

## Article

## Ultrasonic Guided Wave-Based Circumferential Scanning of Plates Using a Synthetic Aperture Focusing Technique

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# Featured Application: Ultrasonic guided wave scanning of plates with the transducer moving along a circumferential path outside the tested area.

**Abstract:** Tanks are essential facilities for oil and chemical storage and transportation. As indispensable parts, 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 from the edge outside the tank using ultrasonic guided waves. The zeroth shear horizontal (SH0) mode is selected as an ideal candidate for plate inspection, and the magnetostrictive sandwich transducer (MST) 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. Numerical and 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. Thousands of tanks may be in service at the same time in one oil depot. Because of the harsh working conditions and corrosive storage materials, various kinds of defects, which are hidden hazards, may occur in the tanks. The structural integrity failure of the tanks may cause catastrophic accidents such as environmental pollution and explosions [1]. Thus, tanks require stringent inspection for their long-term and high-level safety. Tank floors are indispensable parts of the tanks. It is found that 80% of corrosion, which makes up the majority of the defects in the tanks, occur in the tank floors, making them key areas in the overhauls [2]. The most common non-destructive testing technologies for tank floors based on flux leakage [3–5] and ultrasonics [6] are limited for the low working efficiency of testing "step by step." The tanks must stop their service and be emptied before the inspection.



The cost and time for the overhaul of the tank floors can amount to hundreds of thousands of dollars and dozens of days. Recently, a technology based on sound emission has been introduced for the structural health monitoring of tanks in service [7–9]. Elastic waves caused by the crack growth and liquid leakage are collected and analyzed for the damage detection. However, useful information is difficult to extract from the signals because of the low signal-to-noise ratios, and the localization of the damage is dissatisfactory with a limited number of transducers. 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 [10,11], plates [12–14], and rails [15]. For the inspection of plate structures such as tank floors, large areas can be inspected at the same time with one transducer using guided waves. Structural health monitoring based on guided waves has been proposed for years. The transducers are permanently installed on the plate around the monitored region. The transducers work as actuators, in turn, and all the others are sensors. The received signals are compared with those acquired when the integrity of the tank floors was confirmed. The coefficients to evaluate the signal changes can be amplitude differences of the direct waves [16] and the variations of the whole signals, named the signal difference coefficient (SDC) [17–21]. Different imaging methods are introduced for guided wave monitoring, such as the filtered back-projection method (FBP) [22], the interpolated FBP (IFBP) [23], the algebraic reconstruction technique (ART) [24], and the probabilistic reconstruction algorithm (PRA) [25], which are all basically drawn from computational tomography (CT). Recently, a method called full waveform inversion (FWI) has been introduced for guided wave monitoring [26,27]. Guided waves with high frequency dispersions are used, and the model of the monitored area is constructed and revised in the frequency domain to match the signals acquired by the model and those collected in the tests. This method performs well in corrosion imaging. However, it should be mentioned that numerous transducers are needed for high sensitivities and localization accuracies in guided wave monitoring, and multiple iterations are required in these methods for high resolutions, which may be time-consuming for large amounts of data.

Guided wave scanning is an alternative 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 [28]. 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) [29,30]. The wave packets of the defect in different signals can be superposed in the image with the distances between the defect and the transducer locations in the scanning. 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 [31–33]. 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 sound field of the magnetostrictive sandwich transducer (MST) used in this study is calculated; the imaging method is developed based on sound field migration in the polar coordinate systems. In Section 3, the proposed method is verified by numerical simulations and compared with other two methods, the B-scan and DAS methods, for different affecting factors. Experimental verifications are carried out in an iron plate in Section 4 and conclusions follow in Section 5.



Figure 1. The diagram of the circumferential scanning using guided waves.

#### 2. Method

#### 2.1. Shear Horizontal Waves

As shown in Figure 1, in circumferential scanning using guided waves, the transducer to generate and receive guided waves moves around the origin point  $O_2$  at the radius  $R_1$ . The wave front of the incident guided waves expands during the propagation. The reflection waves are generated if the defects are covered by the wave front of the incident waves. The flight time and peak values of the reflection waves are used to evaluate the location and size of the defects, respectively.

