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Long Range Cylindrically Guided Ultrasonic Wave Technique for Inspection

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Abstract In this paper, a review of the current status, on the use of long range cylindrically guided wave modes, and their interaction with cracks and corrosion damage in pipe-like structures will be discussed. Applications of cylindrically guided ultrasonic wave modes have been developed for inspection of corrosion damage in pipelines at chemical plants, flow-accelerated corrosion damage (wall thinning) in feedwater piping, and circumferential stress corrosion cracks in PWR steam generator tubes. It has been demonstrated that this inspection technique can be employed on a variety of piping geometries (diameters from 1 in. to 3 ft, and wall thickness from 0.1 to 6 in.) and a propagation distance of 100 meters or more is sometimes feasible. This technique can also be used in the inspection of inaccessible or buried regions of pipes and tubes.

Introduction

The ultrasonic guided waves, unlike bulk wave modes like longitudinal and transverse, are a manifestation of geometrical confinement of acoustical waves by one or more boundaries. [1,2] In many instances, these waves travel long distances, depending on the frequency and mode characteristics of the wave, and follow the contour of the structure in which they are propagating. Usually, these waves not only propagate along the length of the structure but also cover the entire thickness and circumference (in the case of cylinders and rods). The use of guided wave modes is potentially a very attractive solution to the problem of inspecting the embedded portions of structures because they can be excited at one point on the structure propagated over considerable distances, and received at a remote point on the structure, in a pitch-catch mode, as schematically illustrated in Figure 1 for an elbow pipe. The received signal contains information about the integrity of the material that lies between the transmitting and receiving transducers. Alternate approaches, where the receiving and transmitter are co-located, similar to a pulse-echo method is also possible.

Since there are several types of guided waves, there are many ways to classify them. The first classification can be based on the type of structure in which it is generated. These include (a) Plate waves, (b) Cylindrical waves, (c) Rod waves, etc., depending upon the type of structure. The waves mode characteristics for each of the above wave type is distinctly different, but can be theoretically predicted if the material properties are well known.

The second method of classification of the

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wave mode is based on the nature of the particle vibration with respect to the direction of wave propagation (like in the case of bulk waves). In this type of classification, the types include (a) Extensional or Longitudinal waves, (b) Shear-horizontal waves, (c) Flexural waves, and (d) Torsional waves [3-5]. Here, the first two types are similar to the Longitudinal and Shear wave vibration. The Flexural waves are modes where the structure flexes in a wave like pattern and the Torsion waves exists when the particle motion is circumferential in nature while the wave moves along the structure.

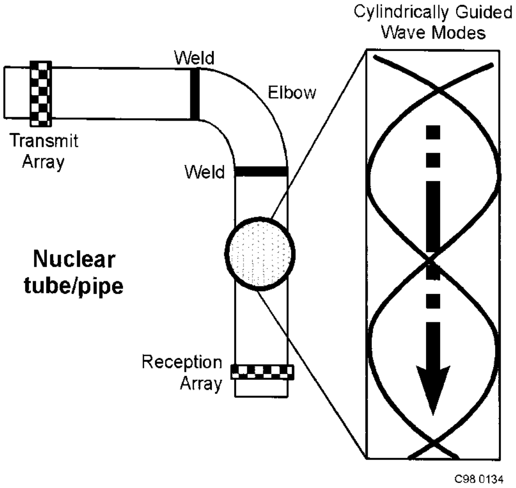

Figure 1 A hypothetical illustration of a elbow section of a pipe that is monitored by cylindrically guided waves using surface mounted array transducers

Also, the wave modes can also be broadly classified into symmetric and anti-symmetric modes based on the type of symmetry of the displacement profile exhibited by the wave during propagation. This classification is based on whether the out-of-plane displacement in a structure is symmetric about the 'neutral' axis of the bounded structure ie. if the two outer particles simultaneously move away from the center axis, then it is a symmetric mode and if they move together, then it is anti-symmetric. This is well illustrated in Figure 2.

