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Research on an Ultrasonic Phased Array Defect Detection System

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Abstract: Pipeline safety is very important. A small defect in pipeline girth weld may lead to an accident. Automatic and accurate nondestructive testing method with fast detection speed is needed. Therefore, an ultrasonic phased array defect detection system has been developed. The deflection and focusing characteristics are analyzed at first. Then, detection principles based on geometrical acoustics approximation are described. And then, keys of system hardware construction and the software design are introduced. Application of this system is carried out on a weld test block of a big inch pipeline girth weld. The experiment results demonstrate the usefulness of such testing configuration and illustrate that the system can increase the testing efficiency.

Key words: Nondestructive testing, ultrasonic phased array, flaw detection, pipeline, girth weld

INTRODUCTION

Pipelines are used to transport oil or natural gas in long distances. Their girth welds have complex structures in terms of geometry. There is an increasing need for low-cost, automatic and accurate nondestructive testing method to detect flaws in spite of irregular geometry because flaws may be formed in the weld during welding. Researches have been carried out in this field (Barandiaran *et al*., 2009; Thomas *et al*., 2009; Gengembre and Lhemery, 1999; Calmon *et al*., 1998; Mahaut *et al*., 2003) among which ultrasonic testing is a widely used method. Traditional monolithic piezo-electric transducer can only focus in a fixed location. To achieve inspecting the weld along the pipe wall's depth direction, different transducers having different focal lengths are required. Obviously, the testing efficiency and velocity are low.

To overcome these difficulties, a possible solution is the application of Ultrasonic Phased Array (UPA) techniques. The phased array transducer consists of multi piezoelectric crystal units which can be separately controlled to transmit the ultrasonic wave or receive the ultrasonic echo. Ultrasonic waves transmitted or received by the transducer not only satisfy the principle of wave interference but respect Snell-Descartes's laws for refraction/reflection at any interface. Therefore, the ultrasonic phased array system has electronic scanning, sectorial scanning and dynamic depth focusing (DDF) inspection modes. Sectorial scanning is used to inspect pipeline girth welds in this article.

Researches on phased array techniques applied in Nondestructive Testing (NDT) industrial field are mainly focused on theoretical modeling and development of ultrasonic phased array system, including design and fabricate the phased array transducer. Based on a "pencil" method, the French Atomic Energy Commission (CEA) has developed several approximate models on the computation of ultrasonic fields and prediction of the echo from the detected flaw (Calmon *et al*., 1998). These can be realized on Champ-sons and Méphisto software platforms (Mahaut *et al*., 2003). As to the inspection system, both universities and commercial companies are devoted to its development. A portable, handy and intelligent system that can rapidly and accurately detect the flaw is the development goal.

P.A.U.L.I. developed in Korea was composed of two PCS and realized sectorial scans and DDF. But the instrument was large (Song *et al*., 2002). Fraunhofer IZFP in Germany developed a miniaturized phased array system ADAPT-US and a rotation detection system to inspect the pipe and achieved high-quality imaging along axial and radial direction (Rider *et al*., 2003). A titanium billet used for the aircraft and an axle used for the train were inspected with a circular matrix array and a detection system called as PAUTs in the Center for Nondestructive

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Evaluation (CNDE) in USA (Utrata and Clark, 2002). PipeWIZARD™ and Omniscan developed by Canada Olympus Corporation (Lupien and Cancre, 2001) and X-32 developed by Sonatest Ltd in UK (Dennis *et al*., 2007) are typical portable ultrasonic phased array systems presently. These researches have different research priorities and goals, promoting applications of the ultrasonic phased array technology in the industrial nondestructive testing field.

This article is based on two linear phased array transducers and our current research results (Chen *et al*., 2006; Li *et al*., 2008).

FLAW DETECTION MODEL AND TESTING PRINCIPLE

The cross-section of the weld is divided into seven layers from top to root, each of which is about 2 mm in height. Two linear UPA transducers are located at both sides of the weld. They transmit ultrasonic beams with specific deflection angles and focus depths to detect layer of half weld[10]. To determine testing parameters, such as sound path, a flaw detection model is established.

Establish the computation coordinate system: An ultrasonic ray emanated from the point source propagates in a straight line and is refracted or reflected at any interface. The inspection path and focal locations should be established in a computation coordinate system firstly to determine the transmission and reception laws.

