Propagation Characteristics of Acoustic Emission Signals in Stiffened Cylindrical Shells Based on the Multipath Propagation Model

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Abstract: A stiffener attached to a cylindrical shell strongly interferes with the propagation of the acoustic emission (AE) signal from the fault source and reduces the fault detection accuracy. The interaction of AE signals with the stiffener on the cylindrical shell is thoroughly investigated in this paper. Based on the proposed model of the AE signal propagating inside the cylindrical shell with a stiffener, the installation constraints for the sensor are derived, resulting in the separation of the direct signal, the stiffener scattering signal, and other signals in the time domain. On this basis, combinations of the excitation frequency and the stiffener height are simulated, and the reflection and transmission of the AE signal in each case are quantitatively characterized by the scattering coefficients. The results indicate that there is a “T-shaped” transformation of the signal at the stiffener, which evolves into a variety of other modes. Moreover, the reflection and transmission coefficients of the incident AE signal are displayed as a function of the excitation frequency and the height of the stiffener. In addition, the accuracy of the scattering coefficients obtained from the numerical simulations is verified by experiments, and a good consistency between simulation results and experiment results is presented. This work illustrates the propagation characteristics of AE signals in a cylindrical shell with a stiffener, which can be used as guidance for optimizing the spatial arrangement of sensors in AE monitoring.

Keywords: acoustic emission signal; the stiffened cylindrical shell; multipath propagation model; reflection; transmission

1. Introduction

Acoustic emission (AE) technology is widely applied in structural health monitoring (SHM) and nondestructive evaluation (NDE) due to its remarkable advantages such as dynamic, sensitivity, integrity, and timeliness [1–3]. The purpose of AE detection is to obtain information about the AE source from the collected AE signals and then to estimate information about material or structural damage [4]. Many scholars have conducted research in this area. Chen et al. [5] measured the AE characteristics of collapsing holes and the movements of dislocations in Mg-Ho alloys during structural collapse, and the analysis showed that porous collapse is fully consistent with Bath’s law, while dislocation movements are not. Chen et al. [6] used the profile analysis of AE signals and characteristic parameters to distinguish dislocation movements and dynamic entanglements in fcc 316L stainless steel. Jiang et al. [7] carried out ring shear friction experiments within a certain shear rate range, and their results revealed that both shear rate and particle size affect the mechanical behavior of shear resistance, specimen compaction and slip displacement, as well as the release of acoustic energy. Salje [8] clarified the local structure of jammed twin boundary patterns using computer simulation and found that the friction in ferroelastomer and martensite...
is associated with movement of the boundary and other microstructures. Salje et al. [9] numerically simulated the microstructure changes of ferroelastic or martensitic materials during mechanical shear and their AE spectrum characteristics during strain-induced yield and detwinning. The types of AE signals generated with different strengths were analyzed from the perspective of energy. Casals et al. [10] concluded through simulations that the AE rise time better reflects the atomic avalanche time profile than the duration of the AE signal. These studies have demonstrated the potential of AE for condition monitoring and structural damage identification.

However, stiffeners are widely used on the surfaces of cylindrical shells such as engine casing or thin-walled vessels to reduce the structural weight. Complicated phenomena, such as scattering, interference, and mode conversion, occur when the fault AE signal passes through these stiffeners. These stiffeners interfere with the fault AE signal and limit the effective range, thus reducing the accuracy of fault diagnosis. Therefore, in order to clarify the interaction mechanism between the stiffeners on the cylindrical shell, such as engine casings and thin-walled vessels, and the AE signal and to improve the ability of AE technology in fault detection, it is essential to investigate the influence of stiffeners attached to cylindrical shell structures on AE signal propagation characteristics.

