

Non-destructive Testing of Multi-bends Pipe Using Guided Waves

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Abstract—Ultrasonic guided waves in pipes have been used as a powerful and effective tool for long-range inspection of pipes as they have the potential of propagating long distances with little attenuation. The propagation phenomena of guided waves in straight pipes have been investigated by many researchers; however, the propagation of guided waves across features such as bends in the pipe network is still not well understood. In order to study the complicated characteristics of guided waves propagating in multi-bends pipe, experiment on detecting multi-bends pipe using guided wave was conducted based on magnetostrictive sensors. Guided wave properties such as propagation speed, mode conversion, energy attenuation were studied in experiment. The result showed as follows: guided waves' propagation speed in multi-bends pipe with slight bend curvature was similar to the one in straight pipe; the bend lead to mode conversion obviously; the energy of guided waves attenuated exponentially along with the propagation time and the attenuation rule was closely associated with excitation frequency. This study would provide reference for the guided waves application in complex pipes with bends.

Keywords- Guided waves; Magnetostrictive effect; Multi-elbow pipe; Mode conversion; Attenuation

I. INTRODUCTION

As the important equipments for transforming water, oil, gas, pipelines are used extensively in industry. So it is essential to test the pipelines timely to assure the pipelines' safety in operation. The guided wave technology has been used widely in the pipe system detecting, as this method enables rapid and long range inspection for pipe systems with difficult access. In practical testing, it is possible to generate guided waves from a single probe position, while providing full ultrasonic energy coverage of the whole pipelines. Because of the simple geometry, the study of guided waves propagation in straight pipe testing has been developed rapidly and substantially^[1-7]. The interaction of guided waves with features such as notches, cracks, and

corrosion patches in straight pipes have been studied by many researchers^[8,9] and the testing performs well for the straight pipes in industry. However, there exist many pipes with complex geometry in practical testing. A typical pipe network is normally composed of straight sections and curved sections, and the curved sections are usually called bends. Because of the structural difference, the propagation characteristic of guided waves in straight pipes performs differently compared with curved pipes. The existence of bends affects the propagation speeds of guided waves, and leads to mode conversion, which brings a lot of difficulties in guided waves application.

In recent years, a number of studies have been carried out on the topic of propagation of guided waves across elbow and U-bends^[10,11]. However, the characteristics of guided waves in pipes with bends is still not well understood so far. In this paper the testing experiment for the multi-bends pipe was conducted using guided waves based on magnetostrictive transducers. The main purpose of this work is to study the guided wave propagation characteristics in multi-bends pipe, to analyze the group speed, mode conversion and attenuation phenomenon of guided waves, which would provide reference for multi-bends pipes practical testing.

II. GUIDED WAVES IN CURVED PIPE

The variational formulation for guided wave propagation in hollow cylindrical pipe is given by^[12]:

$$(\lambda + 2\mu)\nabla(\nabla \cdot U) - \mu\nabla \times (\nabla \times U) = \rho \frac{\partial^2 U}{\partial t^2}. \quad (1)$$

Where U denotes displacement vector, ρ is the material density, and λ, μ represent Lamé's constants. The vector U can be expressed in terms of a dilatational scalar potential ϕ and an equivoluminal vector potential $\vec{\phi}$ according to

$$\bar{u} = \nabla \phi + \nabla \times \bar{\phi} \quad \text{while} \quad \nabla \cdot \bar{\phi} = 0. \quad (2)$$

The boundary condition is defined as:

$$\sigma_{rr} = \sigma_{r\theta} = \sigma_{rz} = 0 \quad (r = a, b). \quad (3)$$

Where a, b denote the inside radius and outside radius of pipe respectively. Using the method of variables separation, combining the equation 1-3 can lead to the dispersion equation:

$$D = |C_{ij}| = 0 \quad i, j = 1, 2, \dots, 6. \quad (4)$$

Dispersion curves can be obtained by solving the dispersion equation. However, this approach is not valid when dealing with curved pipes, as the toroidal geometry of this structure implicitly requires the use of toroidal coordinate, and the method of variables separation can not apply in toroidal coordinate. This means the guided wave propagation along these curved pipes are too complex to solve theoretically. As there is no available analytical solution, computational approach has been opted to derive the dispersion relations for curved pipes.

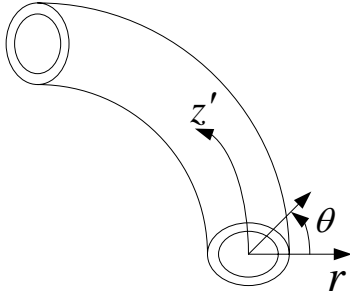


Figure 1. Toroidal geometry of curved pipes

Hayashi^[13] has investigated the guided wave dispersion curves in curved pipe using semi-analytical finite element (SAFE) method. In his research, the cross-section was meshed using finite element, the finite element formulation was established, and the dispersion curves were obtained by solving the FE formulation. Furuhashi^[14] has investigated the guided waves in curved plates and pipes, dispersion curves for curved pipes with different curvature radius were obtained, the result showed that the dispersion curves for curved pipes were similar to the ones for the straight pipe when the curvature radius is much larger than the radius of cross-section. In this case, the shallow curved pipes in testing can be analyzed similarly to the straight pipes.

