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CIRCUMFERENTIAL SCANNING IMAGING OF TANK FLOORS USING ULTRASONIC GUIDED WAVES

Jianjun Wu[1]*, Zhifeng Tang[2], Fuzai Lv[1]
1. State Key Laboratory of Fluid Power and Mechatronic Systems, School of Mechanical Engineering, Zhejiang University.
Hangzhou, China

Keji Yang[1]
2. Institute of Advanced Digital Technologies and Instrumentation, School of Biomedical Engineering and Instrument Science, Zhejiang University.
Hangzhou, China

ABSTRACT

As indispensable parts of the tanks for oil and chemical storage and transportation, the tank floors have stringent nondestructive testing requirements owing to their severe operating conditions. In this article, a synthetic aperture focusing technology method is proposed for the circumferential scanning of the tank floor outside the tank using ultrasonic guided waves. The magnetostrictive patch transducer (MPT) is designed and manufactured for the generation and receiving of the SH0 mode. Based on the exploding reflector model (ERM), the relationships between guided wave fields at different radii of polar coordinates are derived in the frequency domain. The defect spot is focused when the sound field is calculated at the radius of the defect. Experimental validations are performed for the defect inspection in an iron plate. The angular bandwidth of the defect spot is used as an index for the angular resolution. The results of the proposed method show significant improvement compared to those obtained by the B-scan method, and it is found to be superior to the conventional method—named delay and sum (DAS) in both angular resolution and calculation efficiency.

Keywords: SH0 mode; circumferential scanning; synthetic aperture focusing; exploding reflector model

1. INTRODUCTION

Tanks are essential facilities for the storage and transportation of petroleum products. Because of the harsh working conditions and corrosive storage materials, the structural integrity failure of the tanks may occur, leading to catastrophic accidents[1]. Thus, tanks require stringent inspection for their long-term and high-level safety. Tank floors are key areas in the overhauls of the tanks which contain the majority of the defects[2]. The most common non-destructive testing technologies for tank floors based on flux leakage[3] and ultrasonics[4] are limited for the low working efficiency of testing “step by step.” With the sound emission technology, useful information is difficult to extract because of the low signal-to-noise ratios, and the localization of the damage is dissatisfactory with a limited number of transducers[5]. Therefore, it is urgent and highly desirable to develop new methods for testing tank floors in service.

Ultrasonic guided wave methods have been proven to have tremendous potential in the rapid inspections of structures with long and slender dimensions such as pipes[6], plates[7], and rails[8]. Guided wave scanning is an effective method for plate inspection. As shown in Figure 1, the tank floor in service can be evaluated with one transducer moving along the edge outside the tank. The spots of the defects in the image of the original signals (i.e., the B-scan image in this study) have long lateral trailing because of the expansion of the sound fields in the plates. To improve the lateral resolution, the synthetic aperture focusing technique (SAFT) is developed. The traditional method of SAFT is called delay and sum (DAS)[9]. This method is theoretically applicable for arbitrary scanning paths of the transducer. However, the method is carried out in the time domain with poor computational efficiency, and residual trailing exists in the image. Another method of SAFT is proposed based on sound field migration in the frequency domain, providing better computational efficiency as well as imaging quality compared with the DAS method [10]. However, the sound field migration of this method is deduced in the Cartesian coordinate system, which can only manage signals acquired by the transducer moving along a straight path. The paths of the transducer for the scanning of the tank floors are circular, making this method inapplicable. Efficient methods of SAFT for guided wave-based circumferential scanning have not been seen yet.

In this paper, a method of SAFT for circumferential scanning (CSAFT) is proposed. In Section 2, the shear horizontal mode in the plates, named SH0, is selected for inspection, and the imaging method is developed based on sound field migration in the polar coordinate systems. Experimental verifications are carried out in an iron plate in Section 3, and conclusions follow in Section 4.

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[*] Contact author: 11425023@zju.edu.cn

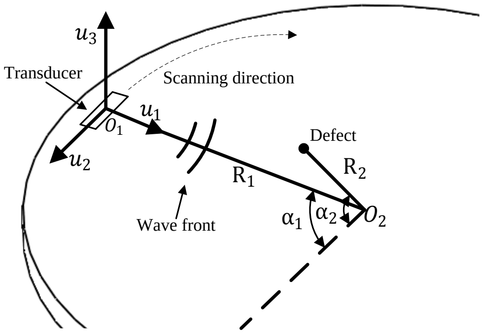


FIGURE 1: DIAGRAM OF THE CIRCUMFERENTIAL SCANNING USING GUIDED WAVES.

