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Assessing Damages in Pipes through Circular Distribution of Ultrasonic Guided Wave Reflections from Defects

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Damages in pipes such as cracks and corrosions may threaten the integrity of pipeline. Using ultrasonic guided waves to detect these defects is efficient. The waves propagate in the pipe wall and carry information of the entire structure. The signal of damages is included in the reflections of guided wave. Ultrasonic guided waves are dispersive in waveguides, which means the speed of the wave is dependent on frequency. And under a certain frequency, there are multiple modes exist. The characteristic of dispersion and multi-mode make guided wave testing difficult to solve in analytical ways. Finite element method is an efficient way to investigate the problems. To assess damages in pipes, a 3-D pipeline finite element model was set up with artificial defects vary with depths and circular lengths. Taking the circular distribution of guided wave reflection into consideration, two series of defects changing in depth and circular length were introduced in numerical simulation. Circular energy distribution was put forward to assess the defect. Mode conversion will occur when the axisymmetric mode of guided wave meet nonaxisymmetric discontinuities in the pipe. The incident L (0, 2) converts into F(1,3) and enhances the energy on the opposite position of the defect. The circular energy distribution was proved feasible for damage assessment in pipes.

1. Introduction

Damages in pipes such as cracks and corrosions may threaten the integrity of pipeline. To detect such defects in pipes, ultrasonic guided wave is an efficient way. Guided waves are elastic waves propagating inside the structure. Constrained by the border of the structure, reflection and refraction will occur on the inter-surface of the mediums. Guided waves are composed of the superposition and coupling of the reflected waves. When there are defects in the structure, these discontinuities will affect the propagation of guided wave, making defects detection realizable.

2. Guided wave in pipes

Wave speed is an important character of guided wave as it is related to the accuracy of the defect location. There are two kinds of guided wave velocities: phase velocity and group velocity. The phase velocity is the transmission speed of a certain point on a wave phase, while the group velocity is the speed of a package of waves. Bulk wave and guided wave are both ultrasonic waves in structures, and they are controlled by the same equation; however, guided wave needs to satisfy boudary conditions of the structure. It is reflected and refracted at the interface of the structure edge. Moreover, guided wave is the dispersive. Dispersion is a phenomenon that wave speed changes with frequency, which means guided wave speed is dependent on the generation frequency. According to the derivation of Gazis (1957), the dispersion equation of guided wave in pipes is Eq(1).

$$|D_{ij}|=0,\ i,\ j=1,2,3,\dots 6 \tag{1}$$

According to the expression of Meitzler (1961), Zemanek (1972) and Silk, Bainton (1979), the modes of guided waves in a pipe could be shown as:
Longitudinal mode: L (0, m) axisymmetric mode
Torsional mode: T (0, m) axisymmetric mode

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Flexural mode: F (n, m) nonaxisymmetric mode
Here n means the circular order of guided wave, and m means the number of modes under a certain circular order n. While n=0, Eq(1) could be expressed as:

$$D=D_1 \bullet D_2=0 \Rightarrow D_1=0,\ D_2=0 \tag{2}$$

The solutions of Eq(2) are L modes and T modes respectively, and there are infinite numbers of L and T modes. While n≥1, under each circular order n, there are infinite numbers of L, T and F modes. This is the mutli-mode characteristic of guided wave in a pipe. The solution of Eq(1) also gives the dispersion curves of guided wave. Curves of 5 typical modes are displayed in Figure 1:

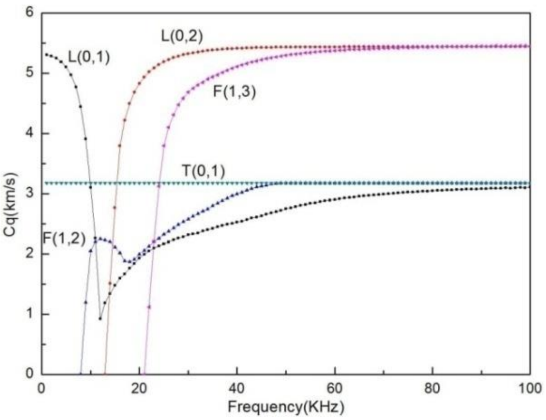

Figure 1: Dispersion curves of a pipe with internal diameter 150 mm and wall thickness 4 mm

