The Structure Design and Simulation of Ultrasonic Inspection Instrument for Inside Pressurized Pipe Elbows

Cunjian Miao, Xingji Du, Junfang Xia, Min Wang, Zhangwei Ling and Ping Tang
Zhejiang Provincial Special Equipment Inspection and Research Institute, Hangzhou 310020, China
*Corresponding author e-mail: miaocunjian@gmail.com

Abstract. Elbows in pressure pipes are important parts which may become serious corrosion locations. Ultrasonic detection is a main technique for pipe inner inspection, and the use of traditional ultrasound and phased array technique for in-line inspection are advanced, long-term interesting and known by researchers. Several devices were invented for inside pipeline inspection and suitable to some extent such as detecting long-distance pipelines. However, elbows especially tight elbows are still difficult to implement inner detection or travelling. To obtain good effect in detecting elbows, the inner inspection technique was investigated. Spherical and flat cylindrical probe holder structures were proposed to ensure the ability to pass through elbows, while the spherical holder has many conventional probes in its shell with a uniform distribution. The flat cylindrical probe structures are suitable for phased array ultrasonic technique to form a convex array. CIVA simulation was conducted and the focal effects were analyzed. Comparing with detecting precision and manufacture process, the phased array technique was chosen, and the elbow inspection experiments were carried out. The ultrasonic system was taken by a robot to travel through the elbow, and the experimental data were used to verify the applicability of the ultrasonic inspection technique.

1. Introduction
Pipelines are important energy transmission systems, which are being subjected to different kinds of corrosion during their service. Uniform loss of material is one of the main forms for pipeline corrosion, which may result in a continuous thinning of the pipe wall, and lead to leakage or rupture of pipelines. It becomes more interesting to do an inner inspection than the traditional outer detections for researchers. Ultrasonic technique is one of the inner inspection techniques, and could be utilized for the detecting of general corrosion and corrosion cracks [1-4]. Elbows are recognized to be such important parts in pipelines that may be one of the serious corrosion locations. Several devices were invented for inside pipeline inspection and is suitable to some extent such as detecting long-distance pipelines. However, elbows especially tight elbows are still difficult to implement inner detection or travelling. In addition, the echo loss is also a major issue for inner ultrasonic detection [5]. To investigate an inner ultrasonic technique for elbows, spherical and flat cylindrical probe holder structures were proposed to ensure the ability of elbow traveling. The holder structures were designed,
and both phased array technique and traditional pulse probe were discussed for their detecting effects. CIVA simulation was conducted based on the above design, and the changeable incident angles induced by the instrument’ motion were considered. Some specific instruments were manufactured, and experiments were conducted, and the results were analyzed to lead conclusions.

2. Ultrasonic Inner Inspection Technique for Elbows

2.1. Probe and Structure Design
To ensure the echo amplitude in elbow inner inspection, the ultrasonic route should be vertical to the inner pipe surface as good as possible. There are two structures that could meet the requirements: one is a spherical structure and the other is a flat cylindrical structure. The former could travel through the elbow with the hydrodynamic pressure, while the latter could move using its wheels.

As regards the spherical structure, it should be ensured that at least one set of elements are perpendicular to the pipe wall. Thus, the spherical surface should be mounted with many elements uniformly (Fig.1), and this made the phased array hard to be done, while the conventional probes could perform well. For the flat cylindrical structure, convex circular phased array elements are suitable.

![Figure 1. The simplified layout of elements mounted on sphere.](image1)

![Figure 2. The inspection mechanism of phased array.](image2)

2.2. Inspection Mechanism
The pulse of ultrasonic waves delivers straight ultrasonic beams at discrete intervals through the pipe wall and waiting for the return signal. By analyzing the echo return intervals and other properties, the pipeline wall thickness could be calculated. The ultrasonic beam will be focused after transmission from water to steel. Fig. 2 shows the focal law of the ultrasonic phased array. In the XOY plane coordinate system, the point O is taken as the origin of the system. The propagation routine of beam in steel is expressed by line $r_1, \ldots, r_m$, while the propagation routine in water (the couplant) is expressed by line $l_1, \ldots, l_m$. The focused point in steel is marked as A, which is also the source point of ultrasonic echo. The No.$m$ element of the phased array probe is located at point C, and the incident point from steel to water is located at point B on the inner surface of the storage well, while the angle $\alpha$ and $\beta$ are the incidence and refraction angle respectively. The distance $r_0$ is the shortest transmission path of ultrasonic beam from point A to the interface between water and steel, while the distance $l_0$ is the shortest from point O to the interface.

