Circumferential SH Wave Piezoelectric Transducer System for Monitoring Corrosion-Like Defect in Large-Diameter Pipes

Hao Zhang, Yuehao Du, Jihua Tang, Guozheng Kang and Hongchen Miao *

Applied Mechanics and Structure Safety Key Laboratory of Sichuan Province, School of Mechanics and Engineering, Southwest Jiaotong University, Chengdu 610031, China; zhanghao@my.swjtu.edu.cn (H.Z.); yuehaodu@my.swjtu.edu.cn (Y.D.); jihuataang1998@163.com (J.T.); guozhengkang@swjtu.edu.cn (G.K.)

* Correspondence: miaohongchen@swjtu.edu.cn

Received: 7 December 2019; Accepted: 11 January 2020; Published: 14 January 2020

Abstract: The fundamental circumferential shear horizontal (CSH0) wave is of practical importance in monitoring corrosion defects in large-diameter pipes due to its virtually non-dispersive characteristics. However, so far, there have been limited CSH0 wave transducers which can be used to constitute a structural health monitoring (SHM) system for pipes. Moreover, the CSH0 wave’s capability of sizing the corrosion-like defect has not yet been confirmed by experiments. In this work, firstly, the mechanism of exciting CSH waves was analyzed. A method based on our previously developed bidirectional SH wave piezoelectric transducers was then proposed to excite the pure CSH0 mode and first order circumferential shear horizontal (CSH1) mode. Both finite element simulations and experiments show that the bidirectional transducer is capable of exciting pure CSH0 mode traveling in both circumferential directions of a 1-mm thick steel pipe from 100 to 300 kHz. Moreover, this transducer can also serve a sensor to detect CSH0 mode only by filtering circumferential Lamb waves over a wide frequency range from 100 to 450 kHz. After that, a method of sizing a rectangular notch defect by using CSH0 wave was proposed. Experiments on an 11-mm thick steel pipe show that the depth and circumferential extent of a notch can be accurately determined by using the proposed method. Finally, experiments were performed to investigate the reflection and transmission characteristics of CSH0 and CSH1 waves from notches with different depths. It was found that transmission coefficients of CSH0 mode decrease with the increasing of notch depth, which indicates that it is possible to monitor the depth change of corrosion defects by using CSH0 wave.

Keywords: SH guided waves; circumferential guided waves; mode conversion; wall thinning defects; reflection and transmission coefficients

1. Introduction

Wall thinning due to corrosion in pipes is a serious problem in the oil and chemical industries. The ultrasonic bulk-wave-based nondestructive testing (NDT) technique and magnetic flux leakage method are available for detecting wall thinning. However, these NDT techniques cannot monitor the growth of damage, since they are usually conducted at regularly scheduled intervals. The limitation of NDT techniques motivates the development of structural health monitoring (SHM) techniques, with the aim of monitoring the overall integrity of structures in a real-time manner [1].

Over the last three decades, the ultrasonic guided-wave-based damage identification approach has demonstrated potential for SHM of pipes [2]. Guided waves can propagate in the axial or circumferential direction of a pipe-like structure [3]. Axial guided waves have attracted the main research interest of this field due to their rapid defect screening capability. Figure 1b shows the group velocity dispersion curves of axial guided waves for a steel pipe (outer diameter 720 mm, wall...
thicknesses 11 mm). Based on the early works by Gazis [4,5] and Silk and Bainton [6], there are three kinds of axial guided waves in a pipe, namely longitudinal-type modes $L(0, m)$, torsional-type modes $T(0, m)$ and flexural modes $F(n, m)$, where the positive integer ‘$n$’ represents the circumferential order of a mode and the positive integer ‘$m$’ denotes the group order of a mode. Since many guided wave modes exist in the axial direction at any given frequency and they are in general dispersive, it is often very difficult to extract relevant information on defects from the complex received wave signals. Therefore, much effort has been made to excite pure longitudinal $L(0, 2)$ mode [7–9] and the fundamental torsional wave $T(0, 1)$ mode [10,11], since $T(0, 1)$ wave is nondispersive at all frequencies while $L(0, 2)$ wave is virtually non-dispersive in the selected frequency range [12]. However, the $L(0, 2)$ and $T(0, 1)$ modes are axially symmetric, so they have difficulty to locate the defect circumferential position and size the defect. This problem becomes more serious in large-diameter pipes, which drives researchers to develop circumferential guided-wave-based damage identification method [13–17].

Figure 1. Group velocity dispersion curves of axial and circumferential guided waves in a steel pipe (outer diameter 720 mm, wall thicknesses 11 mm, Young’s modulus 210 GPa, density 7850 kg/m$^3$ and Poisson’s ratio 0.33): (a) pipe axes configuration; (b) axial guided waves (F modes only shown up to 4th order); (c) circumferential Lamb (CLamb) waves and; (d) circumferential shear horizontal (CSH) waves.

Figure 2 illustrates the basic idea of the circumferential guided-wave-based SHM approach [16]. Transducers are permanently installed on the pipe. The incident guided wave is excited in one direction around the circumference of a pipe and propagates across the defect. By examining the reflected wave and transmitted wave, the defect can be identified. Since the required inspection distance is relatively shorter than that of the axial guided wave, a higher frequency circumferential guided wave can be used to improve the sensitivity to defects. Obviously, circumferential guided-wave-based inspection
is an appealing method for monitoring large-diameter pipes such as pressure vessels and oil tanks, in which a transducer array can be used. As for long range pipes, such as oil transporting pipelines, circumferential guided waves can be a good supplement to axial guided wave inspection. Long range pipes can be inspected by using a combination of axial and circumferential guided waves. For example, circumferential guided waves can be used to inspect the welding zones and pipe support regions, which are highly prone to generating defects [18].

