The 2016 World Congress on
The 2016 Structures Congress (Structures16)
Jeju Island, Korea, August 28-September 1, 2016

Curved Pipeline Damage Identification by using PZT-based Ultrasonic Guided Waves

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ABSTRACT

Pipeline structure is of great importance in transport of liquid or gas products since it has unique advantages of low cost, large volume, less land occupation and environmental pollution. However, since pipeline structures may meet various factors in the process of long-term service, they might produce various defects such as cracks, corrosion damages etc. When these damages occur and cause leakage accidents, the pipeline structure will bring unpredictable economic loss and environmental pollution, and even casualties. Compared with traditional pipeline detection method, a new method called supersonic guided wave examination method based on PZT waves has aroused wide attentions from all over the world. However, so far, many researches on the damage detection of hollow straight pipe are reported, but less on curved pipes. The purpose of the paper is to research on damage detection of curved pipe using PZT-based ultrasonic guided waves, focusing on the mechanism of ultrasonic guided waves propagating in curved pipes and the damage identification algorithm. The basic principle of ultrasonic guided wave monitoring technology is briefly introduced. The pipeline model with circumferential cracks was established by using the finite element analysis software of Abaqus. By using the pulse echo method, through the analysis of the reflected signal to determine the arrival time of crack reflection waves, the crack position can be accurately determined. The signal reflection coefficient is used to identify the damage level. In order to verify the proposed method, an experiment is performed. The parameters of the crack are changed to determine the influence of the parameters on the sensitivity of the pipe. The experimental results and the simulation results match well. Both the numerical simulation and experiment show that the damage identification of curved pipe is deferent from that of straight pipe. The curved

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pipe makes the mode of ultrasonic guided wave changed which makes the damage identification complicated and weakens the identification effects.

1. INTRODUCTION

Pipeline has many advantages, such as the delivery of low cost, large volume, short construction period, less land occupation, safety, no pollution, continuous conveying and realize automatic conveying in harsh natural environment, and this reason make the pipeline has become one of the five major modes of transport, other modes of transport is railway, highway, aviation, and water transport. Pipeline leak not only affect the normal transmission pipeline, when conveying harmful, inflammable and explosive materials, but also pollute the environment, causing explosion and will directly threaten people's living environment and living environment, affecting social stability, resulting in greater economic losses and social panic. The piping system is composed of a straight pipe and a pipe with a joint, a flange joint and an elbow. In the process of manufacturing or using, bending pipe structure is easy to produce such as fold, drum package, crack, pit, stress concentration and other defects, this makes it more complicated and difficult to detect pipes. The blasting leakage accident of the pipeline is often related to the structure of the curved pipe, so it can be seen that it is a very important and weak link in the pipeline system. Therefore, considering the above situation, it is necessary to study the damage identification of bending pipe crack.

Pipeline guided wave detection technology is a new nondestructive testing technology, which is developed in recent years to be able to carry out fast, long distance, large range, relatively low cost of nondestructive testing methods, due to their inherent characteristics, ultrasonic guided wave attenuation along the propagation path is very small, so it can be spread far distance. Thus, it overcomes the shortcomings of point by point scanning to realize long distance and large range detection. At present, based on piezoelectric ceramic array generation and reception of ultrasonic guided wave method in the damage identification of pipeline structure is used more and more widely. In this paper, the ABAQUS analysis of the large finite element program is used to analyze the crack damage identification of a curved pipe, by applying instantaneous axial displacement on the end pipe model simulation of piezoelectric ultrasonic guided wave incident, with curved pipe with different circumferential length, width and depth of the axial radial crack structure model for numerical simulation. Study on bending pipe structure using ultrasonic guided wave damage identification and sensitivity analysis of the problem and is consistent with the experimental results.

2. FINITE ELEMENT ANALYSES

2.1 Finite Element Models

2.1.1 The establishment of the model. The specific size of the model is shown in Table 1, and the material parameters are shown in Table 2.

Table 1. The model size table Unit: mm

External diameter	wall thickness	Straight pipe length	Right angle bend length
38	4	1000*2	119.38

Table 2. Material parameter

Elastic modulus (E/ GPa)	Poisson ratio (v)	Density (g/cm3)
38	4	1000*2

In order to simulate the pipeline weld, the weld will be set as the elastic modulus of pipeline ninety percent, remaining constant material parameters.