Shear horizontal waves (SH waves) and Lamb waves are two kinds of mechanical waves propagating in a solid plate. For waves propagating along the direction  $u_1$  as in Figure 1, displacements along the direction  $u_3$  occur in Lamb waves, which are perpendicular to the plane of the plate, but the displacements of SH waves are along the direction  $u_2$  within the plane of the plate. Considering that the tank floors in service are in contact with liquids (storage materials, such as different kinds of oil) and that the attenuation of shear waves in liquids is much higher than that of longitudinal waves, SH waves may be better candidates for an inspection with less energy leakage. Researches of torsional waves in pipes filled with liquids and bars immersed in liquids can be found in [34,35], respectively, as references. Quantitative comparisons of the SH and Lamb waves will be carried out further under the conditions of different kinds of petroleum products with various volumes. And affecting factors such as the curvatures of the tank floors caused by the gravities of the stored materials and sludge deposition under the tank floors will be investigated as well. The SH waves are hardly affected by liquids [36]. Therefore, in this study, with the purpose of verification of the proposed imaging method, the model is simplified as an isotropic plate with the thickness *d* without contact of liquids, the dispersion equation of SH waves can be expressed as [37]

$$\frac{\omega^2}{c_T^2} - \frac{\omega^2}{c_p^2} = \left(\frac{n\pi}{d}\right)^2 \tag{1}$$

$$c_T = \sqrt{\frac{E}{2(1+\mu)\rho}} \tag{2}$$

where  $\omega = 2\pi f$ , f,  $c_p$ , and n are frequency, phase velocity, and order, respectively, and  $c_T$  is the fundamental shear wave velocity, which is determined by mechanical properties of the plate such as density  $\rho$ , Young's modulus E, and Poisson's ratio  $\mu$ . Combining the definition of the wave number  $k = \frac{\omega}{c_p}$ , the group velocity  $c_g = \frac{d\omega}{dk}$ , and Equations (1) and (2), dispersion curves of phase velocity and group velocity can be calculated:

$$c_p(fd) = 2c_T \frac{fd}{\sqrt{(2fd)^2 - (nc_T)^2}}$$
(3)

$$c_g(fd) = c_T \sqrt{1 - \frac{(n/2)^2}{(fd/c_T)^2}}$$
(4)

where *fd* is the frequency-thickness product. Dispersion curves of phase velocity and group velocity for the iron plates with mechanical properties  $\rho = 7850 \text{ kg/m}^3$ , E = 210 GPa, and  $\mu = 0.3$  are shown in Figure 2. All the modes are named by their orders, and for the wave mode SH*n*, a frequency lower limit exists when *n* is no less than 1, which is called the cutoff frequency.

$$(fd)_n = \frac{nc_T}{2} \tag{5}$$

The thickness of the tank floor commonly used is between 6 and 19 mm [38]. In this study, the thickness *d* of the iron plate used for the verification in numerical simulations and experiments is selected as 4 mm for the easy operations in the laboratory. The wave structures of SH0, SH1, SH2, and SH3 modes in the direction  $u_2$  are shown in Figure 3. It can be observed that the pure SH0 mode without dispersion can be generated when the excitation frequency is lower than the cutoff frequency of the SH1 mode. Compared with high order modes (SH1, SH2 and SH3), the wave structure of the SH0 mode is uniform along the thickness, giving the same detectability for the defects within the plates and on the surfaces. With these advantages, the SH0 mode is selected for inspection in this study.



Figure 2. Dispersion curves of iron plates: (a) phase velocity curves; (b) group velocity curves.



**Figure 3.** Wave structures of shear horizontal (SH) modes in the main vibration direction  $u_2$ : (a) SH0; (b) SH1; (c) SH2; (d) SH3.