![Figure 2. Schematic of circumferential guided-wave-based SHM approach.](image)

The selection of a proper mode is essential to developing a circumferential guided-wave-based SHM system. Two kinds of guided waves can propagate in the circumferential direction of a pipe, namely: circumferential Lamb waves and shear horizontal (SH) waves often abbreviated as CLamb waves and CSH waves [3], respectively, as shown in Figure 1c, d. Early researchers often use plate-wave solutions to model the circumferential guided waves. Liu and Qu [19] and Zhao and Rose [20] developed detailed theoretical models for circumferential guided waves. Their results show that the dispersion curves and wave structures of circumferential guided waves are quite different from that of plate waves especially in thick wall pipes. As shown in Figure 1c, all the circumferential Lamb waves are dispersive and at least two modes coexist at any given frequency. Since CLamb waves have two coupled displacements (radial displacement and circumferential displacement), it is very difficult to excite a pure CLamb mode. Compared with CLamb waves, CSH waves have simpler dispersion equation and less mode conversion when encountering defects. Moreover, CSH waves have simpler wave structures and are less affected by the presence of fluid loads and coatings [21]. In addition, only the fundamental circumferential SH (CSH₀) wave can propagate below the cutoff frequency of CSH₁ mode and the displacement of CSH waves are decoupled with CLamb waves, which means that theoretically pure CSH₀ mode can be excited over a wide frequency range. This characteristic is attractive since CSH₀ mode is also practically non-dispersive over a wide frequency range as shown in Figure 1d.

As CSH waves are attractive, especially CSH₀ mode has practical importance in developing circumferential guided wave inspection system, much effort has been made to utilize CSH₀ wave to detect corrosion-like defects. In laboratory studies, SH modes in plates are often used as an approximation of CSH waves in pipes [22], since numerical model and experiments in the plate are much simpler. The interaction of SH₀ wave with wall thinning defects is highly influenced by the thinning geometry and the operating frequency range [23]. When the operating frequency is below the first cutoff frequency, the SH₀ wave will not convert to higher order SH modes when encountering defects, so the reflection and transmission behaviors of SH₀ wave across thinning defects are relatively simple. Demma et al. [24] investigated the effect of a rectangular notch on the propagation of the SH₀
mode, and it was found that the reflection coefficient is strongly influenced by the axial extent (in the propagating direction) of a notch. It has minima when the axial extent is integer multiples of \( \lambda / 2 \) and maxima when the axial extent is odd multiples of \( \lambda / 4 \), where \( \lambda \) is the wavelength of SH\(_0\) wave. This phenomenon was also confirmed by using the principle of reciprocity of elastodynamics [25,26].

Zhao and Rose [27] used boundary element methods to analyze the SH\(_0\) wave scattering from a surface half-elliptical shaped defect, which is a better approximation to the corrosion defect than a notch. It was found for a low frequency incident SH\(_0\) wave, the reflection and transmission factors change monotonously with the defect depth. Wang et al. [28] investigated the effect of a notch on the propagation of the CSH\(_0\) mode in a pipe by using 3D finite element simulations. Their simulations show that the reflection and transmission coefficients of CSH\(_0\) waves vary monotonously with an increase in the notch depth. The above results show that CSH\(_0\) wave has great potential for corrosion defect sizing when its operating frequency is below the first cutoff frequency. However, there is less experimental evidence to support the CSH\(_0\) wave’s defect sizing capability. Even for a simple rectangular notch defect, there is no available guided-wave-based method to determine the depth of a notch. It should be noted that using SH\(_0\) wave to model the CSH\(_0\) mode in a thin pipe is accurate only for the frequency range below the first cutoff frequency. The simulations conducted by Luo et al. [22] show that, when the operating frequency is above the CSH\(_1\) wave cutoff frequency, the CSH\(_0\) wave’s reflection and transmission characteristics from a notch in a pipe are quite different from those of SH\(_0\) wave from a notch in a plate, even for a thin pipe with a low thickness-to-diameter ratio. Therefore, although there are some investigations which focus on the interaction of SH\(_0\) wave with corrosion-like defects in the high frequency-thickness regime [14,23,29–31], these conclusions obtained from SH\(_0\) wave in the high frequency-thickness regime cannot be extended to CSH\(_0\) wave in the pipe straightforwardly.

Undoubtedly, it is necessary to experimentally study the interaction of CSH\(_0\) wave with corrosion-like defects in pipes directly. However, currently, there are fewer experimental investigations due to the difficulty of exciting pure CSH\(_0\) (or CSH\(_1\)) mode. To develop a CSH-wave-based SHM system, transducers should be designed to meet the following requirements: (a) The transducer should be light-weight and low-power consumption and hence it can be permanently installed on the pipe. This means that electromagnetic acoustic transducers (EMATs) are not feasible due to their relatively bulk size and high-power consumption, although EMATs can excite pure CSH\(_0\) wave [32]. (b) The transducer should be able to excite a pure CSH\(_0\) wave in one direction around the circumference of a pipe [16]. This requires that all the axial guided waves, CLamb waves, and high order CSH modes in the pipe must be suppressed by the designed transducer. In recent years, a series of face-shear piezoelectric transducers for SHM have been developed to excite single mode SH\(_0\) wave [33–36]. Since pure SH\(_0\) wave excited by the face-shear transducer is along four main directions (\(0^\circ\), \(90^\circ\), \(180^\circ\) and \(270^\circ\)) [35], it can be inferred that if these face-shear transducers are straightforwardly used to excite CSH\(_0\) wave, flexural waves will be excited simultaneously in the axial direction of the pipe [11,37]. Theoretically, our recently developed bidirectional SH wave piezoelectric transducer (BSH-PT) is capable of exciting pure CSH\(_0\) wave in the pipe [38], but considering that there are many axial guided waves in the pipe, its capability of suppressing axial guided waves needs to be checked. (c) Besides the above two requirements, it is also expected that this transducer can operate over a wide frequency range, which means that the transducer has tunable detection sensitivity for defects of different sizes. As EMATs are usually able to excite pure CSH\(_0\) wave with fixed wavelength, they cannot meet this requirement.

In this work, a piezoelectric transducer system is proposed to excite pure CSH\(_0\) wave and single CSH\(_1\) mode in large-diameter pipes and the CSH\(_0\) wave’s ability of sizing and monitoring corrosion-like defects in a pipe is demonstrated. Firstly, a method based on our previously developed bidirectional SH wave piezoelectric transducers was proposed to excite pure CSH\(_0\) wave and single CSH\(_1\) mode. Then, experiments were performed to explore the bidirectional transducer’s performance on exciting and receiving CSH\(_0\) wave over a wide frequency range. After that, a method of sizing a rectangular notch defect by using CSH\(_0\) wave was proposed and then confirmed by experiments. Finally, experiments were conducted to investigate the reflection and transmission characteristics of CSH\(_0\) wave and CSH\(_1\)
wave from notches with different depths. The results show that the depth change of a notch can be monitored by extracting the transmission coefficient of CSH₀ wave at different incident frequencies.

