A New Robot-based System for In-pipe Ultrasonic Inspection of Pressure Pipelines

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Abstract: As pressure pipelines are usually mounted overhead or buried underground, the in-pipe inspection equipment that can run through inside pipelines is strongly demanded. Currently, the application of robotic systems for pressure pipelines in-pipe inspection is considered as one of the most attractive solutions available. Therefore, a new robot-based system for pressure pipelines in-pipe inspection was developed. A new defect detection method for pressure pipes was presented based on ultrasonic phased array technique. The developed system mainly included three parts: a tracked mobile robot for providing the driving force of the system movement, a camera used to photograph the inner surface videos or photos inside pipelines and an ultrasonic phased array module for defects detection. The structure characteristics of water/steel interface was investigated, as well as the focusing performance of convex phased array. The detection parameters such as elements size and dynamic apertures were studied and optimized with CIVA simulations. The in-pipe inspection experiments in pressure pipelines with an outer diameter of 219 mm were also carried out. The results show that the robot-based system could successfully go through inside the pressure pipelines and the ultrasonic phased array technique could implement inner surface scanning and defect detecting, which indicates that the new defect detection method can improve the pressure pipelines inspection effect.

Keywords: pressure pipelines; in-pipe Inspection; ultrasonic phased array; robot-based system

1 Introduction

As important transportation facilities, pressure pipelines widely exist in many industrial fields, such as petroleum, natural gas, metallurgy, chemical engineering. They are very useful tools for transporting liquefied petroleum gas, natural gas, hot steam, and other fluids. However, with long-term use of the pressure pipelines, natural deterioration and pipeline failure may occur due to the pipeline defects which may be caused by ageing, corrosion, cracks and mechanical damages [1-3]. Once the failure occurred, unpredictable safety accidents and direct economic losses may arise. Therefore, to eliminate the potential problem and hence avoid the pipeline failure, defect detection method or equipment should be investigated and pressure pipelines periodic inspection should be undertaken.

Currently, the in-pipe inspection of pressure pipelines has become an attractive research field. There are a lot of needs for autonomous inspection equipment that can run through inside the pipelines which are usually mounted overhead or buried underground [2-4]. Hitherto, many in-pipe inspection methods have been reported, while the application of robotic systems for in-pipe inspection of industrial pipelines is considered as one of the most attractive solutions available [3, 5, 6]. The "pig" is a kind of effective in-pipe tool for inside inspection. Visual inspection, remote field eddy current and magnetic flux leakage techniques are nowadays being used for in-line detections [7]. In these inspection techniques, the ultrasonic technique could obtain more precise and quantitative data, and is developing quickly. In 2005, GE delivered the first phased array ultrasonic inline inspection tool to the oil and gas pipeline inspection market [8], for the lines with diameters of 660mm and 860mm. For offshore pipelines, a 254mm inline inspection tool was developed for the detection of circumferentially orientated weld cracks, with the pulse-echo cracks and time-of-flight-diffraction technique [9]. It could be revealed that the inspection instrument is developing for a smaller, precise one, which could be utilized in more complicated and narrow space for inspection work. The inner diameter of the pressure pipe is usually small which makes it difficult or impossible to carry the inspection equipment inside the pipelines, thus further research work should be undertaken.

In order to solve the inspection problem in small diameter pipe with high accuracy, a kind of robotic systems for pressure pipes in-pipe inspection based on ultrasonic phased array technique was researched. The structure characteristics of water/steel interface was investigated, as well as the focusing performance of convex phased array. The detection parameters such as elements size and dynamic apertures were studied and optimized with CIVA simulations. Furthermore, the detecting instrument and the experimental pipe will be manufactured, while several artificial defects were made on the pipe sample. With the robot-based system, the in-

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pipe inspection experiments of the testing pipe with the outer diameter of 219 mm are also carried out.

2 Ultrasonic Phased Array Technique

2.1 The Structure

This ultrasonic phased array approach utilizes an ar-ray of 512 elements, which can be fired sequentially with specific delay time so that one can manipulate the ultrasonic beam profile inside the component. The whole array includes four probes with the same configuration and two layers. The probes 1 and 3 are settled in one layer while the probes 2 and 4 are settled in the other, as shown in Fig. 1. Thus, the ultrasonic beam could cover the whole cross-section of the pipeline. Each probe includes 128 elements, so acquired data will be overlapped automatically.