#### 2.2. The Sound Field of the Transducer

Piezoelectric and magnetostrictive transducers are commonly used in guided wave generation. Because of the differences in the principles of energy conversion and transducer structures, piezoelectric transducers are good at out-of-plane displacement generation, while magnetostrictive transducers have advantages in in-plane displacement generation. The magnetostrictive effect of the ferromagnetic materials is made use of in the wave generation, and the inverse magnetostrictive effect works in receiving waves. Details of the working principles of this kind of transducer can be found in [39].

The transducer used in this study is named the magnetostrictive sandwich transducer (MST), with a structure shown in Figure 4. The magnetostrictive strip is the main component for energy conversion in both wave generation and receiving, with the residual magnetism along the direction  $u_2$  by pre-magnetization. The soft magnet is used to reduce the magnetic resistance of the dynamic magnetic fields, improving energy conversion efficiency. There are two coils in the MST to generate and sense the dynamic magnetic fields. Coil 1 is  $\lambda/4$  ahead of Coil 2 in the direction  $u_1$ .  $\lambda$  is the wavelength of the guided wave. The burst signals in Coil 1 and Coil 2 have a phase difference of  $\pi/2$ . Wires in the working region of the MST are distributed with equal intervals and numbered with wn from 1 to 40. The current direction  $C_d$  and initial phase  $C_{iv}$  of all the wires are listed in Table 1.

| Name         | Value   |      |         |       |         |         |         |       |
|--------------|---------|------|---------|-------|---------|---------|---------|-------|
| wn           | 1~5     | 6~10 | 11~15   | 16~20 | 21~25   | 26~30   | 31~35   | 36~40 |
| $C_d(wn)$    | -1      | -1   | 1       | 1     | 22121   | $^{-1}$ | 1       | 1     |
| $C_{ip}(wn)$ | $\pi/2$ | 0    | $\pi/2$ | 0     | $\pi/2$ | 0       | $\pi/2$ | 0     |

**Table 1.** The current direction  $C_d$  and initial phase  $C_{ip}$  for each wire.

Each wire in the working region can be regarded as a line sound source, and the sound field  $S_{wn}$  for the *wn*th wire can be derived as [40]

$$S_{wn}(r',\theta',t) \approx S_m L \sqrt{\frac{2}{\pi k r'}} \left[ \frac{\sin\left(\frac{1}{2}kL\sin(\theta')\right)}{\frac{1}{2}kL\sin(\theta')} \right] e^{j(kr'-\omega t + \frac{\pi}{4})}$$
(6)

where the wave number  $k = \frac{2\pi}{\lambda}$ ,  $S_m$  is a constant coefficient, and r' and  $\theta'$  denote the relative position between the *wn*th wire and the receiving point as in Figure 4. *L* is half the length of the working region. Equation (6) is valid when  $r' \gg L$ . The sound field of the MST can be calculated as the sound field combinations of all wires:

$$S \approx \sum_{wn=1}^{40} C_d(wn) S_{wn} e^{jC_{ip}(wn)}.$$
(7)

As mentioned in Section 2.1, the thickness of the iron plate used in this study is 4 mm. The group velocity  $c_g$  and phase velocity  $c_p$  of the SH0 mode are both 3208 m/s, as in Figure 2. The wave length  $\lambda$  of the SH0 mode is 25.1 mm as the width of the magnetostrictive strip available is 50.2 mm. Thus, the main frequency f of the designed MST is 128 kHz, which is below the cutoff frequency of the SH1 mode (401 kHz). It should be noted that, as mentioned above, the main frequency of the transducer should be determined with the consideration of both detection sensitivities and testing ranges in field tests. The normalized sound fields of the MSTs with different lengths are shown in Figure 5. The waves are controlled to propagate in one direction, and the amplitudes of the main lobes in the sound fields are much larger than those of the side lobes. It can also be seen that the widths of the main lobes decrease with the increase in the lengths of the MSTs. The divergence angle  $\theta_d$ , defined as the largest angle at which the amplitudes are no less than half of the largest amplitude, is used to denote the width of the main lobes. The relationship between the divergence angles and the lengths of the MSTs from 2 mm to 150 mm are shown in Figure 6.