As the beam is focused without steering, the delay time $\tau$ of the phased array signal on both sides of the reference point O are the same ($\tau_m = \tau_{-m}$). Thus, it is enough to calculate the delay time on the right side for the parameters of the arrays. $\tau_m$ of the No. $m$ element could be calculated from:

$$
\tau_m = \frac{\sqrt{(x_a-x_c)^2 + (y_a-y_c)^2}}{c_{\text{water}}} + \frac{\sqrt{(x-x_c)^2 + (y-y_c)^2}}{c_{\text{steel}}} - \frac{\sqrt{(x_a-x_c)^2 + (y_a-y_c)^2}}{c_{\text{water}}} - \frac{\sqrt{(x-x_c)^2 + (y-y_c)^2}}{c_{\text{steel}}}.
$$

(1)
Where, \( c_{\text{steel}} \) and \( c_{\text{water}} \) are the sound speeds in steel and water, respectively. According to the Snell’s law, an equation is given as:

\[
\frac{\sin \alpha}{\sin \beta} = \frac{c_1}{c_2}
\]

(2)

\[
r_n = \sqrt{(x-x_n)^2 + (y-y_n)^2}
\]

(3)

\[
l_n = \sqrt{(x_n-x)^2 + (y_n-y)^2}
\]

(4)

As the values of AD, OD, \( c_{\text{steel}} \) and \( c_{\text{water}} \) are already known, the coordinates of points A, B, C and D can be obtained numerically when the variables at point No. \( m \) is determined. Then the time delay \( \tau_m \) of the No. \( m \) element could be obtained. The time delay of the elements \( m-1, m-2, \ldots, 1 \) could be calculated as well. Considering that the beam is not deflected, the time delay of phased array elements located on both sides could be obtained too. These delay time of the array elements will be settled as their pre-trigger time, thus the designed focal law could be formed.

3. CIVA Modeling

To study the ultrasonic field distribution of these two kinds of structures in elbows, CIVA software was utilized. The elbow and straight pipe are designed according relevant standards, and inclined angle of the probe is also taken into consideration.

3.1. Elbow Structure

The pipeline of φ219 is a commonly used pipe specification, which is design according to relative Chinese standards \([6-8]\), and a specification with an outer diameter of 219mm and a thickness of 8mm were determined, while the material was 20# steel. The structure diagram was depicted in Fig. 3.

![Figure 3. The structure diagram of the elbow model.](image)

3.2. Inclined Angles

Considering the possible rotation of the probe as it travels through the elbow, the ultrasonic propagation route may obtain an inclined angle at the incident point. Thus, different inclined angles were set in the modeling to investigate the influence of the inclined angles on the ultrasonic field distribution. 0 ° (vertical), 5 ° and 10 ° were listed to represent the changeable angles that may occurred during probe’s traveling, as shown in Fig. 4.
3.3. CIVA Parameter Settings

In CIVA simulation, the conventional ultrasonic probe with a single element of 6mm diameter was used, and the propagation route in water is 10mm, while the working frequency of 5MHz. The parameter of convex cylindrical phased array is more complicated. A cylinder with diameter 130mm was chosen and a water route of 40mm was decided. In order to suppress the side lobe, element width $a$ should be lower and closed to elements’ pitch $d$, and it was determined to be 0.7mm and 0.8mm respectively. The working frequency was 5MHz, while six elements were to be triggered simultaneously.

3.4. Results and Discussion

1) Spherical Structure Probe

The results in Fig.5 with different angles revealed that the angles do affect the ultrasonic field distribution, and the larger the deflection angle is, the more dispersed the echoes from the outer pipe wall are, and the echo’s amplitude become lower too as the angle grows bigger.