Considering the geometrical shape of the tested weld, the inner pipe wall is selected as X-coordinate and the weld centerline is selected as Y-coordinate, as shown in Fig. 1. Only one transducer and half weld are considered for the other half is completely symmetrical and the inspection conditions are the same. The UPA transducer is placed on a wedge. In addition, the outer pipe wall and inner pipe wall can be seen as flat surfaces because the

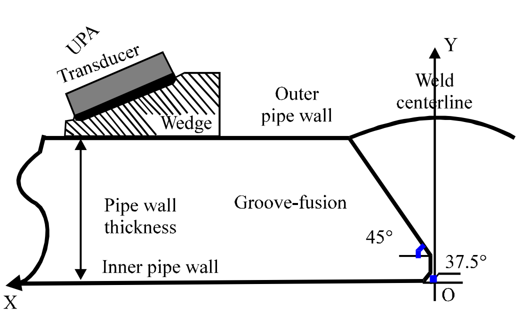

Fig. 1: Coordinate of the UPA inspection system

length of the UPA transducer is very small compared to that of the pipe's circumference.

Determine the focal length: An UPA transducer can transmit deflecting and focusing ultrasonic beams at the focus, which is the inspection area. Normally, the focus is not a desired focal point but a focal column. In Fig. 2, the rectangle ABCD is the projection of the focal column on XOY plane. The center of the focal column is G and is the desired focal point theoretically.

At the same time, not all the echo signal collected from the full sound path is useful for the flaw detection because we are just concerned about flaws in the weld. Therefore, it is only needed to collect ultrasonic echoes near the groove-fusion of the girth weld. Generally, a time gate is set to determine the signal acquisition range. In this case, the time gate is set 3 mm before the grove-fusion and 1 mm after the weld centerline, as Fig. 3 shows. Therefore, in Fig. 2, EF = 3 and HI = 1 mm. It is assumed that the incident beam covers one of seven layers. Its centerline EI passes through the midpoint of the layer's groove which is point F. As the width and height of the layer and the deflection angle of the incident beam are known, the coordinates of point $F(x_F, y_F)$ can be computed. To determine the focal length, namely the coordinates of point G, the coordinates of point E and point I should be determined at first.

In Fig. 3, it is clearly indicated that primary wave and secondary wave of ultrasonic beams are used to inspect different layers to achieve the entire weld's inspection. So, it can be concluded in the following two cases.

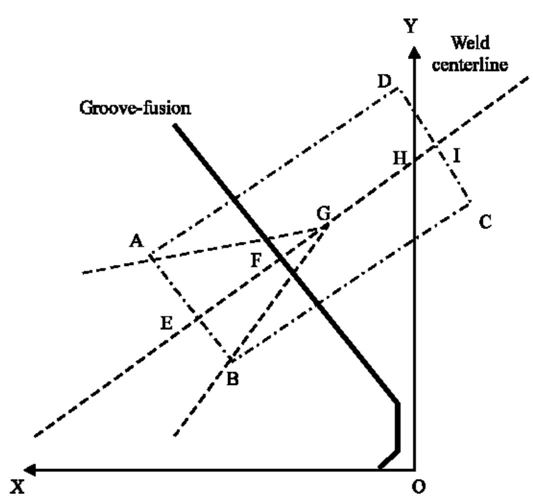

Fig. 2: Diagram of the focal column produced by a UPA transducer

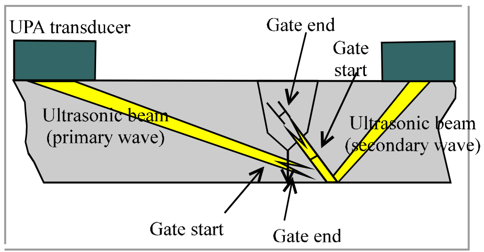

Fig. 3: Schematic diagram for time gate setting

Primary wave inspection method: Primary wave inspection method is descried in Fig. 4. Supposed pipe wall thickness is T. The incident angle of the ultrasonic beam in the wedge is α and the deflection angle in the pipe wall is β. The equation of the incident beam's centerline is:

$$y = \tan\beta\,(x-x_F)+y_F \tag{1}$$

Suppose the groove line and the inner pipe wall intersect at point M, whose coordinate is $(x_1, 0)$. The groove line is parallel to Y-coordinate at the weld root and it can be expressed by:

$$x = x_1 \tag{2}$$

Move the groove line to the positive X-axis by 3 mm:

$$x = x_1+3 \tag{3}$$

Move the weld centerline to the negative X-axis by 1 mm and it is:

$$x = -1 \tag{4}$$

Combine Eq. 1 with Eq. 3, the coordinate values of point E in Fig. 2 (x_E, y_E), can be computed. Similarly, combine Eq. 1 with Eq. 4, the coordinate values of point I in Fig. 2 (x_I, y_I), can be computed too. And the coordinate values of the focal point G are:

$$x_G = (x_E+x_I)/2;\ y_G = (y_E+y_I)/2 \tag{5}$$

Secondary wave inspection method: As to secondary wave inspection method, it can be changed to the primary wave inspection using the mirror of the weld, as shown in Fig. 5.