There are many studies in the literature on the propagation characteristics of AE signal in a cylindrical structure. Alleyne et al. [11,12] investigated the reflection of the axially symmetric guided elastic wave L(0,2) from notches in pipes, and maps of reflection coefficient as a function of the circumferential extent and depth of the defect have been presented. Lowe et al. [13] conducted a series of experiments and simulations to measure the reflection of the axially symmetric mode and of the mode-converted non-axially symmetric modes with an increase in the circumferential extent of the notch, which can be used in pipeline NDE to discriminate the axially symmetric reflectors such as circumferential welds and any non-axially symmetric defects. Zheng et al. [14] carried out numerical simulations on the propagation characteristics of L(0,2) and T(0,1) mode guided waves in pipes and their interaction with defects and demonstrated the propagation process of the ultrasonic guided waves in pipes and the modal conversion of each guided wave. Xiao et al. [15] used the explicit finite difference method to study the propagation characteristics such as reflection, transmission, and attenuation of AE signals in a straight shaft, a stepped shaft, and a stepped shaft with a tool withdrawal groove. The results were verified by experiments. Li et al. [16] analyzed the influence of the stiffeners on the lamb wave via finite element simulation and obtained the lamb wave energy factor curve while studying the impact source location in the stiffened panel of the spacecraft’s sealed bulkhead. However, the structure normally used was attached with multiple stiffeners, and research on the propagation characteristics of acoustic emission signals at a stiffener structure is scarce. Sun et al. [17] investigated the propagation characteristics of the AE wave in a fluid-loaded pipeline and the influence of pipeline auxiliary structures such as weld, tee, and flange on defect location. The results show that these structures could affect the AE signal in different degrees and then affect the fault location accuracy. Li et al. [18] proposed a leak location method for the pipeline based on a modal AE time-frequency analysis to solve the problem of large location errors caused by dispersion during AE wave propagation, which could effectively suppress the dispersion of leakage-induced AE signals. It can be seen from the literature that many explorations on the propagation characteristics and related applications of AE signals in cylindrical structures have been carried out.

However, there is little literature that reported the effect of a stiffened cylindrical shell on the propagation process of an AE signal. The propagation of AE signals in the plate with a stiffener has been studied. Reusser et al. [19,20] developed a simplified explanatory model for the scattering of guided plate waves at normal incidence upon an integral stiffener based on approximate guided wave theories. The guided wave propagation characteristics of plate stiffeners and its influence on the performance of acoustic source location were examined by experiments and simulations. It was demonstrated that operating in the frequency range of a high plate wave stiffener transmission could improve the reliability of
the source location in a plate. Pau et al. [21] shed light on the interaction of guided waves with discontinuities composed of sharp reductions in plate height and demonstrated a novel method for calculating scattering coefficients exploiting the principle of reciprocity in elastodynamics. It shows that the analytical solution provided results that coincide with those of the numerical model, which proves the effectiveness of the proposed method. Liu et al. [22] simulated the modal conversion phenomenon of a hypervelocity impact AE signal at a ring-stiffened plate. Yin et al. [23] experimentally analyzed the effects of the manned spacecraft with a stiffened panel on AE signals caused by a hypervelocity impact in wave mode, frequency domain, and time domain. The results implied that the stiffened panel had filtering effects on high frequency components of the signal. Haider et al. [24] calculated the scattering coefficients of lamb wave modes from geometric discontinuities using an analytical method called complex mode expansion with vector projection (CMEP). The obtained experimental results agrees with the global analytical predictions. Li et al. [25] studied the effects of integral stiffeners with different geometries upon vertically incident Lamb waves. Experiments and simulations showed that stiffeners acted similar to comb filters on lamb waves of different frequencies. Qi et al. [26] compared the differences in the leakage AE signals before and after passing the stiffeners in both the time domain and the frequency domain. The filtering characteristics of different frequency bands was obtained according to the proposed stiffener-passing coefficient, and the accuracy of leakage location could be improved by selecting the proper filtering frequency. In the previous study [27], the author clarified the characteristics of AE signals propagating in the plate with the stiffener and quantified the scattering of AE signals at the stiffener with a different height. It can be learned from these studies on the characteristics of signal propagating in a plate with a stiffener that using scattering coefficients to quantify the scattering characteristics of a signal is an important technical method.