2.1.2 Signal selection. The propagation of guided waves in pipes will be dispersive, in order to reduce that phenomenon of the excitation signal in the propagation process, Expression as:

$$x(t) = \left[1 - \cos\left(\frac{2\pi f_c t}{n}\right)\right] \cdot \sin\left(2\pi f_c t\right) \quad (1)$$

In the formula, n is the number of single audio, as the center frequency of signal. Time domain signal diagram and its spectrum diagram of signal are shown in Fig. 1

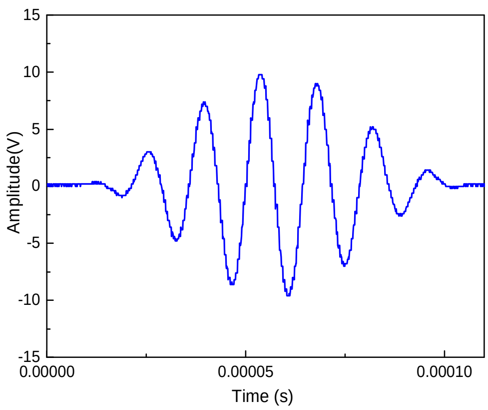


Fig. 1 Incident guided wave waveform

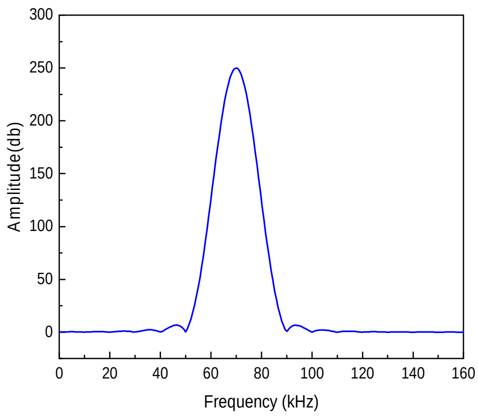
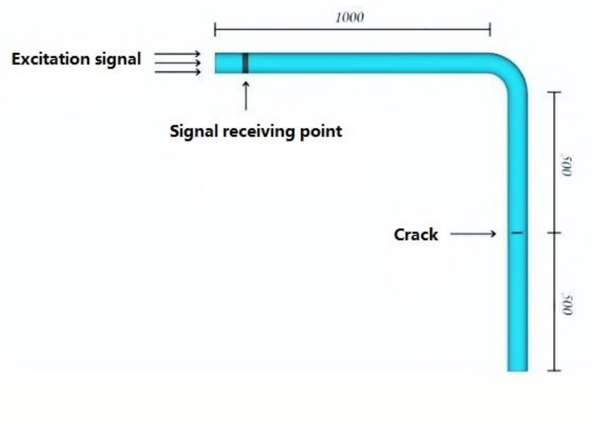


Fig. 2 Incident guided wave spectrums

2.1.3 Numerical simulation and results analysis. The physical model is established, and the model is divided into 11400 units by mesh, the circumferential direction is divided into 48 parts, the unit type by C3D8R, simulation of the defect is the center line to rotate around the central shaft. Therefore, the center of the defect degree of angle is defined for each defect. Explicit dynamic finite element model is adopted in the analysis, Analysis by using explicit dynamic finite element model. Axial pulse form displacement loading applied on the left end of the steel pipe model to Simulated incident ultrasonic guided wave, the distance of the signal receiving point to the left end of model is 100mm, as shown in the following figure.