III. EXPERIMENT FOR MULTI-BENDS PIPE USING GUIDED WAVES BASED ON MAGNETOSTRICTIVE TRANSDUCERS

A. Experimental system

A 110mm-OD, 9mm-wall intact steel pipe was selected for experiment. The pipe had 4 bends where the bend radius were all 84.5cm, and the bend angles were all 90°. The total length of the pipe is 900.66cm, and the geometry is shown in Fig.2. Magnetostrictive transducers and detecting instruments were used in experiment. The excitation signals were generated by detecting instruments and delivered to the exciting transducers, then guided waves were excited in the pipe via magnetostrictive effect. When

guided waves passed through the area of receiving transducers, it was received as electric voltage signal due to the inverse-magnetostrictive effect. For convenience, the transducers were placed near the end of the pipe where this section of pipe was straight, so the guided waves were excited and received at the pipe end.

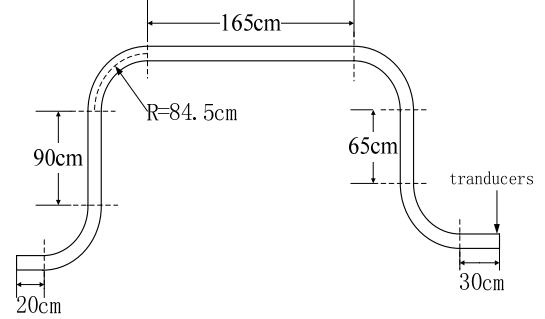
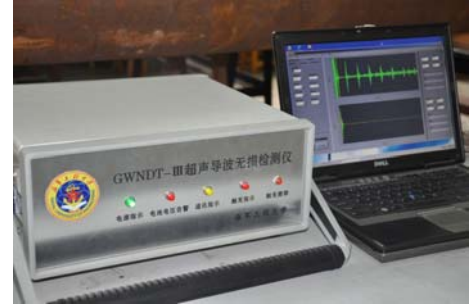


Figure 2. Multi-elbow pipe



(a) Transducer



(b) Detecting instrument

Figure.3 Guided wave transducer and instrument based on magnetostrictive effect

B. Guided wave propagation speed in multi-bends pipe

The L(0,2) mode guided wave signals obtained at the frequency of 29kHz are shown in Fig.4. The first signal is the initial electromagnetic pulse, where the incident guided wave signal was overlapped. The following signals are the echo-signals reflected from the pipe end. Based on the reflected signals and the time intervals, the speed of L(0,2) mode guide wave in multi-bends pipe can be calculated. It can be seen that in Fig.4 the time interval is 3.564ms, so the speed of guided wave can be calculated as 5054m/s in the case of 900.66cm length. The group speed dispersion curves in straight pipe with the same cross-section are shown in Fig.5. The theoretical speed in Fig.4 is 5220m/s at the frequency of 29 kHz, which is a little higher than the one calculated for multi-bends pipe in experiment.

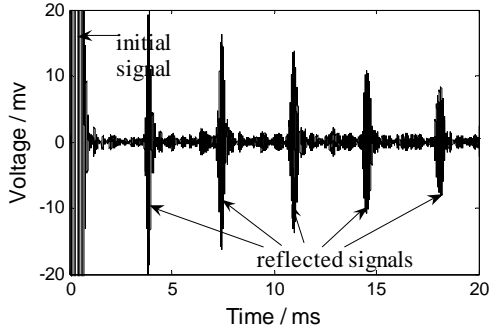


Figure 4. Detecting signals at 29kHz

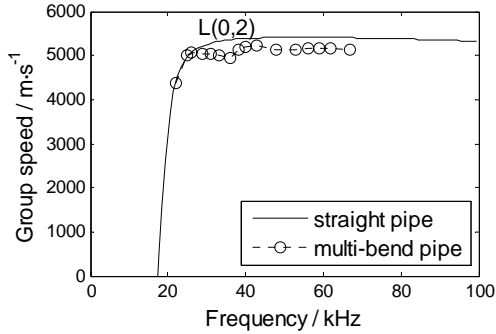


Figure 5. Comparison of group speeds for L(0,2) guided wave in straight pipe and multi-bends pipe

The multi-bends pipe was tested at the frequency range of 20kHz~70kHz, the speeds of L(0,2) mode guided wave has been calculated at different frequencies, and the result were compared with the theoretical result for straight pipe as shown in Fig.5. As a result of the bends, L(0,2) mode guided wave propagates lower in multi-bends pipe than the case in straight pipe, but the difference is slight in this experiment. This is because that the curvatures of pipe bends in experiment were shallow (the ratio of curvature radius to the pipe cross-section' OD is about 15.4), so the effect of pipe bends on the guided wave speed is not distinct.