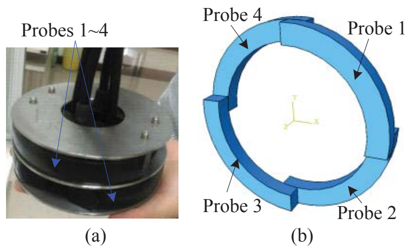


Figure 1. Ultrasonic phased array module, (a)Construction, (b) Two-layer structure.

In each probe, the first 15 elements (No.1~15) are coded the same as the last 15 elements (No.114~128) of the adjacent probe, as shown in Fig. 2. When the electronic scanning begins, the focused beam will be firstly formed at a specific point from the elements No.1 to No.16 of probe 1. Then, the focusing continues from the elements No.2 to No.17. The beams of other elements in probe 1, 2, 3 and 4 are focused, sequentially. The total circumferential electronic scanning will be finished until the focused beam from elements No.113 to No.128 in probe 4 is formed. After scanning, the phased array module is trigged, and the whole image information of the cross section will be integrated and then transformed to the display screen.

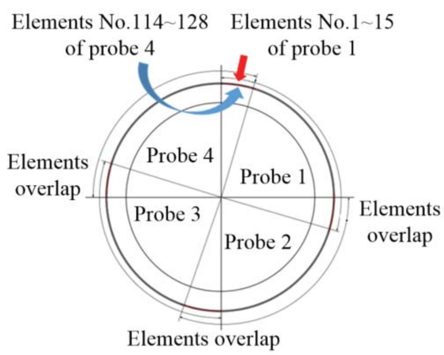


Figure 2. The overlapped elements.

2.2 Defect Detection Mechanism

Fig. 3 shows the principle of the defect detection mechanism of ultrasonic phased array technique. The ultrasound propagation from the water to the wall is displayed, which will be able to detect the pipe thick-ness. The ultrasound T1 through water medium, is along the radial incidence of the water/steel interface. Then the ultrasound echo R1 is produced, and the signal B1 occurs. The transmission wave T2 is formed from the remaining transmission energy and make the bottom echo B2 produced in the steel, which will give the signal B2 in the screen. The pipe wall thickness reduction could be calculated according to the fixed ultrasonic speed in water and the steel.

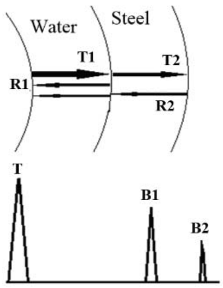


Figure 3. Principle of the defect detection method.

The principle of the focal law for the cylindrical ultrasonic phased array is shown in Fig. 4. In the x-y plane coordinate system, the original convex array with the radius R is transformed to a new concave wave front with the radius F.

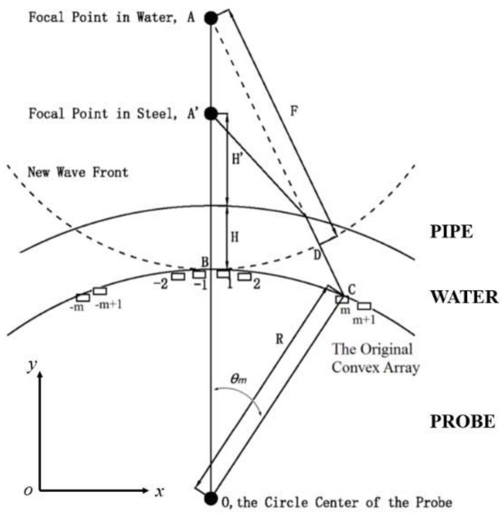


Figure 4. The principle of the focal law.

