ISSN: 0974-5823 Vol. 6 No. 3 December, 2021

International Journal of Mechanical Engineering

Guided Waves in Pipes with artificially made Defects to Simulate Corrosion

Konda Enkelejda
Polytecnical University of Tirana, 1001- Albania

Zeqo Migena and Sotja Dimitraq
Polytecnical University of Tirana, 1001 – Albania

Abstract - **Industrial pipe in-service inspection through Guided Waves, is considered an alternative to conventional wave inspection, under anticorrosive bituminous asphalt coating or, underground coated pipelines. Previously various tests on practice-similar uncovered pipes of several dimensions are made, to obtain the reference test samples since, the wave propagation is not affected by the insulation coating materials. Some defect typologies are artificially created simulating the typology of corrosion defects charactering the cross-sectional area of the pipe.**

The main purpose of this research work is to perform a test inspection using guided waves for application in plants with covered pipe networks, in particular, to determine the maximum length of inspection and sensitivity of defect detection. To achieve this, samples of welded pipes with artificial defects have been prepared, simulating the reduction of wall thickness, as happens in the case of corrosion. This is achieved by using low-frequency longitudinal waves (and torsional waves generally below 100 kHz).

Index Terms - Guided wave, dispersion curves, pipes, in-service inspection, insulation coating, piezoelectric probes, corrosion defects.

INTRODUCTION TO GUIDED WAVE

Integrity evaluation of pipelines, damage defects, corrosion or weld defects, is traditionally performed by means of ultrasonic or radiography; both these methods have disadvantages and operating limitations. Conventional ultrasonic testing requires accessibility to the pipe on the whole area under testing, with particularly request about the surface conditions, this method is slow and surface preparation such as removal of coating or cleaning is always necessary;

Meanwhile the radiographic test has special requirements regarding radiation protection and the need to have direct access to the pipeline welds to be inspected.

Guided Waves is a technique which overcomes all these disadvantages or specific requirements.

This method is very useful to quickly give a general idea of the overall conditions of pipelines especially in relation to corrosion, because guided waves are capable of monitoring large surfaces or long distances from a single point and are capable of traveling in flat structures or even with pipelines, etc. For different metal structures or a combination of their dimensions (eg the outer and inner diameter of a pipe), and a selected frequency will have a single mode of existence of directed waves.

Each of these modes will be propagated by a standard displacement (known as the "mode shape"). Different wave propagation frequencies vary in the type of propagation, the phase velocity, the group velocity and the attenuation ratio.

Essential in analyzing directional waves for NDT control is the generation and analysis of dispersion curves that describe and predict the relationship between frequency, phase velocity, group velocity, propagation mode, and thickness of the material or structure being controlled. (so called because the change of the frequency brings the change of wave velocity and vibrations tent to disperse during the spread).

The data in these curves are used to do the tests controlling the structures, ranging from defining the generating equipment parameters of the guided waves in the structures until the final calculations.

ANALYSIS OF DISPERSION CURVES, MODES AND THEIR GENERATION

In the common literature referring to guided waves [5], it is stated that for a single frequency value eg 100 kHz, there are approximately 50 wave propagation modes. This makes the received signal difficult to interpret, so it is recommended that only one mode be generated or excited. The sensitivity of the test is a function of the reflected signal vs the coherent noise ratio which is caused by the excitation of the unwanted modes. The most favorable modes are those that have uniform propagation throughout the transverse section of the tube.

Analyzing the wave structure and the dispersion curves of the phase velocity and group velocity for a 140 mm outer diameter pipe with 4mm-thick, respectively [1], the two modes that meet these recommended criteria are L (0.2) and T (0.1) (Fig. 1 and Fig. 2). Both modes have the added advantage of being non-dispersive, i.e. their velocities are constant vs frequency, which means that all signal frequencies travel with the same velocity. These two modes can be interpreted reliably. This turns this type of test inspection into a test similar to the conventional pulse-echo.

