_{l1}(0,b) & d_{l2}(0,b) & C_1
& d_{l1}(0,a) & d_{l2}(0,a) & C_2
\end{bmatrix} = 0
\]

The vanishing of the determinant yields \( q = 0 \), or

\[
J_2(qb)Y_2(qa) - J_2(qa)Y_2(qb) = 0
\]

(41)

Clearly, the modes determined from Equation 41 are all dispersive. The lowest mode corresponding to \( q=0 \) however, is nondispersive. Its displacement field is similar to the following equation:

\[
u_\theta = Cr \exp(ik_z z)
\]

(42)

In fact, one can easily show that in the limit \( a \to 0 \), the above equation reduces to the following equation, as expected.

\[
qbJ_q(qb) - 2J_1(qb) = 0
\]

(43)

For the case \( b > a \to \infty \) one can use the asymptotic expressions of the Bessel functions in Equation 8.92, which results in

\[
\sin(qh) = 0
\]

(44)

Where \( h=b-a \) is the wall thickness of the hollow cylinder. This is identical to the dispersion equation for the symmetric horizontally polarized shear waves in a plate of thickness \( 2h \).

Similar to the solid cylinder case, it can be shown that Equation 41 does not have any real roots for \( q^2 < 0 \). Thus, it can be ascertained that the phase velocity of the torsional waves in a hollow cylinder is always greater than or equal to the shear velocity \( C_T \).

**Longitudinal Waves:**

Longitudinal waves refer to the axially symmetrical motion in the cylinder. They are characterized by the presence of displacement components in the radial and axial directions, but none in the \( \theta \)-direction. Furthermore, these nonzero displacement components must be independent of \( \theta \) because of the axisymmetric requirement. It is
seen that these conditions are met by setting \( C_n = m = 0 \) and \( \theta_0 = 0 \) the general solution. The corresponding eigenvalue problem is thus obtained from Equation 39:

\[
\begin{bmatrix}
d_{11}^f(0, b) & d_{12}^f(0, b) & d_{11}^y(0, b) & d_{12}^y(0, b) \\
d_{21}^f(0, b) & d_{22}^f(0, b) & d_{21}^y(0, b) & d_{22}^y(0, b) \\
d_{11}^f(0, a) & d_{12}^f(0, a) & d_{11}^y(0, a) & d_{12}^y(0, a) \\
d_{21}^f(0, a) & d_{22}^f(0, a) & d_{21}^y(0, a) & d_{22}^y(0, a)
\end{bmatrix}
\begin{bmatrix}
A_1 \\
B_1 \\
A_2 \\
B_2
\end{bmatrix} = 0
\]

(45)

Vanishing of the determinant yields the dispersion equation.

**Flexural waves:**
As in the solid cylinder case, flexural waves in a hollow cylinder are defined by setting \( m = 1 \) and \( \theta_0 = 0 \) in the general solution. The corresponding eigenvalue problem is thus obtained from Equation 30 by setting \( m = 1 \).

**Dispersion Characteristic of Pipe And Mode Selection:**
Wave propagation properties in pipes are extremely complicated, much more so than in plates. Figs. 2 show the longitudinal phase and group velocity dispersion curves for a nominal 3 in. (inside diameter 76 mm, wall thickness 5.5 mm) pipe. Also phase and group velocity for all of the modes has been shown in figure 3.

![Figure 2 Longitudinal dispersion curve](image1)

![Figure 3 : phase velocity and group velocity](image2)

ID=78 mm, thickness=5.5 mm, \( C_L = 6.06 \text{ m/ms} \), \( C_T = 3.23 \text{ m/ms} \)
The phase velocity dispersion curves show the velocity of the harmonic wave cycles in the direction of propagation along the pipe; they provide useful information about wave speeds of single tones and of wavelengths of the modes. The group velocity dispersion curves show the velocity at which finite-time wave packets travel; they are therefore useful for the calculation of the travel times of the wave signals which are used in the long range testing.

A key element of the inspection system is the selection and exploitation of a single mode. In general, an excitation source can excite all of the modes which exist within its frequency bandwidth, resulting in a signal which is much too complicated to interpret. Indeed, even with a single mode, great care is needed for the correct identification of the reflections from defects and from normal pipe features such as welds. Therefore, although troublesome to achieve, it is essential to design the transducers and the signal to excite only the chosen mode. Then, since defects and normal pipe features can convert energy to other modes, it is important also to be able to receive selectively. The mode which was chosen for excitation in the inspection system is the axially symmetric L(0,2) mode, at about 70 kHz. This mode is very attractive for testing for several reasons: it is practically non-dispersive over a wide bandwidth around this frequency that is to say its velocity does not vary significantly with frequency so that the signal shape and amplitude are retained as it travels; it is the fastest mode so that any unwanted mode converted signals arrive after it has been received; and its mode shape makes it equally sensitive to internal or external defects at any circumferential location.

Spatial selectivity depends primarily on the use of a ring of transducers around the pipe. If a sufficient number of equally spaced and equally driven transducers is excited around the circumference, then only the axially symmetric (order 0) modes are excited. The number of transducers must be greater than the highest order of the modes which can be present in the frequency range of the signal. For the 3 in. pipe, the highest order for frequencies up to 100 kHz is 13; the testing system uses 16 transducer elements for this size of pipe. Having avoided all non-zero order modes, there remain the T(0,1), L(0,1) and L(0,2) modes within the chosen frequency range. The T(0,1) mode consists of torsion of the pipe and can only be excited by circumferential motion. Its excitation is therefore avoided by using transducers which excite axial motion [12]. Strong excitation of the L(0,2) mode whilst only weakly exciting the L(0,1) mode can be achieved by using two transmitter rings with wavelength axial separation. Fig. 3 shows that the phase velocity (and therefore wavelength) of L(0,1) is markedly different to that of L(0,2). On the same basis, the reception of signals is equally selective, the received signals of the elements of the transducers being summed. A further refinement of the system which is of great practical value is to excite a forward traveling wave without much energy being propagated in the backward direction. This can be achieved by using transducer rings which are spaced a quarter of a wavelength apart and separated by $\pi/2$ in phase [18].

Conclusions:

It can be suggested that Guided Waves is a suitable method for inspection of the pipes over very long distances, and can be efficiently used instead of conventional ultrasonic methods which are based on point by point inspection. Advantages, and disadvantages of the guided wave technique are as follows:

- a high speed of inspection over a long distances;
- in service inspection of gas and oil which has been placed under water or soil.
- inspection of heat exchanger tubes and bends
- high flexibility, safety, and no danger of harmful radiation;
- the possibility of inspecting parts and joining with complex geometry.

Disadvantages of guided wave:

- Small volume defects, like localized pitting cannot be detected
- it operates Poor on heavily corroded pipes and Bitumen and concert coated piping.
- its sizing capabilities is limited and it need UT and VT to follow up
- Requires very experienced technicians
- The lack of existing standards and a desired acceptability level in the field.

Also, in this paper the solutions for phase velocity, group velocity and displacement of guided wave has been described and all the dispersion curve has been drawn for a hollow cylinder with inner radius of 78 mm and thickness of 5.5 mm. also according to mode selection it was found that the best mode is L(0,1) which has a small variation of speed with frequency.
References:


[34] Rose, J.L., Pelts, S., Quarry, M., A comb transducer model for guided wave NDE, Ultrasonics, 36, 163–168, 1998