2. Mechanisms of Exciting CSH₀ and CSH₁ Waves

The first step in developing a guided wave transducer is to analyze the wave structures in the waveguide. Figure 3a shows the particle displacement distributions of CSH₀ wave in an 11-mm thick steel pipe at different frequencies. For better illustration, the particle displacement distributions are normalized against the maximum displacement of each case. For the CSH₀ wave at 0.5 MHz-mm, its particle displacement is uniform across the pipe wall, which is the same as that of a plate-wave solution. Although such a uniform distribution cannot be kept when the frequency increases, the deviation is small and can be neglected especially for the cases below the first cutoff frequency. The quasi-uniform displacement distribution induces that the in-plane shear stress \( \sigma_{\theta z} \) is also almost uniform across the pipe wall as shown in Figure 3b. Moreover, the shear stress \( \sigma_{zz} \) of CSH₀ wave is negligible. Therefore, the CSH₀ wave can be generated by inducing face-shear deformation in the pipe. However, because pure SH₀ wave in a plate is generated by the face-shear transducer along four main directions, it can be inferred that a face-shear deformation in the pipe will not only excite CSH wave but also generate axial guided waves. A previously developed bidirectional SH wave piezoelectric transducer [38] may be able to eliminate the possible guided waves propagation in the axial direction of the pipe. As shown in Figure 4a, the bidirectional transducer consists of two identical face-shear \( d_{24} \) PbZr\(_{1−x}\)Ti\(_x\)O\(_3\) (PZT) wafers, which are bonded together via their lateral faces. The two PZT wafers share a same electrode at the bonding interface and their polarization directions (red arrow in Figure 4a) are the same, so the induced face-shear deformations of the two PZT wafers under drive field are opposite. As demonstrated in a recent work [35], the wave field generated by a face-shear transducer is equivalent to that generated by uniform in-plane tractions along its perimeters. Since the induced shear stresses distributed along the PZT wafer edges are symmetric with respect to the axial direction, as shown in Figure 4b, it can be inferred that all the axial guided waves will be suppressed based on the symmetry principle in the theory of elastodynamics. This principle is independent of frequency, so CSH₀ wave can be excited over a wide frequency range.

Based on the above analysis, it is known that a single bidirectional transducer configuration, shown in Figure 4c, can be used to generate pure CSH₀ wave below the cutoff frequency of CSH₁ mode. However, when the drive frequency is above the first cutoff frequency, the CSH₁ mode will be also excited simultaneously by the single transducer configuration, since the in-plane shear stress \( \sigma_{\theta z} \) of CSH₁ mode is dominant on the surface of the pipe as shown in Figure 3d. Considering that the displacement and shear stress \( \sigma_{\theta z} \) of CSH₁ mode are quasi-antisymmetric across the pipe wall, as shown in Figure 3c,d, the symmetrically mounted transducer configuration shown in Figure 4d can be used to selectively excite CSH₀ mode and CSH₁ mode. With in-phase excitation applied on the two symmetrically-mounted bidirectional transducers, pure CSH₀ mode can be generated while pure CSH₁ mode can be achieved with an out-of-phase excitation [39,40].

Finite element simulations based on ANSYS software (Version 14.5 by ANSYS, Inc., Canonsburg, PA, USA) were performed to confirm the proposed excitation mechanisms. The bidirectional transducer in the simulations is made up of two rectangular PZT wafers with the dimensions of 25 mm × 6 mm × 1 mm. The material parameters of the PZT (PZT-5H) wafers can be found in the recent work [35]. Firstly, the bidirectional transducer’s performance on suppressing axial guided waves and CLamb waves was investigated. In order to reduce the computational cost, a 300 mm long, 300 mm outer diameter, and 1-mm thick steel pipe was used as the waveguide. The bidirectional transducer was bonded on the outer surface of the pipe as shown in Figure 5a. The transducer was driven at 250 kHz (corresponding to 0.25 MHz-mm in the 1-mm thick steel pipe, below the cutoff frequency of CSH₁ mode), so by monitoring the induced displacement time history at point A and point B, the transducer’s performance on exciting pure CSH₀ wave can be assessed. Then the thickness of the steel pipe was changed to 11 mm and two bidirectional transducers were symmetrically mounted on the outer and
inner surfaces of the pipe to explore the excitation mechanism of CSH1 wave. The two symmetrically mounted bidirectional transducers were energized out-of-phase and the central frequency of the drive signal was 250 kHz (corresponding to 2.75 MHz·mm in the 11-mm thick steel pipe, above the cutoff frequency of CSH1 mode). By monitoring the induced displacement distribution across the pipe wall, the pair of bidirectional transducers’ performance on exciting CSH1 wave can be confirmed. In all cases, the Young’s modulus, Poisson ratio, and density of the steel pipe in the simulations were set to be 210 GPa, 0.33, and 7850 kg/m³, respectively. The steel pipes were modeled by SOLID185 elements, while the PZT wafers were modeled by SOLID5 elements. The largest size of elements was set to be less than 1/20 of the shortest wavelength and the time step was less than 1/(20fc) to ensure the accuracy of the computational results, where fc was the central frequency of the drive signal. The drive signal was a five cycle Hanning window-modulated sinusoid toneburst and its amplitude was fixed at 40 V.

Figure 5b shows the simulated axial displacement wavefield in the 1-mm thick steel pipe excited by the transducer at 0.25 MHz·mm. Based on the wave structure of CSH0 wave shown in Figure 3a, it is known that the axial displacement shown in Figure 5b can represent the CSH0 wave. As expected, the CSH0 wave was excited in both circumferential directions away from the transducer. To further explore the purity of the excited CSH0 wave, the displacements time history at point A and point B were extracted (shown in Figure 5a) and the results were plotted in Figure 5c,d. Figure 5c shows that the obtained circumferential and radial displacement components at point A are zero, indicating that no CLamb waves are generated. Moreover, Figure 5d shows that all the displacement components at point B are almost zero, which means that no axial guided waves are excited. Thus, it can be concluded that pure CSH0 wave was successfully excited by the bidirectional transducer.