The characteristics of AE signals, such as the existence mode, the propagation characteristics, and the evolution mechanism, in a stiffened cylindrical shell and a stiffened plate are different due to their structural differences. The propagation characteristics of the signal in the shell are extremely complicated compared with those of the plate, and therefore, the results obtained from the stiffened thin plate do not hold for cylindrical shells. Hence, it is essential to investigate the characteristics of the AE signal propagating in the cylindrical shell with a stiffener and to summarize the interaction mechanism between the AE signal and the stiffener on the cylindrical shell.

It is well known that the AE signal generated by faults consists of different frequencies and multiple modes. It is difficult to acquire a unique characteristic of a certain frequency or mode propagating in the structure due to the complex and confusing waveform if the acquired AE signal is analyzed as a whole. Therefore, from the perspective of the single frequency and the single mode, this paper carries out a fundamental study on the characteristics of the AE signal propagating in the cylindrical shell with a stiffener based on the determined monitoring position according to specific criteria. This study proposes the multipath propagation model about the AE signal propagate in a stiffened cylindrical shell and derives the constraint conditions for monitoring positions to separate the direct signal, stiffener scattering signals, and other signals in the time domain. On this basis, the interplay between the single-mode AE signal and the stiffener on the cylindrical shell is summarized from the numerical simulation results, and the scattering coefficient is employed to characterize the propagation characteristics of the single-mode AE signal at the stiffener with different heights. Then, the numerical simulation is validated by experiments.

In this paper, the theory and methodology are discussed in Section 2. Then, the numerical simulations and the experiments are, respectively, dealt with in Sections 3 and 4. Section 5 shows the results and discussions. Finally, the conclusions are provided in Section 6.
2. The Model for Propagation

2.1. Dispersion Characteristics

Dispersion is a phenomenon in which the propagation velocity (including group velocity and phase velocity) of ultrasonic waves in the medium varies with the frequency. Figure 1 shows the phase and group velocity dispersion curves for a cylindrical shell with an outer diameter of 1000 mm and a wall thickness of 2 mm. With reference to Figure 1, the large number of possible wave modes in a shell is illustrated in the dispersion curves, including longitudinal (L), flexural (F), and torsional (T) motions of the shell wall, which are labeled using the convention of Silk and Bainton [28]. Each mode wave is represented by an integer pair label, where the first integer gives the harmonic order of the circumferential change, and the second integer is the order list of each mode. Therefore, the mode wave with its first integer at zero is axisymmetric, while the mode wave with its first integer at one has a wave period of circumferential displacement and stress variation, etc. Dispersion curves provide useful information about dispersion characteristic of each mode, which is useful for the subsequent calculation of mode identification.

![Figure 1](image_url)

Figure 1. The dispersion curves of a cylindrical shell with an outer diameter of 1000 mm and a wall thickness of 2 mm: (a) phase velocities; (b) group velocities.

Although AE signals have several frequencies and modes originating from fault sources, it should be analyzed in terms of each mode in the fundamental study involving the propagation mechanism. The particle only has circumferential displacement for the torsional mode. When the radius of the cylinder approaches infinity, the mode T(0,1) becomes the simple shear horizontal wave in the plate. There are three displacement components in the flexural mode, which are coupled with each other. The circumferential displacement of the particle in the longitudinal mode is zero, and in the limit of the radius of the cylinder approaching infinity, the longitudinal mode corresponds to all lamb waves in the plate. Among them, the L(0,1) mode dominated by radial displacement is similar to the A_0 plate mode at low frequencies, and the L(0,2) mode dominated by axial displacement is similar to the S_0 plate mode at low frequencies [29]. The majority of the work described in this paper have been carried out using the L(0,1) mode, which is equivalent to the A_0 Lamb wave due to the more sensitive A_0 mode for different damage types [30].

2.2. Scattering from the Stiffener

Complex phenomena, such as scattering, interference, and mode conversion, occur when the fault AE signal encounters deficiencies or discontinuities, generating reflection and transmission responses with a complex superposition of multimode waves converted from the initial signal. The AE signal propagating to the stiffener produces a reflection signal, s transmitted signal, and signals traveling alongside the stiffener. A diagram of the AE signal propagating in a cylindrical shell with a stiffener is depicted in Figure 2. The AE signal propagating in the discontinuity using the scattered response can be described using reflection and transmission coefficients.
Figure 2. Diagram of the signal propagating in a stiffened cylindrical shell.