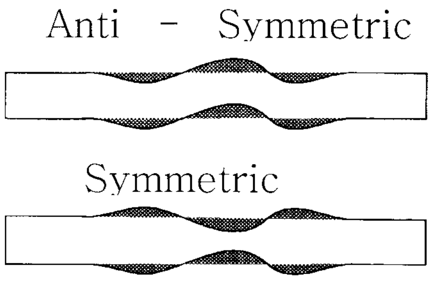

Figure 2 Representation of anti-symmetric and symmetric flexural guided wave modes in a plate

Finally, for a give type of guided wave, there are many orders of modes that can exist. The modes have mode shapes are analogous to vibration modes in a beam. These modes are numbered numerically with zero representing the basic fundamental modes and the higher order modes representing more complex behavior.

Thus, while defining a guided wave mode, a complete description will require the specification of all of the above classifications. For instance, a cylindrically guided, flexural, anti-symmetric, fundamental mode would represent a guided wave that is traveling along the length of a cylindrical structure, that has a fundamental flexural type particle vibration direction, that is not symmetric about the axis. The cylindrically guided wave modes are often represented as L(n,m)-Longitudinal, F(n,m)-Flexural, or T(n,m) - Torsional in nature, where the 'n' and the 'm' represent the mode numbers based on Silk and Bainton [6]. For instance when n=0, the mode is axially symmetric, such as the L and T modes. If n>0, then the mode is not axially symmetric. Here, 'm' is the order of the mode of vibration.

The multi-mode nature of these wave modes can be an advantage since each mode has different sensitivity to a particular type of defect and hence by comparing the wave propagation of different modes, ie. by using one as a reference mode and the other as a sensing mode, defect and/or material characterisation becomes feasible.

The reflectivity of guided waves is governed by very different rules than those for bulk waves; with guided waves, it is possible to find defects whose size is much smaller than a wavelength. At a given defect depth, the reflection coefficient is directly proportional to the circumferential extent of the defect. The reflection coefficient of a half wall thickness notch with a circumferential extent of half a pipe diameter (16% of the pipe circumference) is approximately 5% (-26 dB).

If an axially symmetric mode is incident on an axially symmetric feature in the pipe such as a flange, square end or uniform weld, then only axially symmetric modes are reflected. Such a case is illustrated in Figure 3 that represents results from experiments conducted on pipes with welds and corrosion like defects. However, if the feature is non axially symmetric such as a corrosion patch, some non axially symmetric waves will be generated. These propagate back to the transducer rings and can be detected. For instance, if a L(0,2) mode is incident on a defect, the mode conversion is predominantly to the adjacent F(1,3) and F(2,3) modes which have similar velocities to the L(0,2) mode in the operating frequency range. The amount of mode conversion obtained depends on the degree of asymmetry, and hence on the circumferential extent of the defect. At low circumferential extent (which is the region of interest for the detection of critical corrosion in practical situations) the mode converted F(1,3) reflection is almost as large as the direct reflection. Thus, if these two reflections are of similar size, it can be concluded that the feature is localised to a small region of the circumference [7-9].

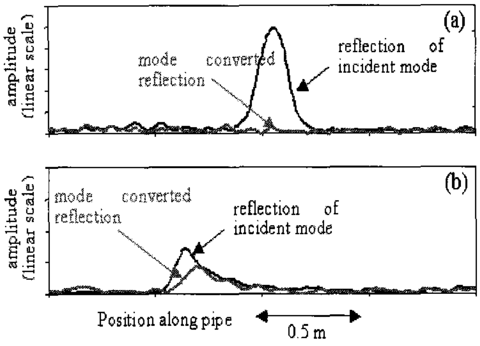

Figure 3 Signals from (a) axisymmetric feature e.g. weld; (b) corrosion[25]

Effects of Dispersion

One of the key aspects of guided wave modes is Dispersion, ie. wave velocity is not a constant for a given material. It additionally depends on geometry (thickness) and frequency of the wave. In most cases, this becomes one parameter (f*d). The consequence of dispersion is that a compact broad-banded signal will not retain its shape while propagating and will elongate considerably with distance of travel. This is because of the fact that a broad band ultrasonic pulse comprises of a range of frequencies (depending on the bandwidth and central frequency of the pulse) and since each frequency is traveling at a different velocity, the pulse duration increases. This is illustrated in Figure 4 where two modes, one non-dispersive mode (2) and a dispersive mode (3) are shown.