In Fig. 5, point g is the mirror of point G and point f is the mirror of point F. Point F is a point on the groove and is the midpoint of the detected layer. So, the equation of the incident ultrasonic beam can be expressed as Eq. 6:

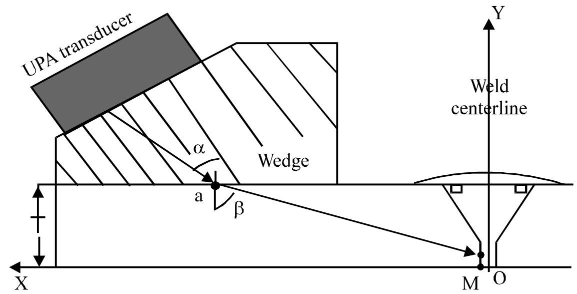

Fig. 4: Diagram for primary wave inspection

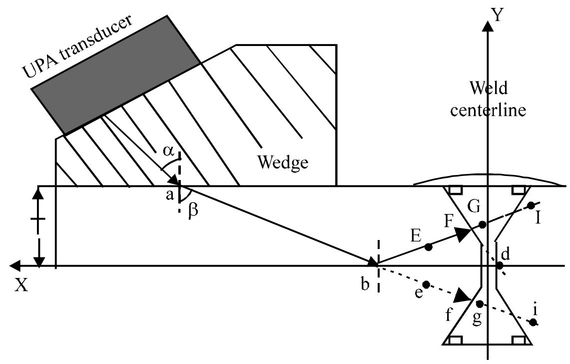

Fig. 5: Diagram for secondary wave inspection

$$y = \tan\beta\,(x-x_F)+y_F \tag{6}$$

Suppose the groove's extended line and the inner pipe wall intersect at point d. Its coordinate is $(x_d, 0)$, the equation of the groove is:

$$y = -\tan 45°\,(x-x_d) \tag{7}$$

Move the groove line to the positive X-axis by 3 mm:

$$y = -\tan 45°\,(x-x_d-3) \tag{8}$$

Combine Eq. 6 with Eq. 8, the coordinate values of point E in Fig. 2 (x_E, y_E), can be computed. Similarly, combine Eq. (6) with Eq. (4), the coordinate values of point I in Fig. 2 (x_F, y_F), can be computed too. The coordinate values of point g and then values of the focal point G can be computed.

Determine the range of the sound path: As the location of the weld and the UPA transducer is fixed and the height of the weld and the layer is known, the range of each inspection sound path can be computed based on the location of the focus point G and the geometry models presented in Fig. 4 and 5.

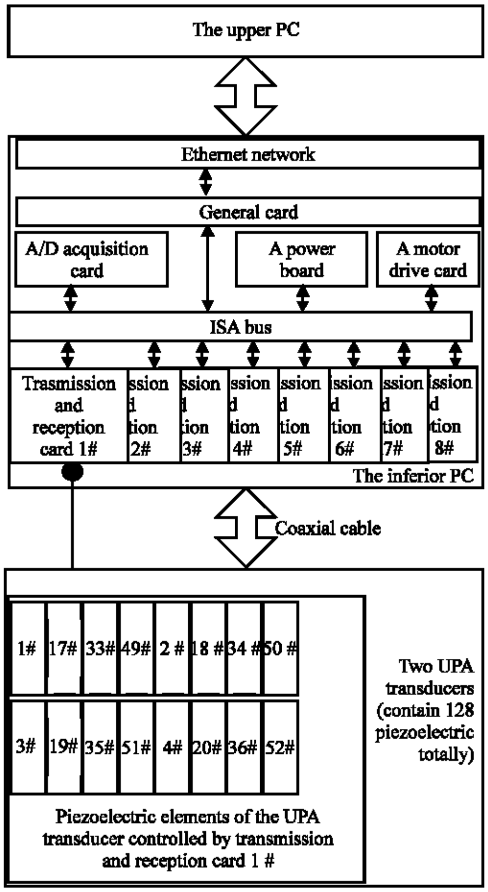

Fig. 6: Block diagram of the UPA inspection system

HARDWARE AND SOFTWARE DESIGNS OF THE DEVELOPED UPA SYSTEM

Keys of system hardware design: The whole system is mainly composed of an upper PC and an inferior PC, as Fig. 6 shows.