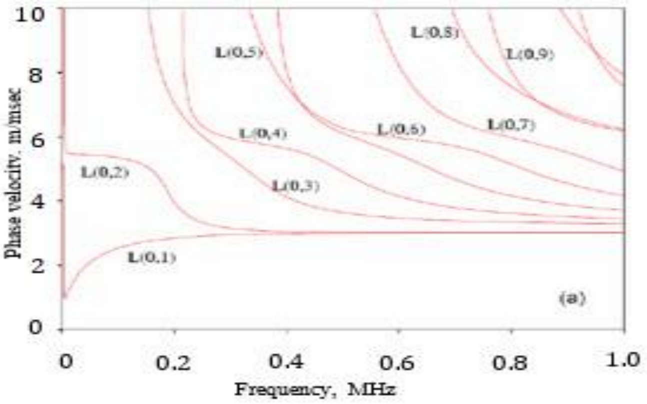

FIGURE 1
PHASE VELOCITY DISPERSION CURVES FOR A 140 MM OUTER DIAMETER PIPE WITH 4MM THICKNESS

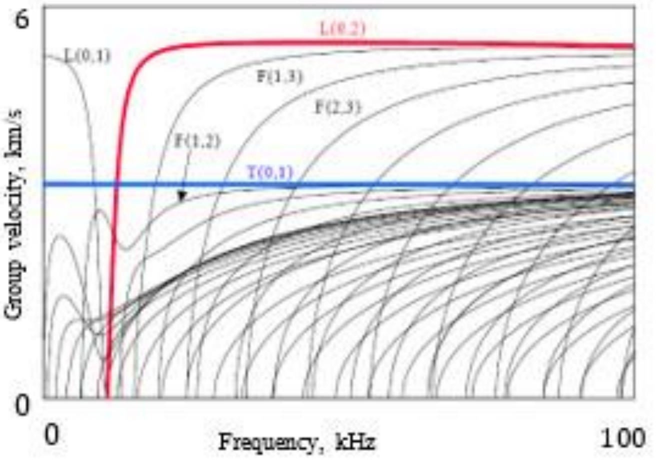

FIGURE 2
GROUP VELOCITY DISPERSION CURVES FOR A 140 MM OUTER DIAMETER PIPE WITH 4MM THICKNESS

So, the L(0.2) mode is more suitable for inspection at long distances, being non-dispersive in this frequency range (70 kHz) and the most favorable used in corrosion detection.

SENSITIVITY TO DEFECTS

Guided waves such as L (0.2), are sensitive to the cross-sectional dimension variations. The principle of guided wave reflections differs from one of the conventional waves. Through guided waves, it is possible to detect defects located at a depth less than a wavelength. The defects' size, extension, and depth are the main reasons for the wave reflection obtained, so it is necessary to perform calibration tests considering defects of different dimensions and at different depths. At the same depth, the wave reflection coefficient is proportional to the defect surface area.

The dimensions of a corrosion type defect will influence the wave reflection, due to the area created by the corrosion effect. In some special cases, the phenomenon of resonance is encountered in the guided waves. This is because there may be no reflection of the wave from the initial and final edge of the defect, so the reflected wave is very weak. This is most often seen in sharp-edged defects. By using two different frequencies during the inspection, this phenomenon can be overcome. The resonance effect is especially noticeable on artificially made defects to fabricate reference samples needed to perform corrosion tests. The areas corroded by corrosion are much more non-uniform in practice, so this problem is not present in the actual tests performed. In recent years it has been scientifically shown that corrosion defects can be reliably detected and measured as a percentage of the cross-sectional area lost by corrosion with high accuracy.

In welded pipe joints, since a change in the cross-section occurs in the weld seam, reflection echoes arise and are created which affect the attenuation of the signal. This makes it difficult to detect welding defects. Furthermore, if there is no information on the location of the weld seam (when the pipes are covered underground e.g.), the weld itself is identified as a defect and confuses the interpretation.

FREQUENCY EFFECT

The sensitivity of guided wave testing for the detection of defects in pipe walls is a function of frequency. In general, the sensitivity of the test decreases as the frequency decreases. Various references state that in given pipe size, with decreasing frequency, the reflect coefficient curves increase concavity, making it difficult to detect defects located near the surface (not located deep in the wall pipe). The reflection coefficient depends on the product of the frequency, with the wall thickness.

High frequencies offer finer volumetric scanning (i.e. higher resolution), better defect detection capacity, and lower costs. EMAT probes for example, (or Electro-Magnetic Acoustic Transducer) are the probes used for testing with high frequency [4].