The velocity of the wave mode for a single frequency is called as its Phase velocity. It must be apparent that the measurement of phase velocity by traditional velocity measurement techniques (such as pulse-overlap, zero-crossing, etc.) is difficult, due to the change in the pulse shape. Hence, a different definition of velocity called the Group velocity is used while measuring the velocities of a dispersive ultrasonic pulse by traditional methods. The Group velocity cannot be faster than the Phase velocity and the dispersive nature of these modes can be theoretically computed if the material properties are known.

The dispersion curves used to gain understanding of the types of modes that can be generated and their dispersive nature [10-12]. These curves are also used for interpretation of the signal. The dispersion curves are represented in different manner in literature. The most userful representation for NDE application is shown in Figure 5. In this representation, the velocity of the wave is plotted as a function of frequency of the wave. Each curve represents a guided wave mode. The wave velocity that is plotted can be either phase or group velocity. But, from our previous discussion, it can be concluded that the group velocity is representative of measurements made with dispersive wave pulses and hence is more useful. In Figure 5, it can be seen that there are several (in fact, too many) modes that can be generated in a pipe. All three types of modes are represented (ie. Torsional, Longitudinal and Flexural). The slope of these curves indicate the dispersive nature of the wave mode. Hence, a curve with a steep slope is very dispersive and may be avoided during NDE. Consequently, a flat region of a curve means the mode is non-dispersive and the wave pulse will propagate effectively and measurements are possible. Hence, in Figure 5, the most preferred mode is the L(0,2) which is the 2nd order axi-symmetric extensional mode within the frequency range between 40kHz -100 kHz.

The dispersion curves can be theoretically computed and plotted using a software package DISPERSE developed by Imperial College, UK. [13].

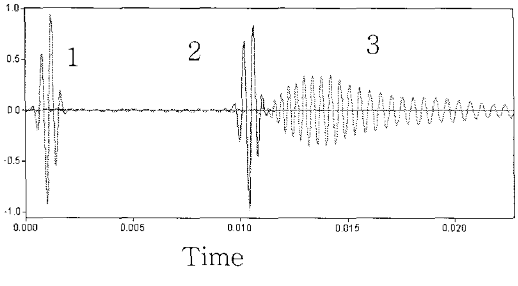

Figure 4 Typical guided wave signals (1) Transmitted pulse, (2) Signal after travel of 30 mm in a component showing no dispersion, and (3) a dispersive mode showing pulse spreading.

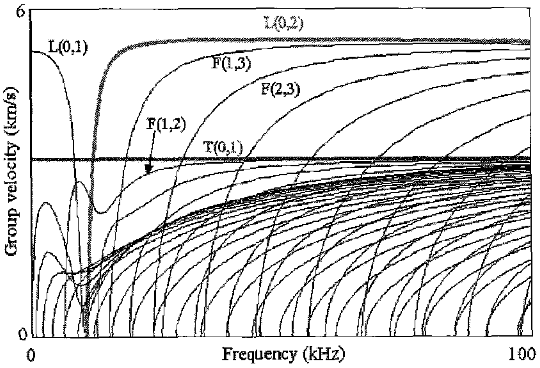

Figure 5 Dispersion curves plotting group velocity, vs frequency for guided waves in a pipe[25]

Advantages and Limitations of the Technique

These guided wave modes represent very different approach to NDE when compared with traditional ultrasonic methods. Some of the key benefits of this technique for pipe and tube inspection is listed below:

1. Use of multimode, guided, plate waves provides a global long-range inspection technique for characterizing any potential in-service damage (impact and delamination) in typical cylindrical structures.
2. In the case of pipes with insulation, these modes allow inspection with minimal removal of insulation.
3. Regions that are inaccessible, such as buried pipes, can be inspected.
4. The multi-mode cylindrical waves can be utilized to identify regular pipeline features such as welds from localized damage such as corrosion.