Figure 4. The structure of the magnetostrictive sandwich transducer (MST).



**Figure 5.** The sound fields and divergence angles of the MSTs with different lengths: (a) 2L = 30 mm; (b) 2L = 50 mm; (c) 2L = 70 mm; (d) 2L = 90 mm.



Figure 6. The relationship between the divergence angles of the main lobes and the lengths of the MSTs.

#### 2.3. Synthetic Focusing Imaging for Circumferential Scanning

The whole procedure of the inspection with the transducer at one location can be described as follows:

- Step 1: The transducer generates guided waves towards the defect;
- Step 2: The defect is motivated and generates scattering waves;

Step 3: Parts of the scattering waves are received by the transducer.

When the defect is motivated by the incident pure SH0 waves, other modes may exist in the scatter waves because of the mode conversions. These modes are not dominant and they can hardly be detected by the MST in the experiments. Therefore, the mode conversion is not considered in this study. Because of the reciprocity of the sound field and the constant group velocity  $c_g$  of the SH0 mode, Steps 1 and 3 can be described in the same way. The defect can be regarded as a sound source that generates guided waves at time t = 0; then, the guided waves propagate to the transducer. Since the sonic path in this assumption is half of the actual path, the group velocity  $\hat{c}_g$  is taken as half of the actual value  $c_g$  to maintain the flight time of the defect, i.e.,  $\hat{c}_g = c_g/2$ . The above equivalent model is also called the exploding reflector model (ERM) [41]. As in Figure 1, the guided waves generated by the defect at the radius  $R_2$  expand before being received by the transducer moving at the radius  $R_1$ . If  $R_1$  is equal to  $R_2$ , there will be no expansion of the guided waves, which are simply generated from the defect at the time t = 0. An optimal lateral resolution can be obtained from the guided wave fields at the radius  $R_2$  with the time term  $e^{-i\omega t}|_{t=0} = 1$ . The relationships of the guided wave fields at different radii can be deduced as follows.

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 [42]:

$$\left[\frac{\partial^2}{\partial R^2} + \frac{1}{R}\frac{\partial}{\partial R} + \frac{1}{R^2}\frac{\partial^2}{\partial \alpha^2} - \frac{1}{\hat{c}_g}\frac{\partial^2}{\partial t^2}\right]p(R,\alpha,t) = 0$$
(8)

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

$$p(R,\alpha,t) = \int P(R, k_{\alpha}, \omega) e^{j(k_{\alpha}\alpha + \omega t)} dk_{\alpha} d\omega$$
(9)

where  $k_{\alpha}$  and  $\omega$  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 Equations (9) into (8):

$$P(R, k_{\alpha}, \omega) = A_{k_{\alpha}} H_{k_{\alpha}}^{(1)}(k_{R}R) + B_{k_{\alpha}} H_{k_{\alpha}}^{(2)}(k_{R}R)$$
(10)

where  $A_{k_{\alpha}}H_{k_{\alpha}}^{(1)}(k_RR)$  and  $B_{k_{\alpha}}H_{k_{\alpha}}^{(2)}(k_RR)$  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 *p*th kind of Hank function of the order  $k_{\alpha} k_R$  is the wave number along the radius.

$$k_{R} = \begin{cases} \sqrt{\frac{\omega^{2}}{\hat{c}_{g}^{2}} - k_{\alpha}^{2}}, \sqrt{\frac{\omega^{2}}{\hat{c}_{g}^{2}} - k_{\alpha}^{2}} \ge 0\\ 0, \sqrt{\frac{\omega^{2}}{\hat{c}_{g}^{2}} - k_{\alpha}^{2}} < 0 \end{cases}$$
(11)

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

$$P(R - \Delta R, k_{\alpha}, \omega) = P(R, k_{\alpha}, \omega) \frac{H_{k_{\alpha}}^{(1)}(k_{R}(R - \Delta R))}{H_{k_{\alpha}}^{(1)}(k_{R}R)}$$
(12)