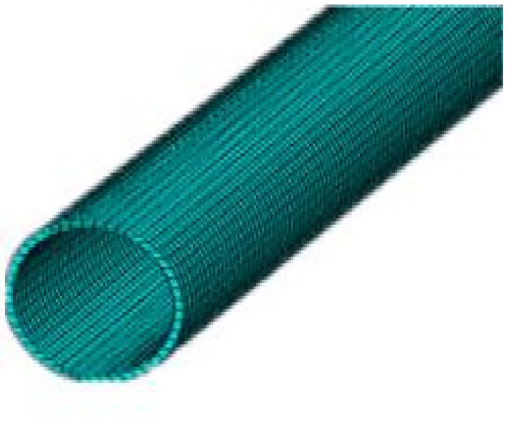
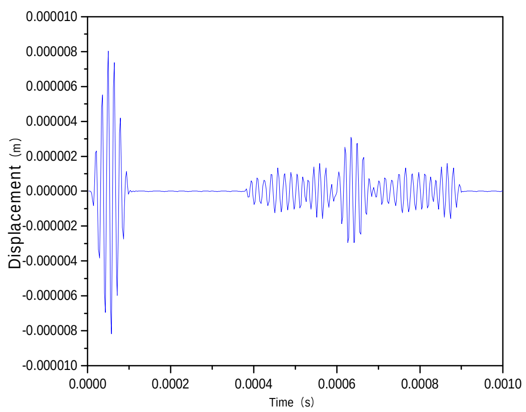


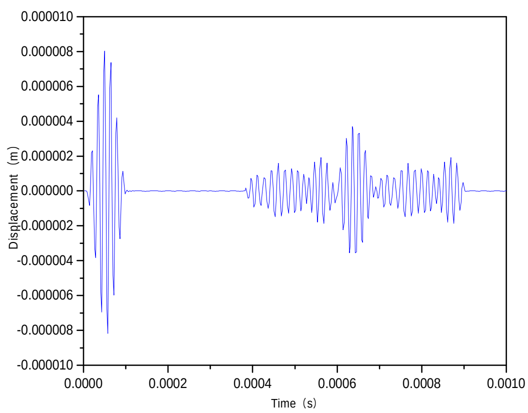
Fig. 3 schematic model

Fig. 4 mesh graph

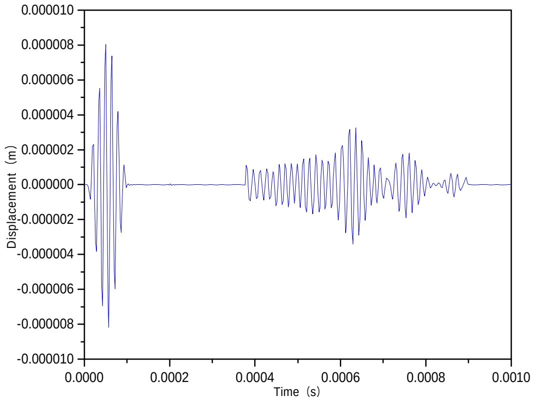
When the guided wave propagates in the pipe, it will be propagating along the pipeline smoothly, before encounter the crack, when meets the crack, it not only can produce the reflection phenomenon, but also can produce the transmission phenomenon. When the guided waves pass through the defects, the phenomenon of mode conversion will be occurring. The selected 320, 560, 11 and 1020 nodes are in the circle of the receiving point, it is different from the circumferential angle of the defect, the circumferential angle between each node and the defect is different, so the conversion of flaw echo mode is also different. In order to eliminate the influence of the bending wave on the recognition of the defect echo, the signals received by each node on the circumference of the receiving position can be added. Displacement time history curve diagram and signal superposition displacement time history curve received on the circumference of a portion of the node is shown at Fig. 5