Figure 3. Wave structures and stresses of CSH waves in a steel pipe (outer diameter 720 mm, wall thicknesses 11 mm, Young’s modulus 210 GPa, density 7850 kg/m³ and Poisson’s ratio 0.33): (a) particle displacement distributions of CSH0 wave at different frequencies, (b) stress components σθz and σrz of CSH0 wave at 2.5 MHz·mm, (c) particle displacement distribution, (d) stress components of CSH1 wave at 2.5 MHz·mm.
Figure 4. (a) Schematics of the proposed bidirectional CSH wave piezoelectric transducer, (b) bidirectional CSH wave driving mechanism, (c) single transducer configuration for pure CSH\textsubscript{0} wave excitation below the first cutoff frequency and (d) dual transducer configuration for selectively exciting CSH\textsubscript{0} or CSH\textsubscript{1} wave above the first cutoff frequency.

Figure 5. Numerical verification of pure CSH\textsubscript{0} wave excitation by a single surface-bonded piezoelectric transducer at 0.25 MHz\cdot mm in a steel pipe (outer diameter 300 mm, wall thicknesses 1 mm): (a) schematics of the finite element simulation setup, (b) axial displacement wavefield (CSH\textsubscript{0} wave), displacements time history extracted from (c) point A and (d) point B.
Figure 6a presents the simulated axial displacement wavefield in an 11-mm thick steel pipe excited by a pair of symmetric bonding piezoelectric transducers under out-of-phase excitation at 2.75 MHz·mm. As expected, the wave beam was focused in two circumferential directions. The purity of the excited CSH waves can be confirmed by the displacement time history shown in Figure 6b, which was extracted from the outer surface node at the circumferential distance of 30° from the transducer. Considering that both CSH$_0$ and CSH$_1$ waves can propagate at 2.75 MHz·mm, the displacement time history from the inner surface node was also extracted for comparison and the results are plotted in Figure 6c. It was found that the direction of the particle vibration at the outer surface is opposite to that at the inner surface, indicating that the excited wave is CSH$_1$. This can be further confirmed by the comparison of the simulated and theoretically predicted wave structures of CSH$_1$ mode. Figure 6d shows that the simulated displacement distribution accords well with the theoretical wave structure of CSH$_1$ mode. Obviously, the above simulation results are in good agreement with the proposed excitation mechanisms.

3. Experiments

3.1. Excitation and Reception of CSH$_0$ Wave by the Bidirectional Piezoelectric Transducer

Figure 7 illustrates the experimental setup for exploring the bidirectional piezoelectric transducer’s performance on exciting and receiving CSH$_0$ wave. The bidirectional transducers used in experiments have the same sizes as that used in the finite element simulations in Section 2.
As indicated in Section 2, the proposed bidirectional transducer requires that each $d_{24}$ PZT element exhibits good face-shear performance within the operating frequency regime. Therefore, we first used a 1-mm thick steel pipe (outer diameter 600 mm, length 1000 mm) to find the frequency regime in which the designed transducer can exhibit good performance. Once the best working frequency range is determined, the transducer’s operating frequency regime in any a given-thickness pipe can be determined based on the corresponding frequency-thickness range. The bidirectional transducer for exciting CSH$_0$ wave was bonded on the outer surface of the pipe using commercial epoxy resins E51 and it located at the center in the axial direction. The transducer was driven by a five-cycle Hanming window-modulated toneburst signal, which was provided by a function generator (DG4062, Rigol, Beijing, China) and amplified to 20 V by a power amplifier (KH7602M, Krohn-Hite Corporation, Brockton, MA, USA) as shown in Figure 7b. A face-shear $d_{36}$ = 1600 pC/N and $d_{31}$ = −360 pC/N, 5 mm × 5 mm × 1 mm) was firstly used as the sensor to check the purity of the excited CSH$_0$ wave in the circumferential direction, since it can detect both CSH$_0$ wave and the possible CLamb waves [33]. As shown in Figure 7a, the distance between the actuator and the PMN-PT sensor was set to be 264 mm. Meanwhile, another $d_{36}$ PMN-PT sensor was placed in the axial direction to detect the possible axial guided waves. After that, another identical bidirectional piezoelectric transducer was placed in the circumferential direction 100 mm away from the actuator as the sensor to check its ability to receive CSH$_0$ wave. In all cases, the signal received by sensors was collected by an oscilloscope (DSOX3024T, KEYSIGHT, Santa Rosa, CA, USA) with 128 times trace averaging.

Figure 8 presents the wave signals excited by the bidirectional piezoelectric transducer at different frequencies. Wave signals received by the $d_{36}$ PMN-PT sensor in the circumferential direction of the pipe are plotted in Figure 8a–d. It was found that pure CSH$_0$ wave was excited over a wide frequency range from 100 kHz to 300 kHz, while CLamb waves were generated at 350 kHz. Correspondingly, Figure 8e–g show that no axial guided waves were generated at the frequency range from 100 kHz to 300 kHz. When the drive frequency increased to 350 kHz, axial guided waves were also excited as shown in Figure 8h. The above phenomenon indicates that the $d_{24}$ PZT elements used in the bidirectional transducer only exhibit good face-shear performance at the frequency range from 100 kHz to 300 kHz. At this frequency range, the bidirectional transducer can work well as the designed principle introduced in Section 2, so no CLamb waves and axial guided waves are generated. However,
when the drive frequency is out of the best working frequency range, the induced deformation of the $d_{24}$ PZT element is no longer a perfect face-shear deformation, so both CLamb waves and axial guided waves will be excited.

Figure 8. Wave signals excited by the bidirectional piezoelectric transducer at different frequencies and received by $d_{36}$ PMN-PT sensors. (a–d) wave signals propagating in the circumferential direction, (e–h) wave signals propagating in the axial direction of the pipe.