There are two modes in Figure 1 worth mentioning. One is L(0,2). This mode appears after a certain cut off frequency and the group velocity of which remains almost constant in a long spectrum. And in practical situation, L(0,2) mode is easy to generate and with low energy attenuation, so this longitudinal mode is widely used in guided wave testing. The other one is T(0,1) mode. It is the only mode without dispersion. It is also popular in defect testing using guided wave.

3. Finite element model of guided wave in pipes

As the dispersion equation of guide wave is still unsolved in analytical ways, many researchers have adopted finite element method to investigate the problem numerically. Moreau (2012) carried out an accurate finite element modelling of guided wave scattering from irregular defects. Benmeddour (2011) studied the interaction of guided wave with non-axisymmetric cracks in elastic cylinders using finite element modelling. Willberg (2012) compared different higher order finite element schemes for the simulation of Lamb waves. Vanli (2014) explored damage detection problems Lamb wave through finite element method.

3.1 Generation of guided wave

Present finite element generation method is uploading excitation signals at the outer surface of one pipe end (Wang, 2010). According to our research, such method will generate surface waves together with guided waves, which is not proper for analyzing. Therefore, we changed the generation position from the outer surface to the central line of pipe end, uploading displacements signals at the central nodes of the end. The generation signal was a 5-cycle sinusoidal wave modulated by Hanning Window. Eq(3) shows the generation signal.

$$U(x)=\frac{1}{2}A\left(1-\cos\frac{2\pi ft}{n}\right)\sin(2\pi ft) \tag{3}$$

Where A is the amplitude parameter, f is central frequency, and n is period number. Figure 2 shows the comparison of two generation ways. The top part is present generation way, and the bottom part is the improved one in this paper. The incident wave and reflected wave are marked in Figure 2.
The surface waves in the present generation were successfully avoided in the improved generation.

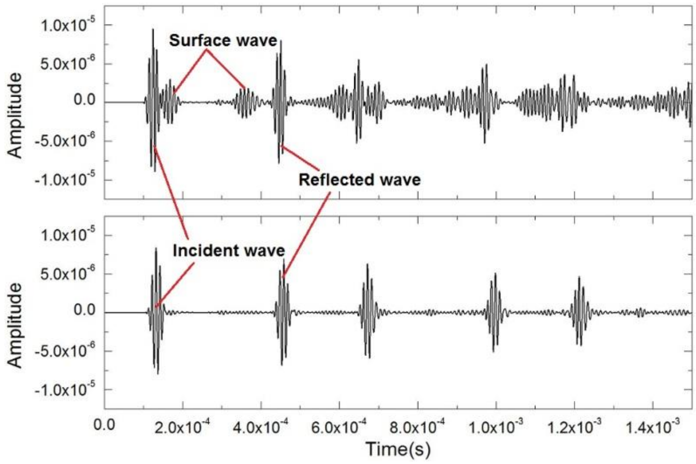

Figure 2: Comparison of two-generation ways of longitudinal guided wave in a pipe

3.2 Finite element model

Using finite element method, a numerical model of a pipe with length 1,500 mm, internal diameter 150 mm and thickness 4 mm was constructed. In order to acquire higher computational accuracy, a “slicing-mapping-sweeping” meshing strategy was proposed. The model geometry was first sliced into several volumes to meet the requirement of mapping, then the lines and areas were meshed with mapped elements, at last, the entire pipe model was swept to form mapped volume elements. Such meshing measure could enhance computational accuracy while reducing the burden of computer.

Figure 3 shows the finite element model of guided wave in a pipe. The distance between the defect and the generation end was 1 m. The defect was magnified and shown on the right part of the figure. Table 1 proposes the material properties used in finite modellings.