Thus, the delay time of the No. m element is

$$\tau_m = \frac{AC - F}{c_{\text{water}}} = \frac{\sqrt{R^2 + (R+F)^2 - 2\cos\theta_m (R+F)R} - F}{c_{\text{water}}} \qquad (1)$$

The delay time of the No.m-1 element could be obtained as

$$\tau_{m-1} = \frac{AC-F}{c_{\text{water}}} = \frac{\sqrt{R^2+(R+F)^2-2\cos\theta_{m-1}(R+F)R}-F}{c_{\text{water}}} \quad (2)$$

These delay time of the array elements will be settled as their pre-trigger time, thus the designed focal law could be formed. The axial focusing of this cylindrical phased array detection instrument was carried out by the acoustic lens, whose sound velocity is higher than that of water. The lens was made to be convex, and could focus at specific locations with relevant curvature de-sign. Fig. 5 showed the beam focusing in different media, and the focal length F in water is,

$$F=\frac{R}{1-\frac{c_{\text{lens}}}{c_{\text{water}}}} \quad (3)$$

Where the radius of curvature of the convex surface is R. For the detection of corrosion in steel, the focusing will be formed twice (as shown in Fig. 5), one is in water and the other is in steel. The distance between the probe and the steel is assumed as H, while the distance between the actual focal point and the surface of the steel is assumed as H'. Then the focal length F' after twice focusing in water and steel could be obtained as:

$$F'=H+\frac{c_{\text{water}}}{c_{\text{steel}}}(F-H) \quad (4)$$

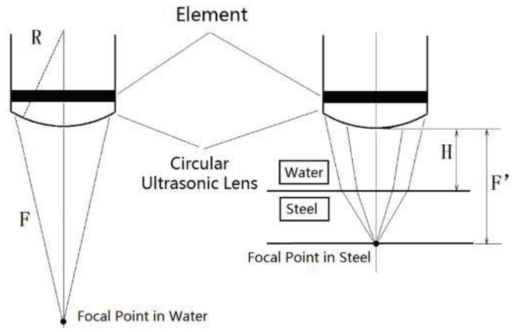


Figure 5. Beam focusing in different media.

3 Ultrasonic Field Simulation

It is difficult to solve the reflection and refraction of the acoustic field at the curved interface by analytic method. Therefore, the CIVA software was used to establish the phased array model and calculate the ultra-sonic field formed by the phased array probe inside the work piece. Element size, frequency and other parameters was considered. The diameter of the phased array instrument is 130mm. The element shape parameters include the pitch d, the element width a, and the element length L, while L is fixed to 10 mm. Therefore, in order to suppress the side lobes, the width a should be closer to the pitch d as possible. To obtain optimized parameters of the pitch d, the element width a and the dynamic aperture, several simulations were conducted with the working frequency of 5MHz. The focal point is located in the pipe wall and the CIVA simulation model is shown in Fig. 6.

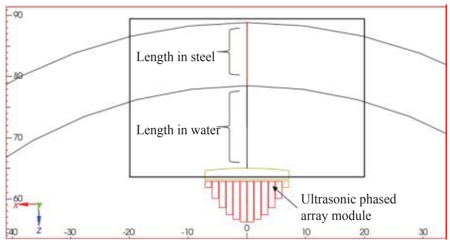


Figure 6. The phased array model in CIVA inspection.

3.1 Dynamic Aperture

In order to get proper values of the dynamic aperture, element width of 0.7 mm, spacing of 0.8 mm, length of 10 mm and deflection angle of 0 degree were deter-mined for the simulation. The ultrasound field of simulation were shown in Fig. 7. From the simulation, it can be found that the bigger the shape of dynamic aperture is, the better the focusing effect in the pipe is, while the ultrasound field in water owns more and more grating lobes and side lobes.

For the detection frequency of 5 MHz, the wavelength of the ultrasonic wave in water is only 0.29 mm and the element spacing is 0.8 mm, which is about 2.8 times of the wavelength. Therefore, when the number of dynamic aperture is 32, even if the beam is not deflected, there will be a grating lobe; the side lobes in the water is serious too using 16 elements as dynamic aperture; however, it is ok to have 4 or 8 elements as the dynamic aperture, while 8 elements gives a better focusing effect in the pipe.