Equation (12) can be simplified using the Rayleigh–Sommerfeld diffraction formula [43]:

$$P(R - \Delta R, k_{\alpha}, \omega) \approx P(R, k_{\alpha}, \omega) \sqrt{\frac{R - \Delta R}{R}} e^{-i\Delta R \sqrt{\frac{\omega^2}{\tilde{c}g^2} - \frac{k_{\alpha}^2}{R(R - \Delta R)}}}$$
(13)

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  $\Delta R$ , the two-dimensional spectrums of the guided wave fields at the radii  $(R - \Delta R, R - 2\Delta R, R - 3\Delta R, ..., R - m\Delta R)$  can be derived with those collected by the transducer at the radius *R* with Equation (13). The focused image can be obtained with the inverse Fourier transforms of the guided wave fields at different radii.

The main steps of the proposed algorithm are described below:

- Step 1: A data matrix is constructed with scanning signals collected by the transducer at the radius  $R_1$  as column vectors.
- Step 2: The two-dimensional Fourier transform of the data matrix is performed to obtain two-dimensional spectrum  $P(R_1, k_{\alpha}, \omega)$ .
- Step 3: The length  $\Delta R$  and number *m* of the radius step are determined; The imaging range of the radius is between  $R_1$  and  $R_1 m\Delta R$ . The counter *q* is 1.
- Step 4: Two-dimensional spectrum  $P(R_1 q\Delta R, k_\alpha, \omega)$  at the radius  $R_1 q\Delta R$  is calculated with Equation (13). Row vector  $R_v(R_1 q\Delta R)$  is constructed with the summation of each column of the two-dimensional spectrum.
- Step 5: The inverse Fourier transform of Row vector  $R_v(R_1 q\Delta R)$  is performed. The result is the *q*th row of the image matrix. The counter *q* is increased by one.
- Step 6: Steps 4 and 5 are executed repeatedly until *q* is larger than *m*. The image matrix is outputted at last.

The attainable angular resolution can be calculated with the similar derivation as in [41]. If the divergence angle  $\theta_d$  is used to determine the angular coverage of the transducer, the thresholds of the angular wave number  $k_{\alpha}$  are  $-\frac{4\pi}{\lambda}R_1\sin\left(\frac{\theta_d}{2}\right)$  and  $\frac{4\pi}{\lambda}R_1\sin\left(\frac{\theta_d}{2}\right)$ , thus, the bandwidth of the angular wave number  $\Delta k_{\alpha}$  is  $\frac{2\pi}{\lambda}R_1\sin\left(\frac{\theta_d}{2}\right)$ . Attainable angular resolution  $\theta_{ar}$  can be calculated as follows:

$$\theta_{ar} = \frac{2\pi}{\Delta k_{\alpha}} = \frac{\lambda}{R_1 \sin\left(\frac{\theta_d}{2}\right)} \tag{14}$$

For the SH0 mode at a certain frequency, the wave length is constant, and the attainable angular resolutions are affected by the divergence angles, which are determined by the structures of the transducers.

The proposed method is applicable for the circumferential scanning of isotropic plates with non-dispersive modes. For dispersive modes like the Lamb waves and higher-order SH waves, dispersion compensation can be achieved with the relationships between the group velocities  $\hat{c}_g$  and the angular frequencies  $\omega$  from the group velocity curves in the calculations of two-dimensional spectrums using Equation (13). For anisotropic plates, the wave equation in Equation (8) is not suitable, since the wave propagations along different directions are not the same. The proposed method may be not applicable.

The detection ability of the circumferential scanning is determined by multiple reasons such as the excitation frequency and the characteristics of the defects (shapes and sizes). With the increments of the excitation frequencies, the detection sensitivities of the waves increase while the propagation distances decrease. The shapes of the defects affect the mode conversions and propagations of the scattering waves. Details can be found in [44].