EFFECT OF GEOMETRY AND TYPE OF MATERIAL ON GUIDED WAVES

Guided waves are modified and redistributed if there are any changes in the geometry of the object being tested, material properties, supporting elements or anchors, reinforcing rib elements, etc. The geometry of the element being inspected may change over time, due to corrosion (reduction of pipe wall thickness), or due to detachment of parts from eventual cracks. It is precisely these types of changes that cause the reflections of the waves which are used to inspect the pipelines. Reflections are also caused by various couplings, valves, supports, i.e., any deviations from the regular geometry of a pipeline.

Such reflections are used in testing. Reflection from non-removable back-strips on pipes welding, for example, is used in practice to calibrate the signal amplitude and obtain the Amplitude-Distance Correction (DAC) curve.

The symmetrical axial nature of this reflection was used to distinguish it from non-symmetrical axial reflections by any defect that may be located in the same area.

But such reflections which depend on the change of the geometric characteristics of the element and not only, are not useful, making it difficult to interpret the signal during the inspection especially when this is done only from an unchanged position of the probe. A good example of a resistance change is a coupling flange in a pipe. The change of the surface area of the cross-section, in addition to the change of the type of material, presents great changes of resistance, and all the energy of the wave may be reflected. In terms of these reflections, it can be confirmed that large changes in the propagation resistance of guided waves cause large-scale reflections.

On the other hand, the reflection caused by a welding seam is small because the welded parts and the welding seam have little difference in geometry and almost zero in material type. Large-scale reflections caused by characteristic changes are disturbing because they create unwanted signals and may mask the proper reflections needed to detect defects, but the energy passing through them also reduces the amplitude of the signal moving forward in the pipe.

When it is necessary to detect an axially oriented crack in a pipe, it has been found that the torsional wave (T (0,1)) reflects much more than the wave (L (0,2)). The reason for this is that the transverse propagation of the torsional wave is what changes the most because it performs a jump of axial displacement from one edge of the crack to the other

GUIDED WAVE TESTING TECHNIQUES IN PIPES

The typical probe system used in this type of inspection is the one with a ring-type probe clamped against the pipe, with peripherally placed elements, which can be piezoelectric, electromagnetic, or other types. Probes may be located longitudinally or peripherally (Fig. 3).

Techniques that address directional wave testing are;

1. Frequency tuning - excitation and reflection of the asymmetric signal.
2. Natural focusing - partial conduction of excitation and signal reflection.
3. Phased Array Focusing - multi-element matrix excitation and delayed signal reflection and amplitude tuning

FIGURE 3
SOLID AND INFLATABLE COLLAR TYPE PROBES [5]

TYPES OF PROBES

Alleyne and Cawley [2] have reported the development of piezoelectric ring-shape probes (Fig. 4) for generating axial symmetric mode L (0, m) in pipes, with piezoelectric elements that are bonded together into a simple transducer and clamped against the pipe.

The number of elements in the transducer must be greater than n where $F(n,1)$ is the highest bending mode, the cut-off frequency of which, is within the excitation signal frequency band [3].

FIGURE 4
COMMERCIAL RING-SHAPE PROBE WITH PIEZOELECTRIC SENSORS

The ring-shaped probe with two rows of elements can excite the L (0.2) mode, in one direction. There is another mode, with particle oscillation in the radial direction L (0.1), which has a much lower velocity than the L mode (0.2). The presence of the L mode (0,1) can make the interpretation of the results difficult, so this mode is avoided by adding other rows of piezoelectric elements to the probe. Adding these elements into the probes greatly increases their cost.

An alternative to the longitudinal mode L (0.2), is the torsional mode T (0.1). The torsional mode has the advantage of being non-dispersive along with the entire frequency range so that only the T mode (0,1) can be excited in the axial direction.

From all the above, it is concluded that adding two rows of piezoelectric elements is more than enough to obtain only one mode, the mode of excitation only in one direction. The torsional mode can be obtained by simply rotating the probes used for L (0.2), by 90 degrees. When the mode T (0,1) is reflected by a non-axial symmetric characteristic, the first converted mode is to F (1,0), or L (0,2) as shown in fig 2.

The torsional mode has the advantage that unlike the L mode (0.2), the wave propagation characteristics are not influenced by the presence of liquids, so in the service inspection of the pipelines, all the above-mentioned concepts are valid.