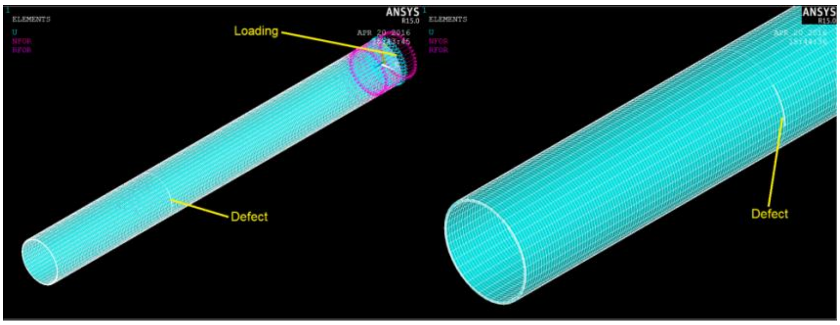

Figure 3: Finite element model of guided wave in a pipe

Table 1: Structural material properties used in numerical process

Content name	Heading 2
Density(kg/m^3)	7,850
Poisson ratio	0.29
Elasticity modulus(GPa)	219

4. Results and discussion

4.1 Efficiency of the model

To verify the efficiency of the finite element model, a series of defects with various axial lengths were introduced to see the changing of reflection coefficient. The T (0, 1) mode was selected and generated in the model by loading tangential displacements on the outer surface of the pipe end. As the degree of freedom of the excitation nodes was constrained while generation, nodes at the location 0.2 m from the pipe end were chosen to collect vibration.

The circular length of the defects was 1° uniformly, and with thorough depth. The axial length of the defects changed from 2.5 mm to 30 mm, and the dimension of axial length was normalized to be shown with percentage of wavelength. Reflection coefficients of defect with each axial length were displayed in Figure 4.

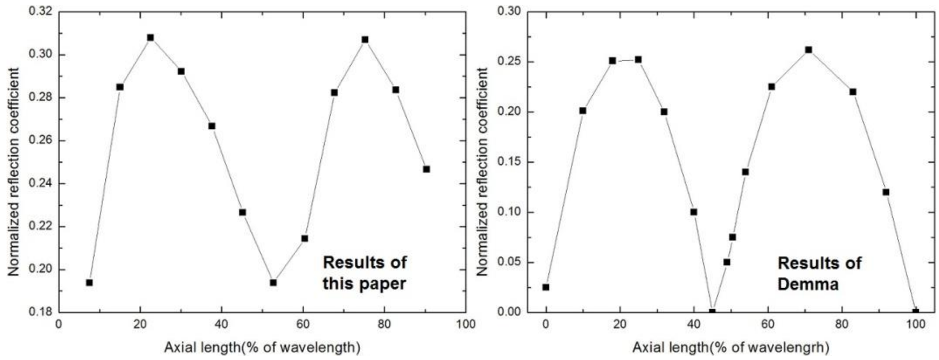

Figure 4: Reflection coefficient of defects with different axial lengths (Compared with Demma, 2003)

Demma (2003) reported an application of T(0,1) mode detecting longitudinal defects and gave the relationship between reflection coefficient and defect axial length. The reflection coefficient of this paper revealed the same regulation with the results of Demma, suggesting the efficiency of the finite element model.

4.2 Reflection from defects with various depths

To understand the relationship between the reflection coefficient and the depth of defects, a series of defects with various depths were introduced in the model. The circular lengths of the defects were all 12.5 % of perimeter and with a constant axial length 3 mm. The depth changed from 20 % to 80 % of pipe wall thickness. Applying axial displacements on the central nodes of a pipe end will generate longitudinal guided wave in the pipe. The generated wave was L (0, 2) mode after checking. 16 monitoring points were selected averagely around the circle of the pipe. Moreover, parts of the circular engergy distributions were shown in Figure 5.