#### 3. Numerical Simulation and Verification

#### 3.1. Simulation Setup

For simplification, only Steps 2 and 3 in Section 2.3 are carried out in the simulation. As in Figure 7, the side length of the iron plate is 1.5 m; the thickness and material properties are the same as in Section 2.1. The original point  $O_2$  is set in the vertex of the lower right corner; the defect is 0.825 m from  $O_2$  with a size of 1 × 10 mm, and the angular position  $\alpha_1$  is 10°. The defect is motivated with a tone-burst signal, which is acquired by filtering a sinusoidal signal of multiple cycles with a Hanning window, as in Figure 8. The main frequency is 128 kHz. With the angular step  $\theta_s$  of 0.5°, 91 receiving points are set at the radius 1.3 m, which are marked from RP1 to RP91. The MST is always towards the original point during the signal being received from RP1 to RP91. The sound field of the MST for receiving is the same as that for generation, and so the signals collected at these receiving points are modulated by the sound field of the MST to construct the B-scan image.



Figure 7. The diagram of the numerical model.



**Figure 8.** The excitation signals with different cycles and their amplitude spectrums: (**a**) three cycles; (**b**) five cycles; (**c**) seven cycles; (**d**) nine cycles. The half-decline frequency bandwidth of the signals is marked.

#### 3.2. Method Comparison and Factor Analysis

The results of the proposed synthetic aperture focusing technology method for circumferential scanning (CSAFT) are compared with the B-scan image and the results by the DAS method [29]. The sound field of the MST with the length 2L = 70 mm is used to modulate the signals from the simulation. The time signals are turned into distance signals with the group velocity  $\hat{c}_g$  by  $R = t \times \hat{c}_g$ ; all the distance signals are stacked to become the B-scan image in the order of the angle positions of the receiving points. By the DAS method, the image region is first divided into pixels; then, the flight time of each pixel is calculated with the group velocity and the distance between the pixel and the transducer in the scanning. The amplitude of each pixel is the superposition of the amplitudes extracted from the time signals of the transducer at different positions according to the flight times. It should be noticed that, since only the procedure of receiving is simulated, the group velocity  $\hat{c}_g$  will be the same as the group velocity  $c_g = 3208$  m/s. The results in Figures 9–11 are all calculated with the excitation signal of three cycles.



**Figure 9.** The results for the angular step 0.5° by different methods: (**a**) B-scan, (**b**) delay and sum (DAS), (**c**) circumferential synthetic aperture focusing technique (CSAFT). The excitation signal is a tone-burst signal with three cycles.



**Figure 10.** Comparisons of three methods with different factors: (**a**) the angular bandwidth  $\theta_w$  by the transducer with different lengths; (**b**) Calculation times with different numbers of signals. The excitation signal is a tone-burst signal with three cycles.

The results for the angular step  $0.5^{\circ}$  are shown in Figure 9. In the B-scan image of Figure 9a, extra waves existing in front of the defect waves are Lamb modes generated by the defect, which travel faster than the SH0 mode. The reflection waves from the boundaries appear after the defect waves. As in Figure 6, the divergence angle of the transducer cannot be zero, and so the defect can also be detected even if it is not directly in front of the transducer. That is the reason for the tailings of the defect waves in the B-scan image, which significantly lower the angular resolution. The image is

improved by the DAS method, as in Figure 9b. However, over adjustments exist as a result, leading to some residual trailing. The result of the CSAFT method is shown in Figure 9c. The best angular resolution of the defect spot with the least trailing can be obtained compared with those by other methods. The defect locations (0.76~0.77 m) in Figure 9 are calculated with the peaks of the defect spots, which results in the localization error of the distances (6.7%) for the width of the defect waves in the time signals. The denoted angular positions  $(9.5~11.5^{\circ})$  have little error compared with the actual value.