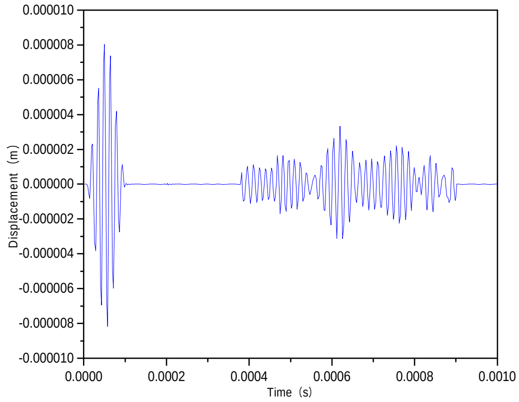
(a) 11nodes



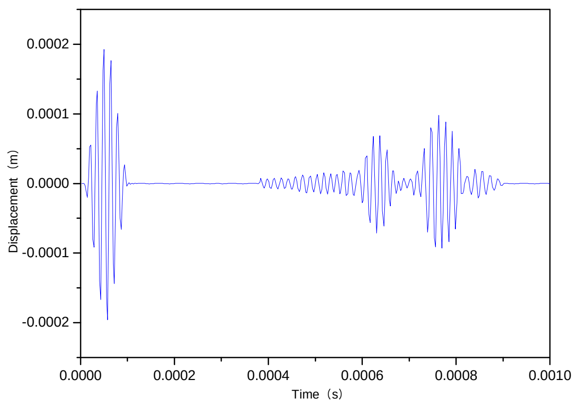
(b) 320nodes



(c) 560nodes



(d) 1020nodes



(e) Displacement time history curve after signal superposition

Fig. 5 Waveform of partial node signal and superimposed signal

According to measure the superposition signal, the propagation velocity of the perfect model is v, t0 is the time of arrival of the incident wave, the t1 is time of arrival of the echo produce at crack, and the location of the crack can be judged:

The time interval between the incident wave and the reflected wave generated by the crack:

$$\Delta t_1 = t_1 - t_0$$

According to the calculation formula of pulse echo, the distance from the receiving point to the defect distance is obtained:

$$x_1 = v \cdot \Delta t_1 \ / \ 2$$

The calculated defect position and relative error are shown in Table 3.

Table 3. Defect position

	defect
Calculated position from the receiving end	1.773954m
The actual position from the receiving end	1.6193m
relative error	9.551%

It can be seen from the table that the simulated calculation of the defect position and the actual position is basically the same.

2.2 Parameter Analysis

2.2.1 *Changing circumferential length of crack.* According to the previous building model method, simulation containing defects were 45 degrees, 60 degrees, 80 degrees, 90 degrees of the pipeline, the crack length respectively for 29.83mm, 39.77mm, 53.03mm, 59.63mm, its location and relative error were calculated, as shown in Table 4:

Table 4. different length defect position

	First defect location (m)	relative error（%）
45°	1.773954	9.551
60°	1.773954	9.551
80°	1.773954	9.551
90°	1.773954	9.551

It can be seen from table 4, that the time of the return of the reflected wave is not related to the length of the crack, which is related to the location of the two cracks. In order to compare the degree of sensitivity of the change of defect length, width and depth for pipeline, this article introduces the concept of reflection coefficients, the expression is as follows:

$$\text{Reflection coefficient} = \frac{\text{echo displacement}}{\text{incident wave}} \tag{2}$$

The echo of the length of the crack displacement and calculate the reflection coefficient of consolidation in the following table:

Table 5. The displacement length crack echo and reflection coefficient

crack length (mm)	29.83	39.77	53.03	59.63
Incident wave displacement (*10-4)	1.96	1.96	1.96	1.96
crack 1 echo displacement	0.714	0.763	0.813	0.845
End echo shift	0.983	0.901	0.857	0.792
crack 1reflection coefficient	0.3643	0.3893	0.4148	0.4311
end reflection coefficient	0.5015	0.4587	0.4372	0.4041

In order to compare the relationship of the change of crack length and reflection coefficient directly, reflection coefficient of different length defect is plotted a line chart, as shown in the Fig. 6

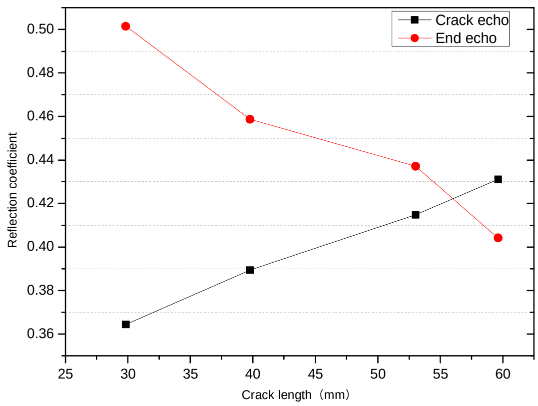


Fig. 6 Crack length and reflection coefficient

From the chart, it can be seen clearly that incident wave displacement does not change along with the increasing of the length of defect, while crack echo displacement increases, and end echo displacement decreases, moreover, defects' reflection coefficient increases gradually, and end reflection coefficient decreases gradually. After the numerical fitting, it is found that they are linear. The linear formula of reflection coefficient y and crack length L respectively:

Crackle y_1 : $y_1=0.00219l+0.30004$
End echo y_2 : $y_2=-0.003l+0.58688$

2.2.2 *Change the axial width of cracks.* Similarly, according to the previous modeling method to establish the pipeline model, when the all defects are 90 degree that meaning the length of the defects are identical, the axial width of the crack was changed to 1.5mm, 2.0mm, 2.5mm, 3.0mm respectively. The same analysis method is used to obtain the echo displacement and reflection coefficient of different width, which is shown in the Table 6.

Table 6. Echo displacement and reflection coefficient of different crack width

crack width (mm)	1.5	2.0	2.5	3.0
Incident wave displacement (*10-4)	1.96	1.96	1.96	1.96
crack 1echo displacement	0.62	0.65	0.68	0.70
End echo displacement	0.98	0.96	0.93	0.89
crack 1 reflection coefficient	0.3163	0.3316	0.3469	0.3571
end reflection coefficient	0.5	0.4898	0.4745	0.4540

The reflection coefficient of different crack depth is plotted as a line graph, shown in Figure. 8

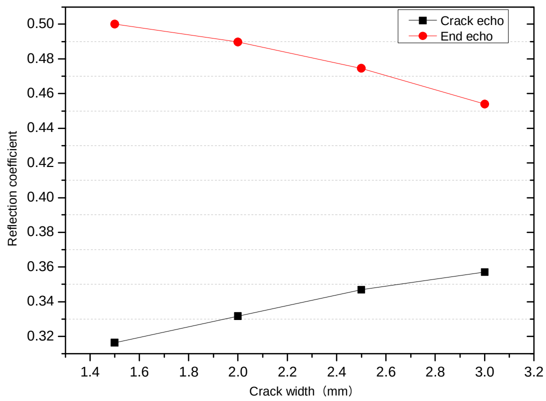


Fig. 8 Crack width and reflection coefficient

From the chart, it can be seen clearly that incident wave displacement does not change along with the increasing of the length of defect, while crack echo displacement increases, and end echo displacement decreases, moreover, defects' reflection coefficient increases gradually, and end reflection coefficient decreases gradually. After the numerical fitting, it is found that they are linear. The linear formula of reflection coefficient y and crack length L respectively:

Crackle y_1： $y_1=0.02754d+0.27601$

Terminal echo y_2：$y_2=-0.03066d+0.54856$

2.2.3 Change the radial depth of crack. Change the radial depth of the crack, so that it was 1.5mm, 2.0mm, 2.5mm, 3.0mm. The same analysis method is used to obtain the echo displacement and reflection coefficient of different depth, as shown in the table:

Table 7. echo displacements and reflection coefficient of each thickness crack

crack thickness (mm)	1.5	2.0	2.5	3.0
Incident wave displacement (*10-4)	1.82	1.82	1.82	1.82
crack 1echo displacement	0.72	0.74	0.78	0.81
End echo displacement	0.98	0.95	0.93	0.88
crack 1 reflection coefficient	0.3956	0.4066	0.4256	0.4451
end reflection coefficient	0.5385	0.5219	0.5110	0.4835

The depth of the crack of the reflection coefficient of drag line graph, as shown in figure:

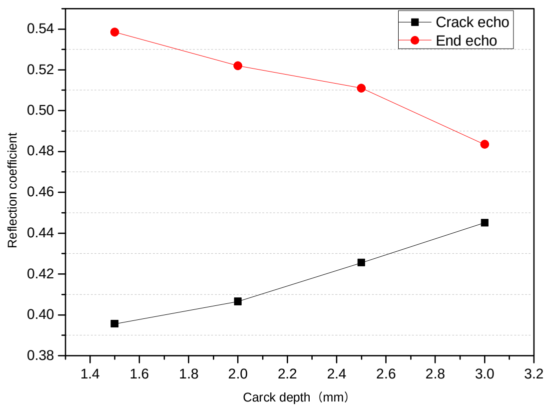


Fig. 8 crack depth and reflection coefficient

It can be seen that with the increase of the crack depth, the displacement of defect echo and the reflection coefficient are gradually increased; while the displacement of end echo and reflection coefficient is decreased with the increases of crack depth, linear relationship is shown.