The equation of displacement for the incident wave is as follows:

\[ u_{\text{inc}} = u \cdot e^{i(kx-\omega t)} \]  

(1)

where \( u, k, \) and \( \omega \) are the amplitude, the wave number, and the angular frequency of the incident signal, respectively. The reflected signal can be described as a superposition of the incident signal mode and all reflected signal modes.

\[ u_l = u(z) \cdot e^{i(kx-\omega t)} + \sum_{n=1}^{N} u_n(z) \cdot e^{i(k_n x - \omega_n t)} \]  

(2)

where \( u(z) \) and \( u_n(z) \) represent the amplitude of the direct signal and that of the \( n \)-th reflected signal, respectively.

The reflection coefficient can be defined as the amplitude ratio of the reflection signal and the incident signal. Then, the reflection coefficients \( R_n \) of the \( n \)-th wave packet can be written as follows:

\[ R_n = \left| \frac{u_n(z)}{u(z)} \right| \]  

(3)

Similarly, the transmitted field can be described as a superposition of all transmitted wave modes.

\[ u' = \sum_{m=1}^{M} u'_m(z) \cdot e^{i(k_m x - \omega_m t)} \]  

(4)

where \( u'_m(z) \) indicates the amplitude for the \( m \)-th transmitted wave. Additionally, the transmission coefficient \( T_m \) of the \( m \)-th wave packet can be calculated as follows:

\[ T_m = \left| \frac{u'_m(z)}{u_0(z)} \right| \]  

(5)

where \( u'_0(z) \) denotes the amplitude of the incident wave propagating to the same position in the unstiffened cylindrical shell.

2.3. Determination of the Optimal Position of the Sensor

A key element of the excitation signal is the selection and exploitation of a single mode. In this study, the single frequency of the AE excitation signal is generated by applying a modulated sinusoidal function, which could reduce the bandwidth for the signal to minimize the dispersion. The excitation signal is exerted to the cylindrical shell, and the AE signal mainly in \( L(0,1) \) mode is obtained. The excitation equation \( Y(t) \) is written as follows:

\[ Y(t) = X(t) \cdot H(t) = \sin(2\pi f_c t) \times [0.5 - 0.5 \times \cos(2\pi f_c t / B)] \]  

(6)
where $H(t)$ is the window function; $f_c$ is the central frequency for the exciting signal; $B$ refers to the amount of peak, here taking 3; and $X(t)$ represents the carrier signal.

The signal then spreads out in all directions based on the composite feature of the structure. The original signal and the signal scattered from edges and characteristic structures arrive at the sensor in order and overlap with each other with their respective phases. To distinguish the main echoes in the stiffened cylindrical shell in the time domain and to highlight the effect of the stiffener on the AE signal, the multipath propagation model for AE signals propagating in the stiffened cylindrical shell is established in this paper, as shown in Figure 3.

![Figure 3](image-url)

**Figure 3.** The propagation model for the cylindrical shell with the stiffener: (a) several reflection paths; (b) several transmission paths.

Figure 3 illustrates multiple simplified shortest signal propagation paths, which include a shortest direct path ($s_1$ and $g_1$) and several other paths ($s_2$, $s_3$, $s_4$, $s_5$, $g_2$, $g_3$, $g_4$, and $g_5$). The direct path refers only the segment between the excitation point (EP) and measurement points for reflection (R) and transmission (T). Other paths not only include indirect paths involving the first segmentation between EP and structural features (such as the edge, stiffener, etc.) and the second segmentation between structural features and R or T but also involves paths where signals travel from EP to R or T after propagating around the circumference. Therefore, the relative positions of EP, R, T, and the stiffener are very important for distinguishing signals of interest. Calculating the arrival time of the mentioned wave in conformity with the corresponding propagation path can derive the installation constraints about ES, R, and T to separate the signal of interest from other unwanted signals in the time domain. In order to maximize the value of the proposed model, not only should EP, R, and T be co-linear but also the connection line should be perpendicular to the plane where the stiffener is located.