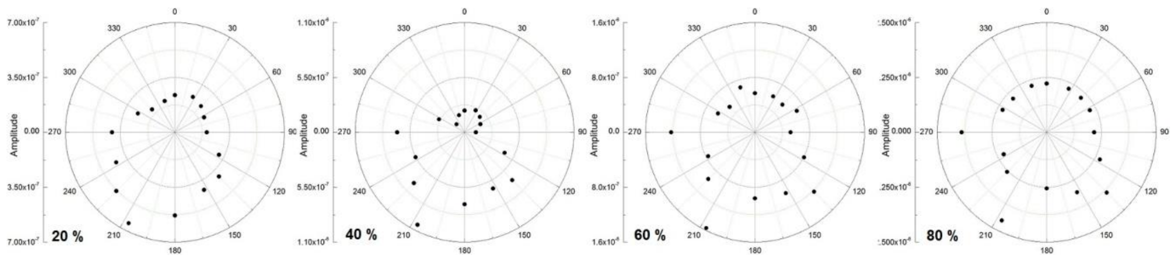

Figure 5: Circular distribution of reflections from defects with various depths (of wall thickness)

It is obvious in Figure 5 the reflection amplitude increases along with defect depth. All of the defects located from 0°-45° on the pipe circle. The energy around this scope is low, and the reflection energy starts to increase at the semi-circle on the other side of the defect. That is, the reflection begins stronger between 135° and 270°, just on the opposite semi-circle of the defect. The circular energy increases from the two directions and reach its maximum at about 207°, which is about the opposite position with the defect.

According to the analysis of Alleyne (1998), guided wave mode will convert into F (1, 3) if the incident mode is L (0, 2). This mode convertion will take place after the incident L (0, 2) mode comes across nonaxisymmetric discontinuities in the pipe. Therefore, if the defect is not axisymmetrc, there will be mode convertion and F (1, 3) will occur on the condition of L (0, 2) generation. Considering cylindrical coordinate system, L (0, 2) mode has motion components on the r and z directions, and the component on the θ direction is zero. However, F (1, 3) mode has motion components on all the three directions. Figure 6 shows motion components of three modes.

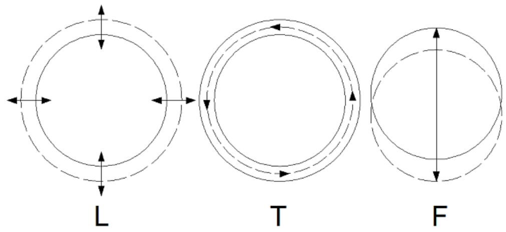

Figure 6: Motion components of three modes of guided waves

It can be seen from the wave motion that the enhancement of the energy on the opposite position of the defect was aroused by mode F (1, 3) converted from L (0, 2). Incident guided wave L (0, 2) encountered such kind of damages and converted into F (1, 3). The F (1, 3) mode has a vibration radially and made the circular energy start to increase at 90° on both sides of the defect, and at last reached the maximum on the opposite position to the defect.

4.3 Reflection from defects with various circular lengths

To study the relationship between the reflection coefficient and the circular length of the defect, a series of defects with different circular lengths were introduced in the simulation. The defects were with a uniform depth 20 % of wall thickness and axial length 3 mm. Circular lengths of the defects changed from 5 % to 40 % of perimeter. All the defects extent started at 0° circularly. Energy distributions of monitoring points on the outer circle 0.2 m from the piep end were collected and shown in Figure 7.