Figure 9 presents the wave signals generated by a bidirectional piezoelectric transducer at different frequencies and measured by another identical bidirectional transducer in the circumferential direction. It seems that pure $CSH_0$ wave was excited over a wide frequency range from 100 kHz to 450 kHz. Bearing in mind that Figure 8 shows that the proposed transducer can only excite pure $CSH_0$ wave from 100 kHz to 300 kHz, so Figures 8 and 9 indicate that the bidirectional piezoelectric transducer can also serve as a sensor, which can receive $CSH_0$ wave only by filtering CLamb waves at the frequency range from 100 kHz to 450 kHz. Obviously, the filtering capability is attractive, since it can reduce the complexity of the received signals.
3.2. Sizing Corrosion-Like Defect with CSH$_0$ Wave

After confirming the proposed bidirectional transducer’s ability to excite and receive CSH waves, a CSH wave piezoelectric transducer system is constituted to monitor corrosion-like defect in thick-wall pipes. As shown in Figure 10a, an 11-mm thick steel pipe (outer diameter 720 mm, length 1000 mm) was used as the waveguide. For simplicity, a rectangular notch was used as an approximation of a corrosion type damage. Note that a real corrosion defect may have rough un-predicted surface conditions, but a rectangular notch could be a first step approximation of a corrosion type defect which is commonly used in the lab tests and theoretical studies [24,26,31]. Four identical bidirectional transducers are used to constitute the monitoring system. The layout of these transducers is shown in Figure 10a. We first consider the simple case where the operating frequency regime is below the CSH$_1$ cutoff frequency. At this case, a single surface-bonded bidirectional transducer (actuator A shown in Figure 10a) is enough to excite pure CSH$_0$ wave. When pure CSH$_0$ wave was incident on the notch, only the CSH$_0$ mode contributes to the reflection and transmission of the wave. Obviously, the CSH$_0$ wave will travel back and forth inside the notch, so there will be a series of consecutive reflections. The first reflection coefficient obtained at a step down (step A shown in Figure 10a) is then given by [24]:

$$ R_{A1} = \frac{\alpha}{2 - \alpha} $$  \hspace{1cm} (1)

where $\alpha = h/t$, where $h$ is the depth of the notch and $t$ is the original thickness of the pipe as shown in Figure 10a. The corresponding transmission coefficient past the step A would be:

$$ T_{A1} = \frac{2}{2 - \alpha} $$  \hspace{1cm} (2)
When the transmitted wave travels to the up step (step B shown in Figure 10a), part of wave energy reflects and then passes though step A, so the obtained second reflection is:

\[ R_{AB2} = T_{A1} \times \left( \frac{-\alpha}{2-\alpha} \right) \times \left( \frac{2-2\alpha}{2-\alpha} \right) = \frac{4\alpha(\alpha-1)}{(2-\alpha)^3} \]  

(3)

Similarly, the amplitude of the third reflection is given by:

\[ R_{AB3} = T_{A1} \times \left( \frac{-\alpha}{2-\alpha} \right)^3 \times \left( \frac{2-2\alpha}{2-\alpha} \right) = \frac{4\alpha^3(\alpha-1)}{(2-\alpha)^5} \]  

(4)

For a typical \( \alpha = 0.5 \), \( R_{AB3} \) is only about 3%. Therefore, the third reflection is negligible. Only the first and second reflections have practical importance for detecting the notch defect. The time delay between the first reflection and the second one is \( 2L/c_g \), where \( L \) is the circumferential extent of the notch and \( c_g \) is the group velocity of the CSH\(_0\) wave. Obviously, if \( L \) is relatively large, the two reflected signals can be separated in time. This characteristic can be used to measure the circumferential extent of the notch. However, if \( L \) is too small, the reflected signals will overlap in time domain, which will induce the total reflection signal complex due to the constructive and destructive interference of the two reflected signals. The target of this work is to size the corrosion-like defect larger than 5\( \mu \)in in area and 0.5\( t \) deep where \( t \) is the original thickness of the pipe. Therefore, the circumferential extent of the notch was set to be 55 mm in the experiments as shown in Figure 10a. This extent can separate the two reflected signals in time domain, so it can be measured. The depth of the notch can be determined by using the amplitude ratio of the two reflected signals:

\[ \kappa = \frac{R_{A1}}{R_{AB2}} = \frac{(2-\alpha)^2}{4(1-\alpha)} \]  

(5)

By measuring the amplitude ratio \( \kappa \), the relative depth \( \alpha = h/t \) can be obtained. It should be noted that calculation of \( \alpha \) by using the amplitude ratio \( \kappa \) is better than using reflection coefficient \( R_{A1} \) or \( R_{AB2} \) directly, since the absolute value of the reflection coefficient is strongly influenced by the beam divergence, roughness of the pipe and the quality of bonding layer between sensor and the pipe. These factors can be minimized by using the amplitude ratio \( \kappa \).

Figure 10. (a) Schematic of the experimental setup for monitoring the corrosion-like defect. (b) Theoretically predicted the change of the amplitude ratio \( \kappa \) of the two reflected signals versus the relative depth \( \alpha \) of the notch defect.
Figure 10b presents the theoretically predicted change of the amplitude ratio $\kappa$ versus the relative depth of the notch defect. It can be seen that the amplitude ratio always increases with the increase of relative depth. When the relative depth $\alpha$ is smaller than 0.5, the ratio $\kappa$ almost keeps constant, indicating that this method is insensitive to shallow defects. However, when the relative depth $\alpha$ becomes larger than 0.6, the increase rate of the ratio $\kappa$ becomes larger and larger. Therefore, the ratio $\kappa$ is a good damage index for deep defects. In order to explore the effectiveness of the proposed method, the shallowest depth of the notch in the experiments is set to be 7 mm. Then the depth of the same notch was machined in 1 mm steps to 8 mm and then to 9 mm. For each case, machining started in the shallowest depth, the measurement experiment was conducted, and then the same notch was remachined to the next depth. In all cases, the incident CSH$_1$ wave was excited by the actuator A at 135 kHz and the reflected signals from the notch were received by the sensor A shown in Figure 10a. For an 11-mm thick steel pipe, 135 kHz is corresponding to 1.485 MHz·mm, which is below the cut off frequency of CSH$_1$ mode, so only CSH$_0$ wave can propagate.