As the AE signal is applied at EP in Figure 3, the excited signal propagates towards different directions guided by the features of the structure. The propagation directions of the signals reflected from edges of the cylindrical shell are dominated by Snell’s law [31]:

$$k_i \cdot \sin(\theta_i) = k_r \cdot \sin(\theta_r)$$

(7)

where $k_i$ and $\theta_i$ are the wavenumber and angle of the incident wave, respectively, and $k_r$ and $\theta_r$ represent the wavenumber and the angle of the reflected wave. Regarding the propagation paths such as $r_5$, $r_6$, $t_2$, and $t_5$, the signal is incident vertical to the edge of the cylindrical shell. In this situation, it is assumed that, for the edge of the plate, the incident $A_0$ mode reflects $A_0$ only and that the $S_0$ mode reflects $S_0$. Similarly, it can also be assumed that, at the edge of the cylindrical shell, the incident L(0,1) mode is reflected as only L(0,1), while the L(0,2) mode is reflected as only L(0,2). Due to no mode conversion occurring, the propagation velocity and the wave number of each mode remain the same as before. Therefore, the angle of incidence and that of reflection are also unchanged.

$$\theta_i = \theta_r$$

(8)
Hence, for the propagation paths \( r_5, r_6, t_2, \) and \( t_5 \), the signal is reflected vertically at the edge. Then, ES and R should satisfy following equations:

\[
\begin{aligned}
T(D_t) &= T(s_1) = \frac{l(s_1)}{v_{L(0,1)}} \\
T(RS) &= T(s_2) = \frac{l(s_2)}{v_{L(0,1)}} \\
T(circle_1) &= T(s_3) = \frac{l(s_3)}{v_{F(1,1)}} \\
T(RE_1) &= T(s_5) = \frac{l(s_5)}{v_{L(0,1)}} \\
T(RE_2) &= T(s_6) = \frac{l(s_6)}{v_{L(0,1)}}
\end{aligned}
\]  

(9)

where \( T(D_t) \) is the time as the direct signal propagating acquired in R; \( T(RS) \) is the propagating time of the signal reflected from the stiffener acquired in R; \( T(circle_1) \), \( T(RE_1) \), and \( T(RE_2) \) are the propagating times acquired in R of the signal propagating around the circumference and signals reflected from edges in the cylindrical shell; \( l(s_j) \) is the length of the path \( s_j \), where \( j = 1, 2, 3, 4, 5, 6 \); and \( v_{L(0,1)} \) and \( v_{F(1,1)} \) are the group velocities of \( L(0,1) \) mode and \( F(1,1) \) mode in the cylindrical shell, respectively.

The parameters in Figure 3 are obtained by the following:

\[
\begin{aligned}
l(s_1) &= d_1 \\
l(s_2) &= d_1 + 2d_2 \\
l(s_3) &= \frac{\sqrt{(d_1)^2 + (2\pi a)^2}}{v_{F(1,1)}} \\
l(s_5) &= 2d_4 + d_1 \\
l(s_6) &= d_1 + 2d_2 + 2d_3 + 2d_5
\end{aligned}
\]  

(10)

The constraint conditions in the time domain for separating the reflected signal from the direct signal and other waves are as follows:

\[
\begin{aligned}
\Delta T_1 &= T(RS) - T(D_t) \geq B/f_c \\
\Delta T_2 &= T(circle_1) - T(RS) \geq B/f_c \\
\Delta T_3 &= T(RE_1) - T(RS) \geq B/f_c \\
\Delta T_4 &= T(RE_2) - T(RS) \geq B/f_c
\end{aligned}
\]  

(11)

Substituting Equations (9) and (10) into Equation (11), the specific separation conditions for the reflection are obtained:

\[
\begin{aligned}
d_2 &\geq \frac{B \times v_{L(0,1)}}{2f_c} \\
\frac{\sqrt{(d_1)^2 + (2\pi a)^2}}{v_{F(1,1)}} - \frac{d_1 + 2d_2}{v_{L(0,1)}} &\geq \frac{B}{f_c} \\
d_4 &\geq \frac{B \times v_{L(0,1)}}{2f_c} + d_2 \\
d_3 + d_5 &\geq \frac{B \times v_{L(0,1)}}{2f_c}
\end{aligned}
\]  

(12)

Hence, the positions for EP and R that satisfy the separation conditions about the interested reflected signal can be deduced from Equation (12).