Some of the key limitations of the technique are:

1. This method requires the understanding of multi-mode nature of the guided waves.
2. The energy that is generated is distributed over a large volume of the structure. Hence, this technique may have difficulty detecting

detecting isolated defects such as pin holes, longitudinal cracks, etc., that offer small cross-sections for wave reflection.

3. Signal interpretation is more complex, particularly due to mode conversion effects when wave interacts with damaged area.

Typical Instrumentation

Like any traditional ultrasonic inspection system, the instrumentation for the guided wave technique involves (a) Transducers, (b) Pulser/receiver with filters and amplifiers, and (c) PC based data acquisition system. The key component is the transducer that is designed specially for generation and reception of guided waves and hence will be discussed in more detail. The Pulser receiver is either an array type or a single channel type depending on the sensor. Usually, an array type is preferred with a capability to change the phase of each signal so that mode selection and tuning is possible. The signal interpretation required precise measurements and interfacing with dispersion relationships. Hence, a PC based system is the best choice for this NDE.

The cylindrically guided waves can be generated and measured using several mechanisms. These wave modes can be generated using circular ring-type array transducers [14] for pipes, or comb-transducer configuration [15] for tubes, or like in the regular weld inspection using an array of variable angle beam transducers located around the circumference of the cylinder. Alleyne and Cawley [14] reported the development of a dry coupled piezoelectric transducer system for the excitation of the axially symmetric L(0,m) modes in pipes. It comprises a ring of piezoelectric elements, that are clamped individually to the pipe surface; no coupling fluid is required at the low ultrasonic frequencies used here. The number of elements in the ring should be greater than 'n' where F(n,1) is the highest order flexural mode whose cut off frequency is within the bandwidth of the excitation signal. In the initial configuration, rings of 16 elements were used on 3 inch pipes, while 32 element rings were employed on 6 and 8 inch pipes. This gave the possibility of operating at frequencies up to around 100 kHz; in practice, most testing is done at 50 kHz and below, so it has been possible to reduce the number of transducers in a ring.

Additionally, non-contact methods using Electro-Magnetic Acoustic Transducers (EMAT) has also been reported [16] These can be located either to the inside or the outside surface of the pipe/tube. The cylindrically guided wave technique has been modified to generate and detect wave-modes without the physical contact with the pipe walls[17]. This is accomplished by using the magnetostrictive property of steel pipes, where the pipe material acts as the transducer, and a coil that encircles the pipe couples the excitation energy into the pipe. A separate receiver coil is used to pick up the signals from the guided waves. These two methods have the advantage of being able to generate and receive waves without physical contact with the structure. But, it has been reported that mode isolation and identification of received signals is more complex.

The length of travel of the guided waves will depend on the frequency that is used, the type of wave mode selected and the minimum size of the crack that has to be detected. It is estimated that these modes can travel up to 100 m in length. The smaller the crack size to be detected, the smaller the wavelength, which results in higher frequencies and consequently smaller travel distances due to ultrasound attenuation, which exponentially increases with frequency.

Typical Applications

The applications of the guided waves in NDE are many. A few typical results that have been reported in literature will be used to illustrate this potential.

(a) Corrosion detection in Pipelines

Significant amount of work has been conducted in the application of this method in the pipeline inspection for corrosion damage in chemical industries [18-20], For example, 70 kHz. guided cylindrical waves in chemical and petroleum pipelines (1-3 meter diameter and 2-6 inch wall thickness) have detected 25% through wall cracks at a distance of 30 meters.

A typical result is shown in Figure 6. From this result, it can be observed that the pipe features such as welds reflect energy while the defects also reflect signals (albeit mode converted) that are significant and detectable. Like in the case of pulse-echo inspection, the arrival time information will provide the location of the defect and the amplitude will indicate the size of the defect.