The linear expressions of the reflection coefficient y and the crack depth h:

Crackle y_1 : y_1=0.0335h+0.34285

Terminal echo y_2 : y_2=-0.03518h+0.59288

3. TEST VERIFICATION

In order to verify the feasibility of the research method, the experiment results are compared with the simulation results. In the test, the size of the bent pipe is the same as the model in the simulation, and the echo signal of the simulation result and the experimental are compared:

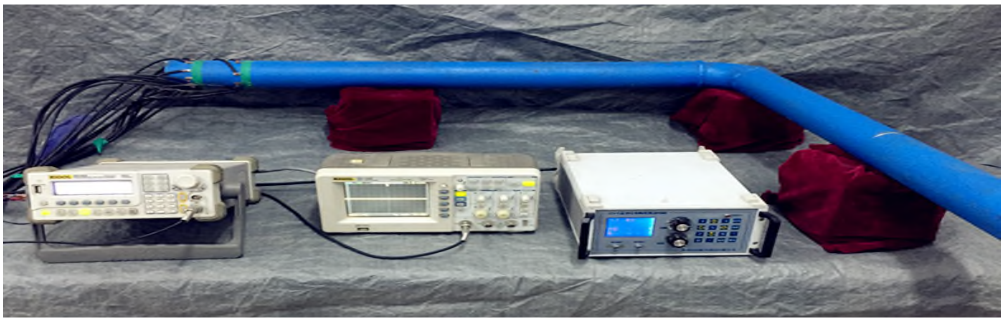


Fig. 9 test device

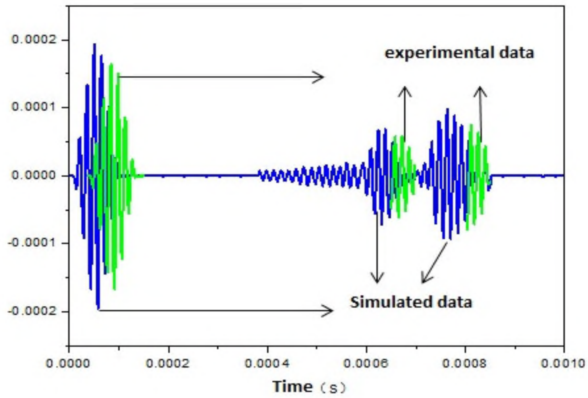


Fig. 10 comparison of experimental and simulated echo signals

It can be seen that phase is difference between the echo signal and the analog signal in the experiment. Through the analysis, in the experiment, the calculated guided wave velocity is 5432.37m/s. while, in computer simulation, the guided wave velocity is 5458.32m/s, so the time difference of the wave packet is existed. When the software is used to simulate the numerical simulation, the environment is relatively ideal, when the ultrasonic guided waves propagate in the steel tube, the energy spread is small.

4. CONCLUSIONS

（1）The ABAQUS software can be used to simulate the bending damage pipe, it can be accurately locate the position of the defect, by encouraging the appropriate frequencies and modes of guided waves.

（2）When the width and depth of the crack is constant, with the circumferential length of crack only be changed, the amplitude of the defect echo gradually increases, and amplitude of the terminal echo is gradually reduced, the reflection coefficient of the defect increases gradually, and the end reflection coefficient decreases gradually. And basically has a linear relationship.

（3）When the other conditions remain unchanged, only to change the axial width of crack, both the amplitude and the reflection coefficient of the defect echo are increased with the increase of the crack width, end echo amplitude and the reflection coefficient is decreased with linear relationship.

（4）When the other conditions remain unchanged, only to change the crack depth, With the increase of the crack depth, the amplitude and the reflection coefficient of the defect echo are gradually increased; And end echo amplitude and the reflection coefficient are decreased with the increase of the crack depth in a linear relationship.

（5）Compared with the experiment, it is very feasible to use ABAQUS software to identify the crack damage of bending pipe.

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