The effect of the length of the transducer is investigated in the simulation. The angular bandwidth of the defect spot  $\theta_w$ , defined as the largest angle range of the region in which the amplitudes are no less than half of the peak, is used to denote the size of the defect spot in the angular direction. The divergence angle  $\theta_d$  of the transducer decreases with the increment of the length of the transducer length 2L as in Figure 6. The angular bandwidth of the defect spot in the B-scan image has the same tendency of decrement as the divergence angle of the transducer, as in Figure 10a, which is 12~29.5° for a length of the transducer between 2 and 150 mm. The DAS method provides a significant improvement of the angular bandwidth (3.4~3.8°), which is basically not affected by the variations of the transducer lengths. The angular bandwidths by the CSAFT method (1.5~2.5°) are slightly superior to those by the DAS method. The CSAFT and DAS method are also compared for different angular steps, which are integral multiples of the minimum angular step 0.5°. The numbers of the receiving signals for different angular steps are listed in Table 2.

The effect of the excitation signals with different cycles is also studied and the results by the CSAFT method marked with the defect positions and angular bandwidths are shown in Figure 12. It can be observed that the widths of the defects along the radius and the angular bandwidths increase with the increment of the cycles. The defect localization accuracy decreases as well. The increment of the signal cycle is conducive to raising the energy of the incident waves for long testing ranges and narrow down the frequency bandwidth to reduce the influence of other frequencies. However, it extends the lengths of the excitation signals in the time domain, which determine the sizes of the focused defect spots. Both resolutions along the angle and radius are decreased. The cycles of the excitation signals should be selected in the consideration of both resolutions and testing ranges in field tests.

The calculation time of the CSAFT and DAS methods are tested with the same number of the signals in the same computer. As in Figure 10b, the calculation time of the CSAFT method is much less than that of the DAS method, which increases linearly with the numbers of the signals. The advantage of the proposed method in calculation efficiency can be more significant when dealing with a larger amount of data. The images by three methods for different angular steps are presented in Figures 9 and 11. Since the angular sampling rate decreases with the increment of the angular step, the defect spots are coarser in the results of the Bscan and CSAFT method. In the results by the DAS method, over-adjustments get more severe with larger trailing in the image, which may become distractions in defect recognition. The proposed CSAFT method provides the best performance for each angular step.

| Name                  | Value |    |     |    |  |  |
|-----------------------|-------|----|-----|----|--|--|
| Angular step (°)      | 0.5   | 1  | 1.5 | 2  |  |  |
| Number of the signals | 91    | 46 | 31  | 23 |  |  |

Table 2. The numbers of the receiving signals for different angular steps.



**Figure 11.** Comparisons of the results by the B-scan (**Left**), DAS (**Middle**), and CSAFT (**Right**) methods for different angular steps: (**a**)  $\theta_s = 1^\circ$ ; (**b**)  $\theta_s = 1.5^\circ$ ; (**c**)  $\theta_s = 2.0^\circ$ . The excitation signal is a tone-burst signal with three cycles.



**Figure 12.** Comparisons of the results by the CSAFT method for excitation signals with different cycles: (a) five cycles; (b) seven cycles; (c) nine cycles.  $\theta_w$  is the angular bandwidth of the defect spot.

#### 4. Experimental Investigation

#### 4.1. Experimental Setup

Experiments were carried out to verify the proposed method. As shown in Figure 13, the equipment named the magnetostrictive guided wave detector (MSGW30, Zheda Jingyi Tech, Ltd., Hangzhou, China) was used in the experiments. The equipment has the ability to generate and receive guided waves with the modules including signal generation, power amplification, pre-amplification

and A/D conversion under the control of the computer. The coils in the magnetostrictive sandwich transducer (MST) 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 Figure 14. The iron plate is the same size as that in the simulation. An iron mass scatterer with the additional cross-sectional area of 100 mm<sup>2</sup> was coupled on the iron plate at the radius 0.825 m from the original point  $O_2$  and  $12^{\circ}$  from the start position of the scanning as the artificial defect using the epoxy coupling agent. The MST moved around the original point  $O_2$  at a radius of 1.3 m with the angular step  $1.5^{\circ}$  to scan the fan area with an angle of  $45^{\circ}$ . The MST was used both as an actuator and sensor. The excitation signal used in the experiment is the same as that in the simulation, which is shown in Figure 8a. The sampling ratio is 2 MHz. Thirty-one signals were collected in the scanning. It should be mentioned that the coupling agent used for the coupling between the transducer and the plate is the shear wave coupler (UGW30, Zheda Jingyi Tech, Ltd., Hangzhou, China).