Figure 11 presents the wave signals excited by actuator A at 135 kHz and received by the sensor A shown in Figure 10a. As expected, pure CSH$_0$ wave was successfully generated in the 11-mm thick steel pipe. After the incident CSH$_0$ wave travels across the notches, the two reflected signals can be totally separated in the time domain. By extracting the time interval of 136.15 $\mu$s between the incident signal and the reflected signal from step A, the CSH$_0$ wave’s group velocity of 3283 m/s can be obtained based on the propagation distance of 447 mm shown in Figure 10a. Combining the time interval of 35.47 $\mu$s between the reflection from step A and that from step B, the circumferential extent of the notch is estimated as 58.1 mm, which agrees with the real value of 55 mm. Moreover, by extracting the amplitudes of the two reflected signals from notches with different depths, the amplitude ratio $\kappa$ was calculated and then the depth of notches can be obtained from Equation (5). Table 1 presents the notch depth sizing results for the rectangular notches with different depths. As shown, the estimated depths by using the amplitude ratio $\kappa$ accord very well with the true values of the notches. The estimation errors for the cases of 7 mm and 9 mm are within 2%. However, larger error is observed in the case of 8 mm, which is attributed to the machining error of the notch.

| Amplitude Ratio $\kappa$ | Measured Depth (mm) | True Depth (mm) | Error  |
|---------------------------|---------------------|----------------|--------|
| 1.298                     | 7.128               | 7             | 1.8%   |
| 1.831                     | 8.855               | 8             | 10.7%  |
| 2.010                     | 9.126               | 9             | 1.4%   |

Subsequently, the case where the operating frequency regime is above the CSH$_1$ cutoff frequency is investigated. Note that this discussion is limited to that the pipe thickness only supports CSH$_0$ and CSH$_1$ modes. Figure 12a presents the wave signals generated by a single outer-surface-bonded bidirectional transducer (actuator A shown in Figure 10a) at 250 kHz and received by the sensor A. The corresponding frequency-thickness of 2.75 MHz·mm is above the cutoff frequency of CSH$_1$ mode, so both CSH$_0$ and CSH$_1$ modes are simultaneously excited in the pipe. For comparison, the inter-surface-bonded bidirectional transducer (actuator B shown in Figure 10a) was then energized with the same drive signal used in actuator A. The obtained wave signals are also plotted in Figure 12a. As shown, the CSH$_0$ wave excited by actuator A is almost the same as that generated by actuator B, while the two excited CSH$_1$ modes are out-of-phase. Analogously, if the drive signal for actuator B is antiphase relative to that for actuator A, Figure 12c shows that the CSH$_0$ wave excited by actuator B is also antiphase relative to that generated by actuator A, while the obtained two CSH$_1$ modes are in-phase. This phenomenon is attributed that the wave structure of CSH$_0$ mode is uniform across the thickness of the pipe, while the corresponding distribution of CSH$_1$ mode is antisymmetric across the pipe wall as shown in Figure 3. Therefore, when actuators A and B are energized in-phase, Figure 12b shows that the excited CSH$_0$ wave is significantly enhanced, while the CSH$_1$ wave decreases.
significantly. By contrast, when actuators A and B are energized out-of-phase, Figure 12d presents that almost pure CSH\textsubscript{1} mode is obtained, since the weak CSH\textsubscript{0} mode can be neglected. Obviously, these results are in good agreement with the excitation mechanisms proposed in Section 2.

**Figure 11.** Experimental CSH\textsubscript{0} wave signals showing the reflections from the rectangular notches with different depths.

**Figure 12.** Selective generation of CSH\textsubscript{0} and CSH\textsubscript{1} modes by using dual excitation. (a) Actuator A and actuator B are driven one by one in phase, (b) the two transducers are simultaneously energized in phase, (c) the two transducers are driven one by one out-of-phase and (d) the two transducers are simultaneously energized out-of-phase.
Although pure incident CSH\textsubscript{0} wave is generated by using dual excitation, Figure 12b shows that the reflected signals from the notch (depth: 7 mm) are still more complex than that shown in Figure 11a. The reflections contain not only the two reflected CSH\textsubscript{0} waves but also the CSH\textsubscript{1} mode due to mode conversion. These wave modes overlap in time domain, so the above methods to determine the depth and circumferential extents of the notch become invalid. Therefore, we move to explore the transmission signals. After the incident CSH\textsubscript{0} wave passes through a 7-mm deep notch, its transmitted signals are measured by sensor B (shown in Figure 10a) and the results are plotted in Figure 13a. Obviously, both CSH\textsubscript{0} and CSH\textsubscript{1} modes are generated in the transmitted signals and their waveforms also overlap in the time domain. Similarly, when pure CSH\textsubscript{1} mode is excited as the incident wave, the transmitted wave measured by sensor B also contains CSH\textsubscript{0} and CSH\textsubscript{1} modes as shown in Figure 13b.

**Figure 13.** Experimental wave signals showing the transmission from a 7-mm deep rectangular notch.

**Figure 14.** Equivalent transmission coefficients for notches with different depths by sending pure (a) CSH\textsubscript{0} and (b) CSH\textsubscript{1} wave at different frequencies.

By analyzing the group velocity, it is found that when the incident wave is CSH\textsubscript{0} mode, most of the transmitted wave’s energy comes from the CSH\textsubscript{0} mode. Analogously, when CSH\textsubscript{1} mode is used as
incident wave, CSH\textsubscript{1} wave is the dominant mode in the transmitted signals. Therefore, by extracting the amplitude of the transmitted signal and combining the incident wave measured by sensor A, the equivalent transmission coefficient can be calculated. By sending pure CSH\textsubscript{0} wave at different frequencies, the equivalent transmission coefficients for notches with different depths can be obtained as shown in Figure 14a. It can be seen that the transmission coefficients for all the notches first decrease monotonically with frequency and then keep almost constant after 200 kHz. This phenomenon accords very well with the simulations conducted by Luo, Zhao and Rose [22].