2. METHOD

In Figure 1, the polar coordinate O_2 is constructed without considering the direction along the thickness, in which the displacement of the SH0 mode is uniform. The wave equation in a polar coordinate can be written as[11]:

$$\left[\frac{\partial^2}{\partial R^2}+\frac{1}{R}\frac{\partial}{\partial R}+\frac{1}{R^2}\frac{\partial^2}{\partial \alpha^2}-\frac{1}{\hat{c}_g}\frac{\partial^2}{\partial t^2}\right]p(R,\alpha,t)=0 \tag{1}$$

where $p(R,\alpha,t)$ is the wave field of the point (R,α)at time t, which can be written in the form of an inverse Fourier transform:

$$p(R,\alpha,t)=\int \boldsymbol{P}(R,k_\alpha,\omega)e^{j(k_\alpha\alpha+\omega t)}\,dk_\alpha d\omega \tag{2}$$

where k_α and ω are the angular wave number and angular frequency, respectively. $P(R,k_\alpha,\omega)$ is the two-dimensional spectrum of $p(R,\alpha,t)$, which can be solved by substituting Eq. (2) into Eq. (1):

$$\boldsymbol{P}(R,k_\alpha,\omega)=A_{k_\alpha}H_{k_\alpha}^{(1)}(k_R R)+B_{k_\alpha}H_{k_\alpha}^{(2)}(k_R R) \tag{3}$$

where $A_{k_\alpha}H_{k_\alpha}^{(1)}(k_R R)$ and $B_{k_\alpha}H_{k_\alpha}^{(2)}(k_R R)$ denote the guided wave propagating away from the original point and towards the original point, respectively. $H_{k_\alpha}^{(p)}(p=1,2)$ is the pth kind of Hank function of the order k_α, k_R is the wave number along the radius.

The guided waves generated by the defect propagate away from the original point to the transducer; thus, the transfer function for the guided wave fields at different radii can be derived as

$$\boldsymbol{P}(R-\Delta R,k_\alpha,\omega)=\boldsymbol{P}(R,k_\alpha,\omega)\frac{H_{k_\alpha}^{(1)}(k_R(R-\Delta R))}{H_{k_\alpha}^{(1)}(k_R R)} \tag{4}$$

Eq. (4) can be simplified using the Rayleigh–Sommerfeld diffraction formula[12]:

$$\boldsymbol{P}(R-\Delta R,k_\alpha,\omega)\approx\boldsymbol{P}(R,k_\alpha,\omega)\sqrt{\frac{R-\Delta R}{R}}e^{-i\Delta R\sqrt{\frac{\omega^2}{\hat{c}_g{}^2}-\frac{k_\alpha{}^2}{R(R-\Delta R)}}} \tag{5}$$

This function is valid if $\cos(\alpha_1-\alpha_2)$ is approximately equal to $1-\frac{(\alpha_1-\alpha_2)^2}{2}$, With a given step ΔR, the two-dimensional spectrums of the guided wave fields at the radii $(R-\Delta R, R-2\Delta R, R-3\Delta R, \ldots, R-m\Delta R)$ can be derived with those collected by the transducer at the radius R with Eq. (5). The focused image can be obtained with the inverse Fourier transforms of the guided wave fields at different radii.

3. RESULTS AND DISCUSSION

Experiments were carried out to verify the proposed method. The equipment named the magnetostrictive guided wave detector was used in the experiments, which has the ability to work in the pulse- echo mode under the control of the computer. The coils in the magnetostrictive patch transducer (MPT) were processed as a flexible printed circuit (FPC), and the material of the magnetostrictive strip is Fe-Co alloy. The circumferential scanning is shown in Fig. 2. An iron mass scatterer with the additional cross-sectional area of 100 mm^2 was coupled on the iron plate at the radius 0.825 m from the original point O_2 and 12° from the start position of the scanning as the artificial defect using the epoxy coupling agent. The MPT moved around the original point O_2 at a radius of 1.3 m with the angular step 1.5° to scan the fan area with an angle of 45°. The MPT was used both as an actuator and sensor. The excitation signal is a sinusoidal signal of four cycles filtered by the Hanning window at the frequency 128 kHz. Thirty-one signals were collected in the scanning. The coupling agent used for the coupling between the transducer and the plate is the shear wave coupler.