The upper PC and the inferior PC communicate with each other through Ethernet. This flexible combination mode makes the system become a portable system. The upper PC can be seen as the processing background for inspection and is responsible for setting parameters, generating the inspection schemes, displaying real-time echo waveforms and carrying out qualitative analysis of the collected flaw echo. The inferior PC can be seen as the inspection foreground, which excites transducers to emit ultrasound waves into the pipe wall, receive ultrasonic echoes and process the signal data before transmitted them to the upper PC.

The inferior PC is the core of the system and is made up of the general card, a motor drive card, 8 transmission and reception cards, a high speed A/D acquisition card and a power board, which are inserted in the PC's slots. The general card communicates with other cards through ISA bus. Two linear UPA transducers are connected with the inferior PC through the coaxial cables. Each transducer has 64 piezoelectric elements. Every transmission and reception card has the same structure and has the ability to control transmitting/receiving four ultrasonic beams at the same time. In Fig. 6, piezoelectric elements controlled by transmission and reception card 1# is exemplified. Others can be determined under this analogy. Every four elements are selected to form a group, such as 1, 17, 33 and 49# in Fig. 6, in which only one can work. Therefore, 16 elements of a UPA transducer can simultaneously work.

Before inspection, parameters, such as those computed above, can be entered on the upper PC. They and delay laws are then directly written into an FPGA on each transmission and reception card. Then, the hydraulic pump starts to spray coupling medium on the tested surface. Transducers move and inspect on a motor car which is controlled by the motor drive card. When transmission and reception cards receive the synchronization signal produced by the general card, they transmit waves and receive echo signals according to time sequences that have been already set. Then signals are filtered, amplified, digitized and stored in RAM. All signals are stored and are used to synthesize the total echo waveform under the delay law, which is based on the principle of wave interference. Signal delay is carried out by FPGAs and the analog delay lines on the transmission and reception cards. After the data of each signal are read out simultaneously, they are converted into analog signals correspondingly and then are sent to the general card, on which they are added into the total echo.

The total echo is then transmitted to a high speed A/D acquisition card, whose sampling rate is 100 MHZ, by the general card. These data are sent to the upper PC and are displayed. In addition, they can be stored for the following flaw quantitative or qualitative analysis.

The power card supplies various powers that are needed in the system.

Structure of system software design: System software is composed of upper-PC software and inferior-PC software. It can be divided into three main parts by function, as shown in Fig. 7.

The first part is the human-computer interaction software, which manages the input various parameters, establishes the inspection models and timing schemes, computes and stores the control parameters. This part software can be seen as preparation for the inspection.

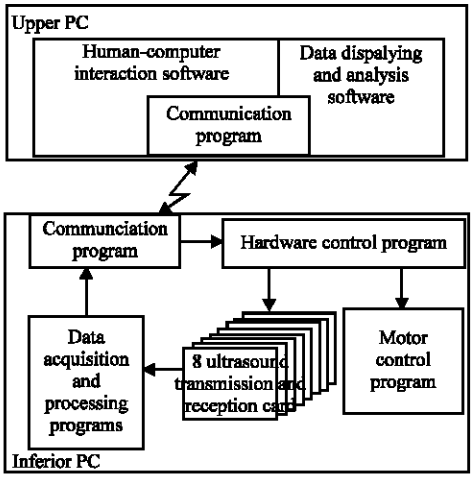

Fig. 7: Sketch of system software structure

The second part is the hardware control software, which can control corresponding hardware circuit according to calculated parameters.

The third part is the data displaying and analysis software, which can display collected echo waveform in A-scan, B-scan and C-scan modes and can indicate changes of signal amplitude and position by color change. The operator can estimate whether it is a flaw echo or even assess the size, position and character of the flaw further. This part software can be seen as follow-up processing after inspection.

EXPERIMENTS

One experiment was to validate deflection and focusing ability of system. It was carried out on a steel block with an angle of 30 degree between test surface and horizontal surface. As the ultrasonic wave travels at 3300 m s^{-1} in the steel, delay time of neighboring elements is 76 ns and the range of the sound path is 23.25 mm. Twelve signals were used to synthesize the total echo waveform and are shown in Fig. 8. The waveform, which is at point a, is the synchronization pulse. The waveform, which is at point b, is the interference signal. The waveform, which is at point c, is the synthesis echo. Its amplitude is much larger than that of the wave received by a single element. But if there is any control error exists under the delay laws, the ultrasonic energy will diverge and it is very difficult to synthesize a total echo. The experiment indicated that the system has good ability of beam deflecting and focusing.