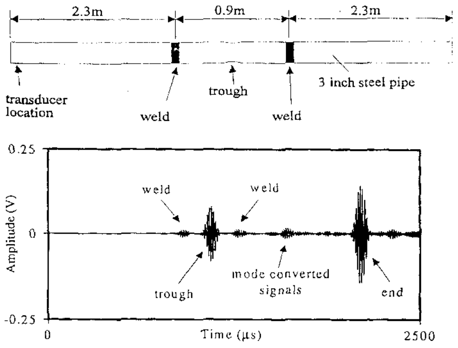

Figure 6 Guided wave results from a pipe with simulated defects. A pulse echo type approach was employed[8,9].

Figure 7 shows an epoxy painted 4 inch buried pipe at a test position adjacent to a road crossing. This result indicates the ability to test areas of pipes that are inaccessible. The test range extends over more than 20 m on either side of the ring type transducers, which are located in the middle of the plot. A distance-amplitude correction (DAC) curve was computed from the weld indication (using prior information on the weld locations). Then the defect call level by comparison with the weld echo level and the output amplitude were calculated, knowing that a typical site weld is a -14 dB reflector. The echo identified as +F2 is the only indication where the mode converted signal is significant compared to the incident mode reflected signal and this indicates possible corrosion at the entry point to a road crossing.

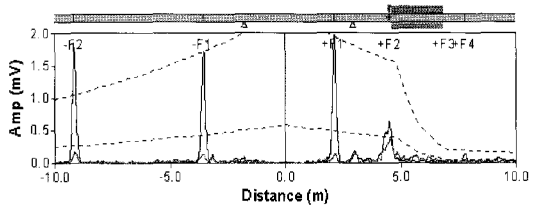

Figure 7 Cylindrically guided wave inspection of buried pipe with corrosion damage, under a rail crossing (the crossing is between F2 and F3 as indicated)[25].

(b) Defect detection in Tubes

Many results are available for steam generator tube corrosion detection in the nuclear industry [21,22]. Applications of cylindrically guided ultrasonic wave modes have been developed for inspection of flow-accelerated corrosion damage (wall thinning) in LWR feed-water piping, and circumferential stress corrosion cracks in PWR steam generator tubes. In most cases, the wave is generated using a probe that is attached to the inside. Frequency and angle tuning techniques are used to optimize the wave generation and reception mechanisms.

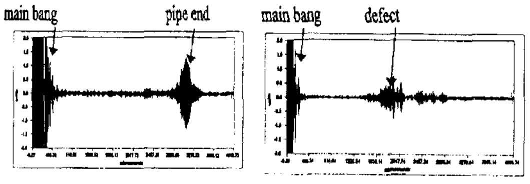

Figure 8 Typical signals from tube inspection from (a) defect free, and (b) defective tubes[15].

In Figure 8, a typical result is illustrated for a steam generator tube inspection. Here, the wave is generated using the Comb transducer. The indications from the corrosion damage defect are clearly identified.

(c) Guided Waves in Composite Materials

These guided wave are also feasible in tubes and pipes made from composite materials. Although, the calculations must be made using the anisotropic and layered nature of these advanced material, it has been shown that guided waves are sensitive to damage mechanisms such as fatigue in composites[23]. One of the issues that must be addressed will be that the energy flow of these waves are dependent on the anisotropic nature of the material[24].

Summary

Like any non-destructive examination (NDE) method, the guided wave inspection method will have a defined false alarm rate and probability of detection, which will have to be determined. The associated signal-to-noise ratio of the NDE system under a field operating condition is also a factor that must be considered. The effects of the various parameters that influence the technique must be determined, such as accuracy, precision, and sensitivity guidelines, before attempting this technique for solving practical problems. Also, the procedures and limitations of applying this technique must be well understood for the successful implementation of this powerful technique.

This method will substantially improve efficiency and reduce the inspection time and cost, especially when utilized as a precursor to a more detailed local inspection. Also, for critical applications, where inaccessible pipes and tubes have to be inspected, this technique provides an opportunity to perform NDE which otherwise may not be possible.

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