2) Flat Cylindrical Structure Probe

In Fig. 6, the beam route in water is much longer than that in steel, which lead to a small picture for the ultrasonic distribution in pipes and a lower resolution. However, it is obvious to reveal that the amplitudes of the outer wall echo vary with the angle changes. The echo amplitude is higher at 0 °, and the echo become sparser as the angle raised.

It can be found that in spite of the longer route in water, which could weaken the focusing effects, the method using the convex flat cylindrical phased array technique could obtain stronger echo amplitudes. This will be significant to the detection of elbow. Thus, the subsequent experiment will be conducted utilizing the convex flat cylindrical phased array technique.
4. Inner Inspection Experiments in Elbow

4.1. Experiment Platform
The experiment platform was built for inside ultrasonic inspection in pressure pipe elbow, which includes elbows, vertical pipes, horizontal pipes and a number of accessories. The experiment platform is shown in Fig. 7. Some artificial defects were designed and machined on the pipe outer surfaces. During the experiment, the ultrasonic phased array probe will be pushed by a tracked robot.

![Figure 7. The experiment platform and artificial defects.](image1)

![Figure 8. The B and C Scan Images.](image2)

4.2. Results Discussion
According to the experiments, ultrasound images could be gained in the pipe, especially in the elbow. The images of B and C scan were shown in Fig. 8 and the results were listed in Table 1. A maximum deviation of 1.7mm and a maximum error of 20% were deduced from the table, and the shallow tapered holes with a diameter above 8mm could be detected.

| Defects | Actual dimensions/mm | Detection results/mm | Deviation/mm |
|---------|----------------------|----------------------|--------------|
| Defect 1 | 10.0 | 9.0 | -1.0 |
| Defect 2 | 8.5 | 6.8 | -1.7 |
| Defect 3 | 8.5 | 7.1 | -1.4 |

5. Conclusion
1) The probes with spherical and flat cylindrical structures could avoid being stuck in elbows effectively. The spherical frame is hydrodynamically driven, without the need for centering and power supply, while the flat cylindrical probe structure could utilize ultrasonic phased array to obtain a good detection effect.
2) According to the CIVA simulation, the inclined angle of the probe in the elbow detection will lead to changes of ultrasonic field distributions. The ultrasonic phased array approach is more suitable for elbow inspection than the method using the spherical structure.
3) The flat cylindrical convex probe with phased arrays was moved by a tracked robot, and can obtain ultrasonic echo and images from the pipe elbow. Some specific defects can be detected according to the present results and uniform corrosion condition may also be detected.

Acknowledgments
This work was financially supported by the Major Project of Zhejiang Bureau of Quality and Technical Supervision (No. 20160122) and the Public welfare technology research social development project (No. 2017C33162).
References

[1] Stefan Bauer, Henning Brueske. Detection and Sizing of Subcritical Cracks Using Ultrasonic In-Line Inspection Methods [C]. 2014 10th International Pipeline Conference. Calgary, AB, Canada: American Society of Mechanical Engineers. 2014.

[2] Lisa Barkdoll, Herbert Willems. Post Assessment of Ultrasonic Crack Detection Inline Inspection Data [C]. 2008 7th International Pipeline Conference: American Society of Mechanical Engineers. 2008. 567-573.

[3] Stephen P Ohl, Robert E Allison. Ultrasonic Inline Inspection of the Moomba to Sydney Pipeline [C]. 2006 International Pipeline Conference: American Society of Mechanical Engineers. 2006. 667-676.

[4] Neil Bates, David Lee, Clifford Maier. A Review of Crack Detection in-Line Inspection Case Studies [C]. 2010 8th International Pipeline Conference: American Society of Mechanical Engineers. 2010. 197-208.

[5] Alfred Barbian, Michael Beller. In-line inspection of high pressure transmission pipelines: State-of-the-art and future trends [C]. Proceedings of the 18th world conference on nondestructive testing, Durban, South Africa: Citeseer. 2012.

[6] GB/T 8163, Seamless steel tubes for liquid service [S]. 2008.

[7] GB/T 17395, Dimensions, shapes, masses and tolerances of seamless steel tubes [S]. 2008.

[8] GB/T 12459, Steel butt-welding seamless pipe fittings [S]. 2005.