Another advantage of this mode is that it can detect longitudinal cracks, while longitudinal modes are insensitive to fine defects placed parallel to the axis of the pipe. However, a disadvantage regarding this sensitivity of axial characteristics is that the reflections of the torsion modes are relatively strong, created by supports or anchors that are welded axially along the tube. Due to these large reflections from the presence of these supports, the length of the inspection interval decreases and makes it even more difficult to detect corrosion on these supports. This problem becomes even more delicate when the diameter of the pipes is small. For these types of pipes, the longitudinal mode may be more preferred, except when the pipes are filled with liquids.

TESTING PROCEDURE

Piping networks consist of coated pipes and this coating will bring a significant reduction of the power of the guided waves. The experience in covered pipes is preceded by tests in uncovered pipes thus creating a database to refer to.

Various typologies of artificial defects have been made to analyze the axial (longitudinal) resolution and sensitivity of the system, and the data obtained in this case, to be used to compare the results with that of real defects made by corrosion.

The types of artificial defects made are cuts or erosions in a segment of the perimeter or in the whole perimeter, where all in general terms are considered "reduced area" (in terms of surface area). The inspection was done with a Teletest device (Plant Integrity ltd) illustrated in the Figure below, which uses the matrix focusing technique (Fig. 5).

FIGURE 5
PHASED ARRAY FOCUSING PROBE. TELETEST DEVICE, COURTESY OF I&T NARDONI INSTITUTE, BRESCIA – ITALY

The following table (Tab. 1) gives the geometric and material characteristics of the samples used in the following tests.

TABLE 1
GEOMETRIC AND MATERIAL CHARACTERISTICS OF THE SAMPLES USED FOR THE TESTS

ID	Pipe outer surface	Outer diameter [mm]	Thickness [mm]	Length [mm]	Welded joints	Number of defects	Defect type	To aim
Sample #1	uncoated	100mm	4.1	6,000	2	1	Deep cuts	Axial resolution
Sample #2	uncoated	88mm	3.5-4.1	14,160	7	2	Corrosion	Corrosion defects

1. *Artificially made defects on Sample #1*

The first sample is designed for a quick measurement or quick control of instrument performance with an important reference versus axial resolution. the sample under inspection consists of two welded pipes, 1 meter and 4 meters long. A large-scale defect D1 is artificially created in the middle of the short tube (Fig. 6).

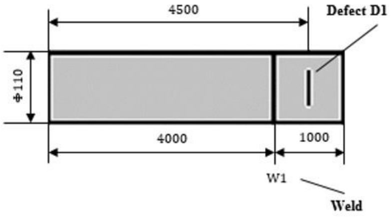

FIGURE 6
SCHEME OF SAMPLE #1

Defect D1 is a complete cut in-depth with a circular orientation, 84 mm wide which reduces the surface of the transverse section of the pipe, by 26%. The inspection was done with the device mentioned above with a ring-shaped probe with 16 sensors located 1m from the tube border which work in torsional mode T (0.1) at frequencies 28kHz, 36kHz, 44kHz, and 64kHz. With the frequency of 44 kHz, the axial resolution is in the limits and is estimated at 0.25m (Fig. 7).

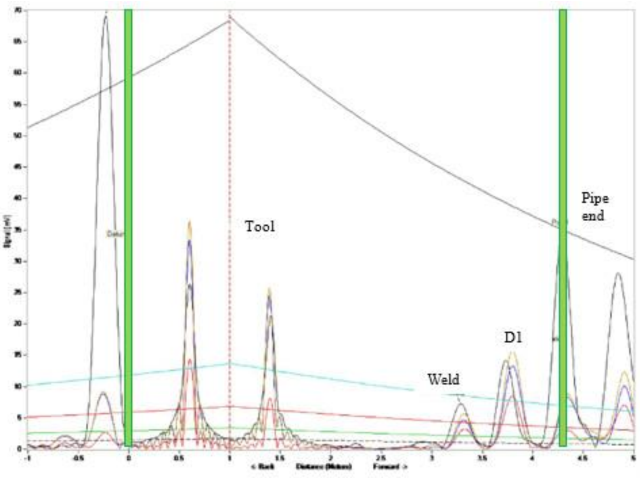

FIGURE 7
SIGNAL EXAMINATION OF SAMPLE #1

2. *Artificially made defects on Sample # 2*

This sample was designed starting from a pipe with the same outer diameter but with different thicknesses in the range 3.5-to 4.1mm. This modification was used to test the design procedure of making artificial defects, similar to corrosion in practice (Fig. 8 and Fig. 9).