C. Mode conversion

When the L(0,2) mode guided wave propagate through the bend, mode conversion occurred. As there exist 4 bends in the pipe, the mode conversion was complicated. Fig.6 and Fig.7 show signals obtained in experiments with their time-frequency representations at the frequency of 31kHz and 59 kHz separately. It can be seen that there exist other modes between echo-signals. Because the mode conversion occurred at every bend, so the signals obtained were disturbed. It can be seen that the mode conversion in Fig.6 is obvious, and different mode guided wave signals exist. But in Fig.7, the mode conversion is slight. So it can be concluded that the mode conversion effect relates closely to the guided wave frequencies.

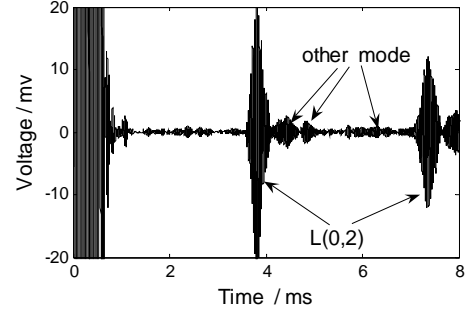


Figure 6. Detecting signals at 31kHz

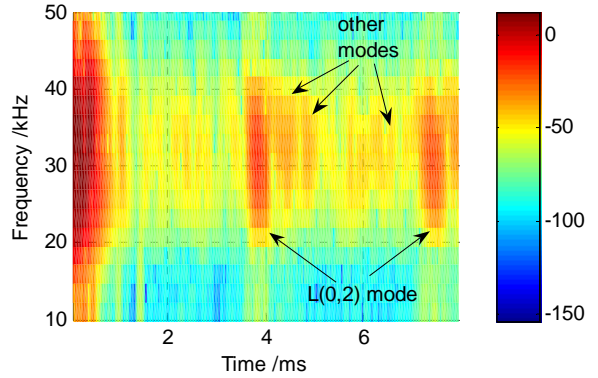


Figure 7. Detecting signals at 59kHz

D. Attenuation of guided waves

The attenuation of guided waves has an important effect on the detecting range and sensitivity of guided waves. In order to learn the attenuation phenomenon, the amplitudes of echo-signals were obtained at different frequencies as shown in Fig.8.

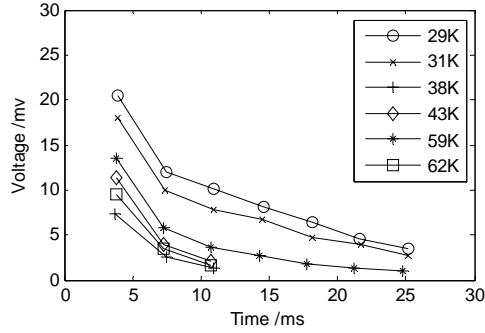


Figure 8. Variation of echo-signals magnitude at different frequencies

Because the guided wave attenuates quickly in multi-bends pipe, the number of echo-signals is limited. So in Fig.8, there exist 6 echo-signals at 29kHz, 31kHz and 38kHz, 3 echo-signals at 43kHz, 59kHz and 62kHz. The function of echo-signal amplitude and time at 31 kHz can be explained as:

$$U = 5.3234 - 5.76 \times 10^{-3} e^{0.2472t} + 32.697 e^{-0.2472t}. \quad (5)$$

When the frequency is 59 kHz, it can be explained as:

$$U = 1.913 - 7.55 \times 10^{-4} e^{0.291t} + 34.519 e^{-0.291t}. \quad (6)$$

The result showed that L(0,2) mode guided wave attenuated exponentially with the propagation time, and the attenuation function varied at different frequencies. So it is essential to choose the appropriate frequencies in practical testing at which the guided wave attenuates slowly.

IV. CONCLUSION

Experiment on detecting multi-bends pipe using guided wave was conducted based on magnetostrictive sensors. Guided wave properties such as propagation speed, mode conversion, energy attenuation were studied in experiment. The result showed as follows: guided waves' propagation speeds in slight curved pipe were similar to the one in straight pipe; the bends lead to mode conversion obviously, the mode conversion effect relates closely to the guided wave frequencies; the energy of guided waves attenuated exponentially along with the propagation time and the attenuation rule was closely associated with excitation frequency.

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