Transmission paths such as \( g_1, g_2, g_3, g_4, \) and \( g_5 \) should be calculated in the same way to find the position of \( T \).

\[
\begin{aligned}
T'(D_t) &= T(g_1) = \frac{l(g_1)}{v_{L(0,1)}} \\
T(circle_2) &= T(g_3) = \frac{l(g_3)}{v_{L(0,1)}} \\
T'(RE_1) &= T(g_2) = \frac{l(g_2)}{v_{L(0,1)}} \\
T'(RE_2) &= T(g_5) = \frac{l(g_5)}{v_{L(0,1)}}
\end{aligned}
\]  

(13)

where \( T'(D_t), T(circle_2), T'(RE_1), \) and \( T'(RE_2) \) are the propagation times acquired in \( T \) for the signal transmitted from the stiffener, signals propagating around the circumference, and signals reflected from edges in the cylindrical shell, respectively. \( l(g_a) \) is the length of propagation path \( g_a \), where \( a = 1, 2, 3, 4, 5 \). Based on the parameters in Figure 3, the equations can be written as follows:

\[
\begin{aligned}
l(g_1) &= d_1 + d_2 + d_3 \\
l(g_3) &= \frac{\sqrt{(d_1 + d_2 + d_3)^2 + (2\pi a)^2}}{v_{L(0,1)}} \\
l(g_2) &= d_1 + d_2 + d_3 + 2d_5 \\
l(g_5) &= d_1 + d_2 + d_3 + 2d_4
\end{aligned}
\]  

(14)
The specific separation conditions for the transmission can be inferred as follows:

\[
\begin{align*}
\Delta T_5 &= T(circ((D_1)) - T'(D_1) \geq B/f_c \\
\Delta T_6 &= T'(RE_1) - T(D_1) \geq B/f_c \\
\Delta T_7 &= T'(RE_2) - T(D_1) \geq B/f_c
\end{align*}
\] (15)

Substituting Equations (13) and (14) into Equation (15), a system of equations that enable us to separate the transmission signals from other signals is obtained.

\[
\begin{align*}
\sqrt{\left(d_1 + d_2 + d_3\right)^2 + \left(2\pi a\right)^2} - \frac{d_1 + d_2 + d_3}{v_g(F(1,1))} &\geq \frac{B}{f_c} \\
d_5 &\geq \frac{2v_g(L(0,1))}{B} \\
d_4 &\geq \frac{2v_g(L(0,1))}{B}
\end{align*}
\] (16)

3. Simulations

A 3-D finite element model (FEM) of the stiffened cylindrical shell was built for numerical analysis of the interaction between the AE signal and the stiffener. The corresponding specification is shown in Figure 4.

![Figure 4](image-url)

**Figure 4.** The 3-D model for the cylindrical shell with a stiffener used in simulations.

The outer diameter for the cylindrical shell in the model was 1000 mm, the wall thickness was 2 mm, and the axial length was 600 mm. The stiffener’s axial length was 5 mm, and the outer diameter was (1000 + 2h) mm. The stiffener was attached to the cylindrical shell and located in the middle of the shell. h varied from 0 to 40 mm for different demands and practical dimensions. A dynamic displacements was excited along the z-axis on ES to generate the simulated AE signal with L(0,1) mode as the main mode. The excitation signal was a modulated sinusoidal pulse with three cycles, with its center frequency \(f_c\) varying from 100 kHz to 170 kHz based on the bandwidth in which fatigue cracks occur and grow. The time domain waveform for the excited signal with \(f_c = 150\) kHz is shown in Figure 5. The parameters that meet the waveform separation conditions in Section 2.3 were specifically chosen as \(d_1 = 30\) mm, \(d_2 = 50\) mm, \(d_3 = 100\) mm, \(d_4 = 220\) mm, and \(d_5 = 200\) mm, which was utilized to determine the placements of EP, R, and T.