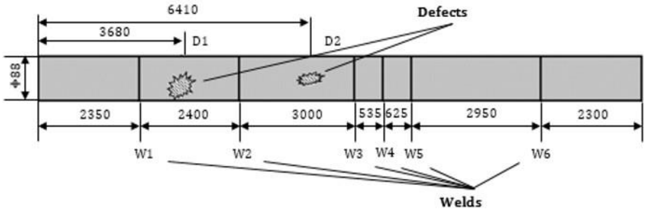

FIGURE 9
SCHEME OF SAMPLE #2 WITH TWO TYPES OF ARTIFICIALLY MADE DEFECTS (SURFACE SCRATCHES, SIMULATING CORROSION IN PRACTICE)

FIGURE 10
SAMPLE #2, NON-UNIFORM SURFACE SCRATCHES (SIMULATING CORROSION IN PRACTICE)

The area is irregularly grinded on the outside of the pipe, to simulate a corroded area in practice. A careful measurement gives us the dimensions of the cross-sectional area reduction. The characteristics of these artificial defects are as follows;
D1 - width 123 mm, length 55 mm, reduction of area surface 16.32%
D2 - width 10 mm, length 70 mm, reduction of area surface 7.76%
Fig. 10 shows photos of artificially made defects, to simulate corrosion in practice. The inspection was done with a ring-shaped probe with 12 sensors, working in torsional mode T (0.1) and the best frequency is 36 kHz (Fig. 11). Reflections from welded joints are non-uniform, due to the presence of non-uniform thickness. Both defects D1 and D2 are detectable with good amplitude echo correspondence, referring to the reduction of the pipe cross-sectional surface area, caused by the defects.

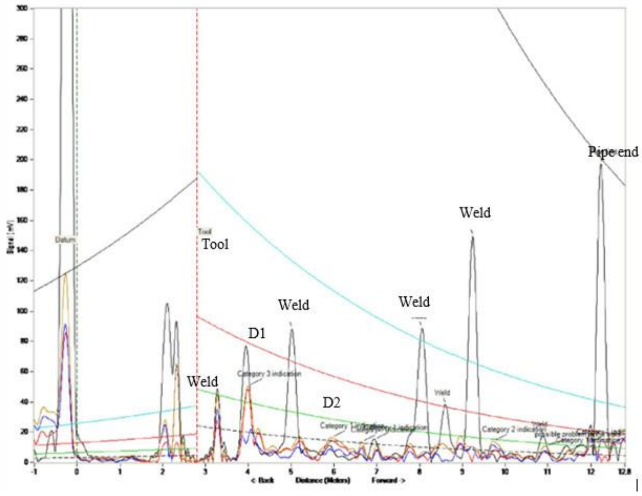

FIGURE 1
SIGNAL EXAMINATION OF SAMPLE #2

DISCUSSIONS AND RESULTS

-Types of mode excitement are selected by preferring less dispersive modes;

- The torsional mode is the most preferred, gives the best axial resolution, in the detection of defects such as corrosion has the highest expected sensitivity;
- Despite the presence of insulating coatings material, it was shown that the performance sensitivity of the system does not decrease, only the inspection length is reduced in the worst case goes to 8m, but the length can be increased up to 12 - 15m, versus 50m in the case of uncoated pipes;
- Sensitivity against the reduction of the cross-sectional surface area of the pipe is high, having in mind that, conform to the standard for these detections, the reduction of the cross-sectional surface area should not be greater than 10%;
- All defects are always detectable, which means that inspection in a heat exchanger plant can be reliable with the guided wave method, but it is important to have a high-precision map regarding the position of the welded jointsIn the following Tab. 2, are summarized the echo amplitudes of the defects in correspondence with the reduction of the real cross-sectional surface area.

TABLE 2
ECHO AMPLITUDES OF THE DEFECTS IN CORRESPONDENCE WITH THE REDUCTION OF THE REAL CROSS-SECTIONAL SURFACE AREA

ID	Defect nr.	Reduced Cross-Sectional surface area [%]	Evaluation of reducted section [%]	Attenuation (as max of inspection length per meter)
Sample #1	D1	26	>30	>50
Sample #2	D1	16.32	9	>50
	D2	7.76	3	>50

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