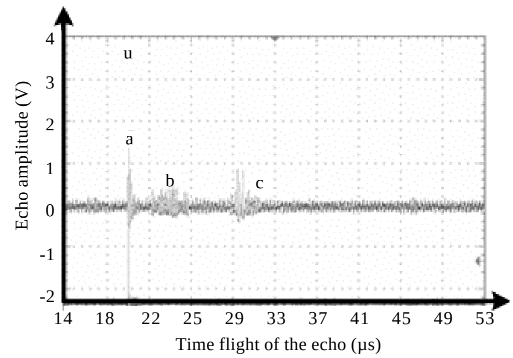

Fig. 8: Experiment result of synthesis waveform

Another experiment was carried out on a pipeline girth weld block. The diameter of the pipe is 1016 mm. Flaws of σ 2 mm are machined in the block. The moving step of the UPA transducers can be set as 1 or 2.5 mm. Correspondingly, time to inspect the whole weld is 5.5 min or 2.2 min. The system increases the inspection velocity and it has good flaw detection and locating abilities.

CONCLUSION

A developed ultrasonic phased array system used for automatic flaw detection of pipeline girth weld is introduced. The inspection model is established and detection principles are described based on geometrical acoustics approximation. The hardware construction and software system are introduced. Experiment results prove the designed system has good beam deflection and focusing capabilities and has high inspection efficiency. In the future, we are devoted to make the instrument more compact and develop new uses of the system, such as flaw detection of aircraft composite material.

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REFERENCES

Barandiaran, J.M., G.V. Kurlyandskaya, D. de Cos, A. Gaecia-Arribas and V.O. Vas'kovskiy, 2009. Multilayer magnetoimpedance sensor for nondestructive testing. Sensor Lett., 7: 374-377.

Calmon, P., A. Lhemery, I. Lecaeur-Taibi, R. Raillon and L. Paradis, 1998. Models for the computation of ultrasonic fields and their interaction with defects in realistic NDT configurations. Nucl. Eng. Des., 180: 271-283.

Chen, S.L., X.L. Zhan and S.J. Jin, 2006. Design of ultrasonic phased array system on pipeline girth weld inspection. J. Tianjin Univ., 39: 235-239.

Dennis, M., C. Latiolais and B. Thigpen, 2007. Weld overlay examination using ultrasonic phased array technology. Proceedings of 6th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components, October 8-10, 2007, Budapest, Hungary.

Gengembre, N. and A. Lhemery, 1999. Calculation of Wideband Ultrasonic Fields Radiated by Water-Coupled Transducers into Heterogeneous Media. In: Review of Progress in Quantitative Nondestructive Evaluation Volume 18, Thompson, D.O. and D.E. Chimenti (Eds.). Springer-Verlag, USA., pp: 1131-1138.

Li, J., X.L. Zhan, J.C. Zhuge, Z.M. Zeng and S.J. Jin, 2008. Research on automatic flaw classification and feature extraction of ultrasonic testing. Key Eng. Mater., 381-382: 631-634.

Lupien, V. and F. Cancre, 2001. Ultrasonic phased array inspection of titanium billets. Proceedings of the Review of Progress in Quantitative Nondestructive Evaluation, Volume 20, July 16-20, 2000, Ames, Iowa USA., pp: 919-926.

Mahaut, S., S. Chatillon, R. Raillon-Picot and P. Calmon, 2003. Simulation and application of dynamic inspection modes using ultrasonic phased arrays. Proceedings of the 31th Annual Review of Progress in Quantitative Nondestructive Evaluation, July 27-August 1, 2003, Green Bay, Wisconsin, USA., pp: 777-784.

Rider, H., M. Spies, R. Licht and P. Kreier, 2003. Development and optimization of a rotating phased array inspection system. Proceedings of the 30th Annual Review of Progress in Quantitative Nondestructive Evaluation, Volume 22, July 14-19, 2002, Bellingham, Washington, USA., pp: 785-792.

Song, S.J. H.J. Kim and H. Cho, 2002. Development of an intelligent system for ultrasonic fiaw classification in weldments. Nucl. Eng. Des., 212: 307-320.

Thomas, V., P.Y. Joubert and E. Vourch, 2009. Study for the design of an eddy current array probe for the imaging of aeronautical fastener holes. Sensor Lett., 7: 460-465.

Utrata, D. and R. Clark, 2002. Groundwork for Rail Flaw Detection Using Ultrasonic Phased Array Inspection. Proceedings of the Review of Progress in Quantitative Nondestructive Evaluation, Volume 22, July 14-19, 2002, Bellingham, Washington (USA)., pp: 799-805.