The transmission coefficient of CSH\textsubscript{0} wave first decreases monotonically with frequency when the frequency range is approximately below the first cutoff frequency and then keep almost constant when the frequency range exceeds the cutoff frequency of CSH\textsubscript{1} mode. This is the first experimental evidence for the simulated transmission characteristics of CSH\textsubscript{0} wave across a notch at different frequencies. Moreover, Figure 14a shows that the transmission coefficients at all the frequencies decrease with increasing the notch depth. This phenomenon is valuable because it makes possible the depth monitoring through transmission coefficients. Analogously, by sending pure CSH\textsubscript{1} wave at different frequencies, the corresponding equivalent transmission coefficients can also be obtained as shown in Figure 14b. It can be seen that the transmission coefficients for all the notch depths are almost independent of the frequency of the incident CSH\textsubscript{1} wave. Moreover, no obvious change is observed when changing the notch’s depth. Therefore, CSH\textsubscript{0} mode is more useful than CSH\textsubscript{1} mode to monitor the change of the defect depth by using the transmission coefficient.

4. Summary and Conclusions

In summary, a circumferential SH wave piezoelectric transducer system was developed to monitor corrosion-like defect in large-diameter pipes. Firstly, a previously proposed bidirectional SH wave piezoelectric transducer’s performance on exciting CSH waves was investigated by using both finite element simulations and experiments. Results show that the bidirectional piezoelectric transducer is capable of exciting pure CSH\textsubscript{0} mode traveling in both circumferential directions of a 1-mm thick steel pipe from 100 to 300 kHz. All the axial guided waves and circumferential Lamb waves are suppressed within this frequency range. Moreover, the bidirectional transducer can also serve as a sensor to detect CSH\textsubscript{0} mode only by filtering CLamb waves over a wide frequency range from 100 kHz to 450 kHz. After that, a method of sizing a rectangular notch defect by using CSH\textsubscript{0} wave was proposed and then confirmed by experiments. Experiments on an 11-mm thick steel pipe show that the depth and circumferential extent of a notch can be accurately determined by using the reflection signals from the notch. This inversion method is valid only below the cutoff frequency of CSH\textsubscript{1} mode. When the operating frequency is above the first cutoff frequency, dual excitation with symmetrically mounted bidirectional transducers was validated as a useful method for selectively exciting CSH\textsubscript{0} or CSH\textsubscript{1} mode. When pure CSH\textsubscript{0} mode above the first cutoff frequency passed through notch defects, it was found that the equivalent transmission coefficients at all the frequencies decreased with the increasing of notch depth. This phenomenon was not observed when pure CSH\textsubscript{1} mode was used as the incident wave. Therefore, CSH\textsubscript{0} mode is more useful than CSH\textsubscript{1} mode to monitor the change of the defect depth by using the transmission coefficient. This work indicates that for a simple rectangular notch, defect sizing is possible by using CSH\textsubscript{0} mode. Future investigations will focus on studying the reflection and transmission characteristics of CSH waves encountering half-elliptical shaped defects, which are more approximate to corrosion defects than notches.

**Author Contributions:** Conceptualization, H.M.; Methodology, H.M. and H.Z.; Software, H.Z.; Validation, H.Z., Y.D. and J.T.; Formal Analysis, H.Z., Y.D. and H.M.; Investigation, H.Z., Y.D. and J.T.; Resources, H.Z., Y.D. and J.T.; Data Curation, H.Z.; Writing-Original Draft Preparation, H.Z.; Writing-Review & Editing, H.M and G.K.; Visualization, H.Z., Y.D. and J.T.; Supervision, H.M. and G.K.; Project Administration, H.M.; Funding Acquisition, H.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work is supported by the National Natural Science Foundation of China (11802249) and the Fundamental Research Funds for the Central Universities of China (2682019CX41 and 2682019LXCGKY002).
Conflicts of Interest: Authors declare no conflict of interest.

References
1. Su, Z.Q.; Ye, L. Identification of Damage Using Lamb Waves: From Fundamentals to Applications; Springer Science & Business Media: Heidelberg, Germany, 2009; Volume 48.
2. Guan, R.; Lu, Y.; Duan, W.; Wang, X. Guided waves for damage identification in pipeline structures: A review. Struct. Control Health Monit. 2017, 24, e2007. [CrossRef]
3. Rose, J.L. Ultrasonic Guided Waves in Solid Media; Cambridge University Press: New York, NY, USA, 2014.
4. Gazis, D.C. Three-Dimensional Investigation of the Propagation of Waves in Hollow Circular Cylinders. I. Analytical Foundation. J. Acoust. Soc. Am. 1959, 31, 568–573. [CrossRef]
5. Gazis, D.C. Three-Dimensional Investigation of the Propagation of Waves in Hollow Circular Cylinders. II. Numerical Results. J. Acoust. Soc. Am. 1959, 31, 573–578. [CrossRef]
6. Silk, M.G.; Bainton, K.F. The propagation in metal tubing of ultrasonic wave modes equivalent to Lamb waves. Ultrasonics 1979, 17, 11–19. [CrossRef]
7. Alleyne, D.N.; Lowe, M.J.S.; Cawley, P. The Reflection of Guided Waves from Circumferential Notches in Pipes. J. Appl. Mech. 1998, 65, 635–641. [CrossRef]
8. Kim, Y.Y.; Kwon, Y.E. Review of magnetostrictive patch transducers and applications in ultrasonic nondestructive testing of waveguides. Ultrasonics 2015, 62, 3–19. [CrossRef]
9. Alleyne, D.N.; Cawley, P. The excitation of Lamb waves in pipes using dry-coupled piezoelectric transducers. J. Nondestr. Eval. 1996, 15, 11–20. [CrossRef]
10. Liu, Z.H.; He, C.F.; Wu, B.; Wang, X.M.; Yang, S.M. Circumferential and longitudinal defect detection using T (0, 1) mode excited by thickness shear mode piezoelectric elements. Ultrasonics 2006, 44, e1135–e1138. [CrossRef]
11. Miao, H.C.; Huan, Q.; Wang, Q.Z.; Li, F.X. Excitation and reception of single torsional wave T (0,1) mode in pipes using face-shear d24 piezoelectric ring array. Smart Mater. Struct. 2017, 26, 025021. [CrossRef]
12. Alleyne, D.N.; Vogt, T.; Cawley, P. The choice of torsional or longitudinal excitation in guided wave pipe inspection. Insight Non-Destr. Test. Cond. Monit. 2009, 51, 373–377. [CrossRef]
13. Liu, Z.; Xie, X.; Wu, B.; Song, G.; He, C. Thick Wall Pipes Inspection by Using Circumferential Shear Horizontal Waves and Continuous Wavelet Transform Approach Tions. In Proceedings of the 2013 International Congress on Ultrasonics, Singapore, 2–5 May 2013; pp. 81–86.
14. Clough, M.; Fleming, M.; Dixon, S. Circumferential guided wave EMAT system for pipeline screening using shear horizontal ultrasound. NDT E Int. 2017, 86, 20–27. [CrossRef]
15. Howard, R.; Cegla, F. On the probability of detecting wall thinning defects with dispersive circumferential guided waves. NDT E Int. 2017, 86, 73–82. [CrossRef]
16. Howard, R.; Cegla, F. Detectability of corrosion damage with circumferential guided waves in reflection and transmission. NDT E Int. 2017, 91, 108–119. [CrossRef]
17. Luo, W.; Rose, J.L.; Van Velsor, J.K.; Avioli, M.; Spanner, J. Circumferential guided waves for defect detection in coated pipe. AIP Conf. Proc. 2006, 820, 165–172.
18. Chua, C.A.; Alleyne, D.N.; Calva, M. Crack growth monitoring using low-frequency guided waves. Insight 2017, 59, 64–71. [CrossRef]
19. Liu, G.L.; Qu, J.M. Guided circumferential waves in a circular annulus. J. Appl. Mech. Trans. ASME 1998, 65, 424–430. [CrossRef]
20. Zhao, X.L.; Rose, J.L. Guided circumferential shear horizontal waves in an isotropic hollow cylinder. J. Acoust. Soc. Am. 2004, 115, 1912–1916. [CrossRef]
21. Zhao, X.L.; Varma, V.K.; Mei, G.; Ayhan, B.; Kwan, C. In-line nondestructive inspection of mechanical dents on pipelines with guided shear horizontal wave electromagnetic acoustic transducers. J. Press. Vessel Technol. ASME 2005, 127, 304–309. [CrossRef]
22. Luo, W.; Zhao, X.L.; Rose, J.L. A guided wave plate experiment for a pipe. J. Press. Vessel Technol. ASME 2005, 127, 345–350. [CrossRef]
23. Kubrusly, A.C.; Freitas, M.A.; von der Weid, J.P.; Dixon, S. Interaction of SH guided waves with wall thinning. NDT E Int. 2019, 101, 94–103. [CrossRef]
24. Demma, A.; Cawley, P.; Lowe, M. Scattering of the fundamental shear horizontal mode from steps and notches in plates. *J. Acoust. Soc. Am.* 2003, 113, 1880–1891. [CrossRef]