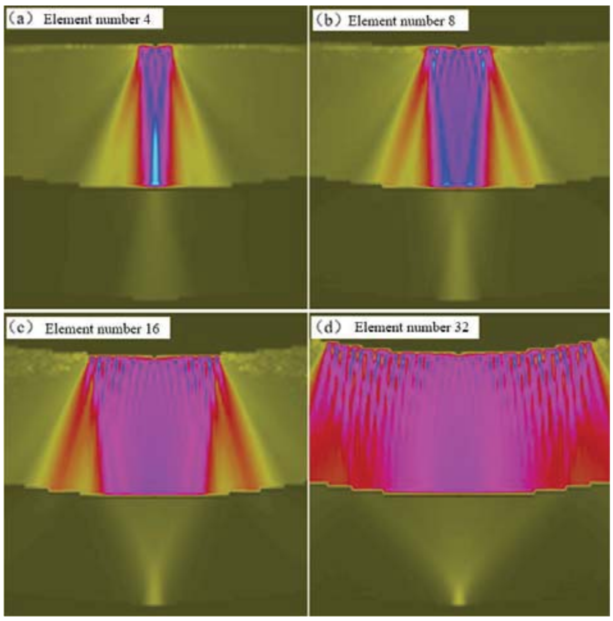


Figure 7. Simulation results with different dynamic aperture.

3.2 Elements Size Parameters

In the simulation, 8, 16 and 32 elements of the dynamic aperture were used to help optimize the element size parameters. There are three sets of parameters here, a = 0.3

mm and d = 0.4 mm, a = 0.7 mm and d = 0.8 mm, a = 1.1 mm and d = 1.2 mm, as shown in Fig. 8.

The results show that the sets with a = 0.3 mm and a = 0.7 mm did a better job in controlling the side lobes and the grating lobes in water, when the aperture was lower than 16 for a = 0.3 mm and 12 for a = 0.7 mm, respectively. Thus, a = 0.3 mm and a = 0.7 mm were better to be used in the instrument, to avoid the occurrence of some serious grating lobes and side lobes. When the economy cost was in consideration, the set of a = 0.7 mm and d = 0.8 mm was a better choice.

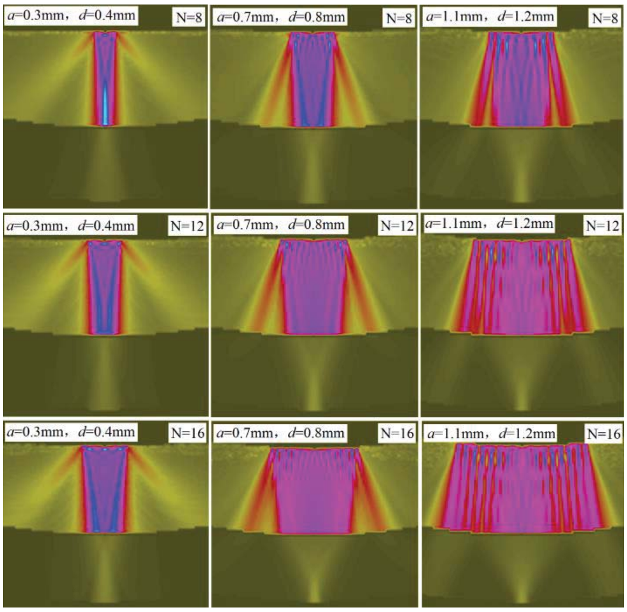


Figure 8. Simulation results of CIVA sound field with different element sizes.

4 Robot-based In-pipe Inspection System

The new robot-based in-pipe inspection system mainly includes four parts: a tracked mobile robot with a charge coupled device (CCD) assembly, an ultrasonic phased array module, a data acquisition unit and a micro-computer for system control, data processing and image reconstruction, as shown in Fig. 9.

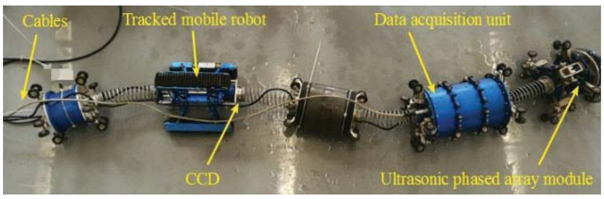
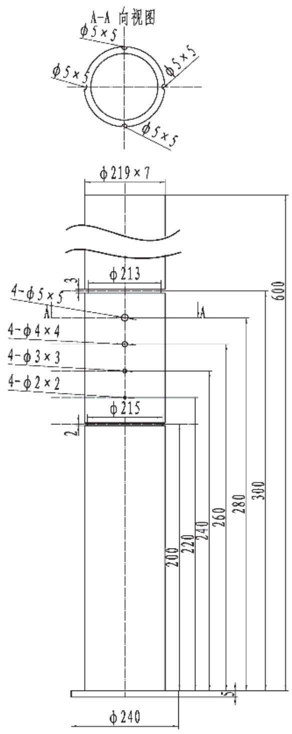


Figure 9. New robot-based in-pipe inspection system.