**Figure 13.** The magnetostrictive guided wave inspection system for circumferential scanning in the plate.



Figure 14. Circumferential scanning in the iron plate using guided waves.

#### 4.2. Results and Discussion

The temperature variations should always be considered in guided wave inspections. The wave velocities are affected by the mechanical properties of the plates, which are changed by the temperature. Wave velocities of collected signals may be different if the scanning is carried out under large temperature variations, affecting the quality of the scanning image. Therefore, wave velocity compensation should be considered. In field tests, the scanning is usually finished within minutes and the temperature does not change rapidly in a short time. However, the situation can be different when the scanning is carried out at a different time (in the day or at night). Thus, wave velocity estimation is necessary before scanning. In this study, the guided waves were generated directly towards one boundary of the plate. The flight time of the reflection waves from the boundary and the distance between the MST and the boundary were used to calculate the group velocity, which is 2714 m/s. The reason for the error (15.4%) of the velocity may be the same as described in Section 3.2, since the peak of the reflection wave was used to determine the flight time.

The results of the three methods are shown in Figure 15. 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 Figure 15a 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 Figure 15b; 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 Figure 15c, 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 Table 3. The position of the defect is denoted by the peak of the spot, and the angular bandwidth is defined as in Section 3.2. 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.



Figure 15. Experimental images by the three methods: (a) B-scan; (b) DAS; (c) CSAFT.

| Table 3. Defect estimation | by | the | three | method | s. |
|----------------------------|----|-----|-------|--------|----|
|----------------------------|----|-----|-------|--------|----|

| Name                                    |              | Actual Values    | B-Scan | DAS   | CSAFT |
|---|--------------|------------------|--------|-------|-------|
| Position                                | Angle (°)    | 12               | 13.5   | 12.5  | 12    |
|   | Distance (m) | 0.825            | 0.823  | 0.815 | 0.821 |
| Angular bandwidth (°)                   |              | NAN <sup>1</sup> | 4.5    | 3.8   | 2.0   |
| Peak value ratio<br>(defect/boundaries) |              | NAN <sup>1</sup> | 0.25   | 0.14  | 1.71  |

<sup>1</sup> NAN means no value for this option.

#### 5. Conclusions

A synthetic aperture focusing technique method is proposed for circumferential scanning of plates using guided waves. The SH0 mode is selected for the inspection, which can be effectively generated by the magnetostrictive sandwich transducer (MST). 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. Numerical and experimental validation was successfully performed for the circumferential scanning of the defects in an iron plate. The main findings are summarized as follows:

- 1. The SH0 mode has the same detection sensitivity for the cross section of the plate with a uniform wave structure along its thickness; it is nondispersive in frequency and has little energy leakage for the inspection of plates contacted with liquids, which can be generated purely at the frequency below the cutoff frequency of the SH1 mode. The SH0 mode is ideal for the inspection of tank floors in service.
- 2. The MST used for SH0 wave generation can control the wave propagation direction. The main structure of the MST is designed for the SH0 mode at a certain frequency, and the divergence angle can be adjusted with the length of the transducer.
- 3. The angular bandwidth of the defect spot by the proposed method (1.5~2.5°) in the numerical simulations are found to be better than those by the traditional delay and sum (DAS) method (3.4~3.8°) for transducers with different lengths (2~150 mm), both of which have a significant improvement compared with those by the B-scan image (12~29.5°). The proposed method has better calculation efficiency than the DAS method, particularly for a large amount of data. No additional trailing occurs in the image of the proposed method with the increment of the angular step. In circumferential scanning, there should not be too many cycles of the excitation signal when the testing range is sufficient.
- 4. 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.

The CSAFT method is expected to be effective for the non-destructive scanning of tank floors in service to minimize the risks and costs of the maintenance operations. 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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