25. Pau, A.; Capecchi, D.; Vestroni, F. Reciprocity principle for scattered fields from discontinuities in waveguides. *Ultrasonics* 2015, 55, 85–91. [CrossRef] [PubMed]

26. Pau, A.; Achillopoulou, D.V. Interaction of Shear and Rayleigh-Lamb Waves with Notches and Voids in Plate Waveguides. *Materials* 2017, 10, 841. [CrossRef] [PubMed]

27. Zhao, X.G.; Rose, J.L. Boundary element modeling for defect characterization potential in a wave guide. *Int. J. Solids Struct.* 2003, 40, 2645–2658. [CrossRef]

28. Wáng, S.; Huang, S.; Zhao, W.; Wei, Z. 3D modeling of circumferential SH guided waves in pipeline for axial cracking detection in ILI tools. *Ultrasonics* 2015, 56, 325–331. [CrossRef]

29. Nakamura, N.; Ogi, H.; Hirao, M.; Nakahata, K. Mode conversion behavior of SH guided wave in a tapered plate. *NDT E Int.* 2012, 45, 156–161.

30. Nurmalia, N.; Nakamura, N.; Ogi, H.; Hirao, M. Detection of Shear Horizontal Guided Waves Propagating in Aluminum Plate with Thinning Region. *Jpn. J. Appl. Phys.* 2011, 50, 07HC17. [CrossRef]

31. Kubrusly, A.C.; von der Weid, J.P.; Dixon, S. Experimental and numerical investigation of the interaction of the first four SH guided wave modes with symmetric and non-symmetric discontinuities in plates. *NDT E Int.* 2019, 108, 102175. [CrossRef]

32. Hirao, M.; Ogi, H. An SH-wave EMAT technique for gas pipeline inspection. *NDT E Int.* 1999, 32, 127–132. [CrossRef]

33. Miao, H.C.; Dong, S.X.; Li, F.X. Excitation of fundamental shear horizontal wave by using face-shear (d36) piezoelectric ceramics. *J. Appl. Phys.* 2016, 119, 174101. [CrossRef]

34. Miao, H.C.; Huan, Q.; Li, F.X. Excitation and reception of pure shear horizontal waves by using face-shear d24 mode piezoelectric wafers. *Smart Mater. Struct.* 2016, 25, 11LT01. [CrossRef]

35. Miao, H.C.; Xu, L.; Zhang, H. SH guided wave excitation by an apparent face-shear mode (d36) piezocomposite transducer: Experiments and theory. *Smart Mater. Struct.* 2019, 28, 115045. [CrossRef]

36. Huan, Q.; Chen, M.; Li, F. A Comparative Study of Three Types Shear Mode Piezoelectric Wafers in Shear Horizontal Wave Generation and Reception. *Sensors* 2018, 18, 2681. [CrossRef] [PubMed]

37. Zhou, W.; Yuan, F.G.; Shi, T. Guided torsional wave generation of a linear in-plane shear piezoelectric array in metallic pipes. *Ultrasonics* 2016, 65, 69–77. [CrossRef] [PubMed]

38. Miao, H.C.; Huan, Q.; Li, F.X.; Kang, G.Z. A variable-frequency bidirectional shear horizontal (SH) wave transducer based on dual face-shear (d24) piezoelectric wafers. *Ultrasonics* 2018, 89, 13–21. [CrossRef] [PubMed]

39. Su, Z.Q.; Ye, L. Selective generation of Lamb wave modes and their propagation characteristics in defective composite laminates. *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.* 2004, 218, 95–110. [CrossRef]

40. Kubrusly, A.C.; Freitas, M.A.; von der Weid, J.P.; Dixon, S. Mode Selectivity of SH Guided Waves by Dual Excitation and Reception Applied to Mode Conversion Analysis. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* 2018, 65, 1239–1249. [CrossRef]