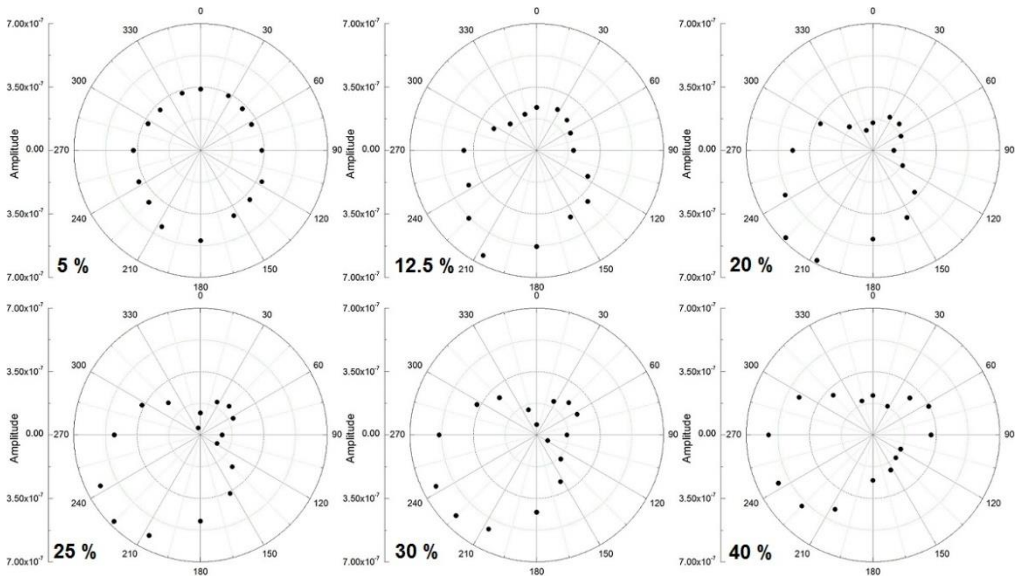

Figure 7: Circular distribution of reflections from defects with various circular lengths (of perimeter)

The energy distribution in Figure 7 reveals a similar law with Figure 5, that is, on the scope of defect, the energy is low and remains almost unchanged under each circular length. The energy begins to increase at the semi-circle on the other side of the defect, and reaches the maximum on the opposite position of the defect. Like the previous analysis, such energy distribution was caused by mode convertion from incident L (0, 2) into F (1, 3). The guided waves in the pipe could not be treated as a single longitudinal mode. The circuar energy distribution was a compositive result of L (0, 2) and F (1, 3) together.

In Figure 7, when the circular length of defect is 5 % of perimeter, which means the extent of defect is 0°-18°. The amplitude of circular energy starts to increase from around 270° and 90° on the two sides of the defect. The opposite position of defect is 180°-198°, and the maximum amplitude lies in the area in the picture. When the circular length is 12.5 % of perimeter, the defect extended from 0° to 36°. The circular energy starts to increase from about 300° and 120° and reach the maximum between 180° and 216°. Which means the circular energy rises at the semi-circle on the opppostie side of the defect in the pipe. The last four distributions also show such a rule. Moreover, as the circular length of the defect increases, the entire circular distribution appears a “rotation” inclination.

5. Conclusions

Guided wave reflections from defects in pipe were investigated in the paper. Guided wave is a kind of elastic wave in solid media. Ultrasonic waves reflect and refract at the bourder of the structure and form guided waves through superposition and coupling. Detecting damages in pipes using ultrasonic waves is attractive and efficient. The group velocities were acquired by solving the dispersion equation of guided wave in a pipe numerically. There are three basic modes of guided waves in a pipe: longitudinal mode, torsional mode and flexural mode, and each mode has an infinite number of orders. Group velocities of 5 typical modes were put forward.

To assess damages in pipes using guided wave, a numerical model was constructed by finite element model. Applying excitation signals on the central nodes of a pipe end could generate guided waves in the pipe and avoid surface waves existed in other studies. After efficiency validation of the model, a series of defects were introduced to invest the circular energy distributions of guided wave reflections. For nonaxisymmetric defects, the discontinuities will bring about mode convertion and F(1,3) will occur when the incident mode is L (0, 2). The vibration of F(1,3) also makes the circular energy higher on the opposite position of the defect. The energy starts to increase at the semi-circle on the other side of the defect and reaches the maximum at the opposite position. The distribution of reflection from circular length changing defects shows a “rotation” inclination. The changing rule of the circular energy distribution of guided wave reflections from defects can serve as assessment of damages in pipes.

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