The results of the three methods are shown in Fig. 3. The amplitudes of the images are all normalized between 0 and 1. The estimated peak value of the environmental noise is less than 0.12. The defect spot of the B-scan method in Fig. 3(a) has large trailing, as expected, which may lower the angular resolution. By the DAS method, the trailing around the defect spot is eliminated, as in Fig. 3(b); however, some trailing occurs in other regions of the image, which have similar amplitudes to the defect spot, becoming a severe distraction in defect recognition. In Fig. 3(c), the defect spot is improved in the angular direction despite some residual trailing. It can be observed that the defect spot by the DAS method is less obvious than that by the B-scan method, whereas the defect spot by the CSAFT method is much more recognizable. Quantitative comparisons of the defect spot by three methods are listed in Tab. 1. The position of the defect is denoted by the peak of the spot, and the angular bandwidth is as the largest angle range of the region in which the amplitudes are no less than half of the peak. The reflection waves from the boundaries are taken as references to show the significance of the defect spots by the three methods. The peak value ratio between the defect and the boundaries by the proposed method is 580% larger than that by the B-scan method, whereas the result with the DAS method does not give any improvement. Apart from the largest significance of the defect, the results by the CSAFT method have the least error in the angular localization and smallest angular bandwidth of the defect compared with the other two methods.

TABLE 1: DEFECT ESTIMATION BY THE THREE METHODS.

Name		**B-Scan**	**DAS**	**CSAFT**
Position	Angle (°)	13.5	12.5	12
	Distance (m)	0.823	0.815	0.821
Angular bandwidth (°)		4.5	3.8	2.0
Peak value ratio (defect/boundaries)		0.25	0.14	1.71

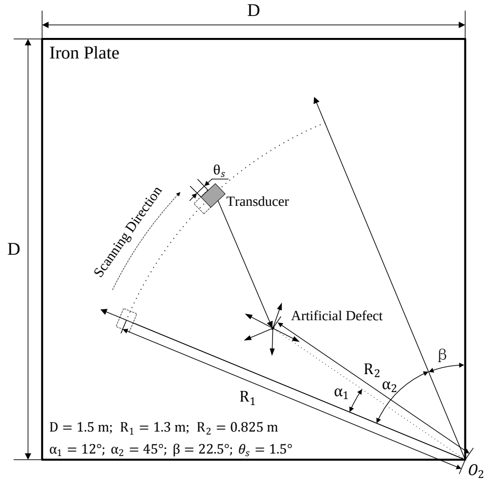
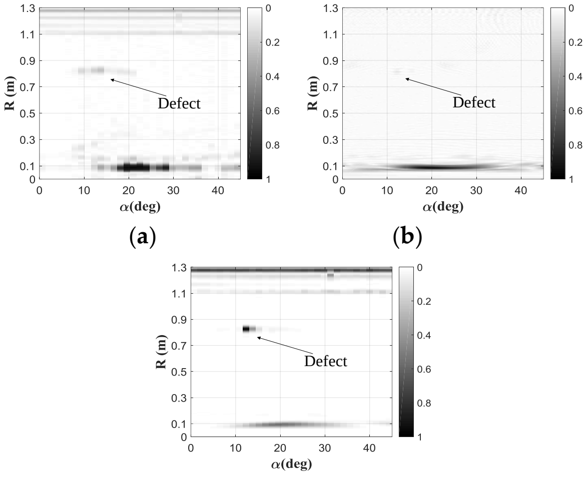


FIGURE 2: CIRCUMFERENTIAL SCANNING IN THE IRON PLATE USING GUIDED WAVES.



(a)

(b)

(c)

FIGURE 3: EXPERIMENTAL IMAGES BY THE THREE METHODS: (a) B-SCAN; (b) DAS; (c) CSAFT.

4. CONCLUSION

A synthetic aperture focusing technique method is proposed for circumferential scanning of plates using guided waves. The SH0 mode is selected for the inspection. The proposed imaging method is based on the exploding reflector model (ERM) by solving the wave equation in a polar coordinate system and deriving the relationships between guided wave fields at different radii in the frequency domain. Experimental validation was successfully performed for the circumferential scanning of the defects in an iron plate. By the proposed method, the peak amplitude of the defect spot can be increased, providing a significant improvement for the defect spot compared with those by the B-scan and DAS methods. For future study, actual oil tank floors installed with accessories will be examined. Defects of different kinds, sizes, and numbers will be inflicted on the tank floor, which will be tested when the oil tank is empty and filled with different kinds of liquids in the field.

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