The tracked mobile robot, which is designed on the basis of three caterpillar bands (driven by six DC motors) as well as the corresponding mechanical structures, is applied to provide the driving force of the system movement. It uses the spring tensions to press the inside surface of the pipeline and can realize the adaption to the pipe diameter by adjusting pressing force. The charge coupled device (CCD) assembly, which is in-stalled at the front part of the body frame of the tracked mobile robot, is used to photograph the in-pipe videos or photos. The ultrasonic phased array module, which is the core inspection component of the system, is employed to detect the pipeline defects and thickness as described in the above chapters. The data acquisition unit, which is built up with a micro controller, is used to receive the measured data/signals and hence send them to the micro-computer.

5 Inspection Experiments

According to the parameters from simulation, a cylindrical convex array phased array module and the corresponding probes with a large array elements were manufactured, while the array element width was 0.7mm, the spacing was 0.8mm, and the dynamic aperture was made as 8. The test pipe is designed with the accordance of some kind of typical pressure pipes, as shown in Fig. 10. Several specific artificial defects, such as different flat bottom holes and rectangular cross-section grooves, were machined as described in the figure.



(a) design sketch

(b) actual pipe with the defects

Figure 10. the Experimental pipe.

During the inspection experiments, the pipe is filled with water, and the probe is settled in the pipe and held by the probe holder for centering. The encoder recording stroke is set to trigger the scanning of A, B, C and D. The scanning results could be displayed in different colors according to the wall thickness. The whole pipe thickness condition could be shown after the wall thick-ness is detected. The A scan, B scan, C scan and D scan images obtained from the inspection tests were shown in Fig.11. It can be seen that the C-scan thickness imaging clearly showed the location and shape for different defects, and the measurement error for the wall thickness is about 0.1 mm. Some dislocation can be found in the figure, which could be caused by the influence of the relative locations of the two layers in the structure holder.

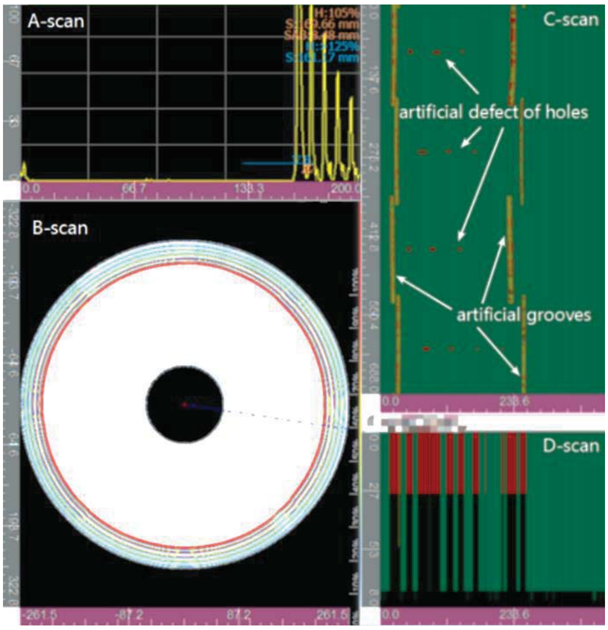


Figure 11. Experimental results.

6 Conclusions

1) The characteristics of the detection in the pressure pipe and the cylindrical convex array are analyzed, and the focal law of ultrasonic phased array applicable to the water-steel interface in the pipeline is proposed.

2) Based on the CIVA simulation, the influence rule of different array parameters and array aperture on the ultrasonic field distribution characteristics in pipeline is analyzed. Under the premise of ensuring less lobe and side lobes as well as good focusing effect in water steel, the inspection parameters of the array in the pipe are optimized.

3) The experimental pipe was built, and the inspection tests for artificial defects were conducted. The reliability of convex ultrasonic phased array detection technology in tubular equipment is verified, as well as the detection capabilities for pipe defects and corrosion.

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