Table 1 summarizes the material properties employed in the simulations. Free boundary conditions are imposed to the FEM in simulations ensuring consistency between simulations and experiments. All FEM models are meshed by tetrahedral grid elements. To ensure proper calculation precision and convergence, for the wave with the highest frequency, more than 20 elements in the wavelength were used, and the time step was set
to at least 1/20 of the highest frequency. Therefore, the maximum cell grid is 0.2 µs, and the time step is determined to be 0.7 mm. To reduce the time cost of simulation, the response period obtained from simulations continues for 0.15 ms, which contained the interested scattered signals.

Figure 5. The time domain waveform for the excited signal with \( f_c = 150 \) kHz.

Table 1. Properties of the employed material.

| Material Name | \( E/\text{GPa} \) | \( v \) | \( \rho/\text{kg/m}^3 \) |
|---------------|-----------------|--------|-----------------|
| Aluminum      | 70              | 0.33   | 2700            |

4. Experiments

The experiments are performed on two aluminum specimens sharing the same material properties as the model in the simulation. Specimen 1 was a cylindrical shell with an outer diameter of 1000 mm, a wall thickness of 2 mm, and an axial length of 600 mm. Specimen 2 was a stiffened cylindrical shell. The cylindrical shell was the same as in specimen 1. The stiffener was attached to the cylindrical shell and located in the middle. The axial length of the stiffener was 5 mm, and the outer diameter was 1032 mm. The positions of the sensors were selected on the conclusions in Section 2.3 and correspond to the settings in the simulations for both specimens.

Schematic diagrams of the experimental system and equipment are illustrated in Figures 6 and 7, respectively. The experiment set up consists of three modules. The excitation wave generator generates a sinusoidal tone sweeping from 100 kHz to 170 kHz in steps of 10 kHz. The signal is delivered to the specimen via sensor #1. Sensor #2 and sensor #3 are, respectively, used to measure the reflection and transmission signals in the signal acquisition module. At each excitation frequency, the reflection and transmission response are recorded and then are sent to the AE system via the pre-amplifier. A resonant sensor is used in the experiments, and a coupling agent is added between the sensor and the specimen. Table 2 shows the acquisition setup of the AE software.

Table 2. Parametric settings for AE system acquisition.

| Parameter      | Sampling Rate /MHz | Sampling Points /k | Threshold /dB | Preamplifier /dB | Pre-Trigger /µs |
|----------------|--------------------|--------------------|---------------|-----------------|-----------------|
| Value          | 2.5                | 1                  | 40            | 40              | 256             |
5. Results, Analysis, and Discussion

5.1. The Process of Signal Propagation

Figure 8 displays the simulated displacement contour plot in the z-direction before and after the stiffener is used at the given time instants after the AE signal with $f_c = 150\text{ kHz}$ encountering the stiffener at $h = 16\text{ mm}$.

With reference to Figure 8, the stiffener interferes with the signal propagation. This figure clearly shows that the stiffener influences the signal propagation. The excited AE signal dominated by the $L(0,1)$ mode spreads around at the beginning and then interacts with the stiffener. A mode conversion can be observed, which interferes with the propagation of the original signal, as shown in Figure 8b–d. These scattered waves with multiple modes and other waves (including the wave reflected from edges and the wave traveling around the circumference) were then received successively by R and T. Although their propagation phenomenon is complicated, it should be noted that the color of $L(0,1)$ is darker than that of $L(0,2)$, which indicates that the $L(0,1)$ mode accounts for the dominant component in propagation.
A qualitative description about the interaction between the L(0,1) mode and a change in the height of the stiffener is presented below. Figures 9 and 10, respectively, show the time amplitude relations acquired by R and T for the reflection and transmission of the incident L(0,1) signal with a stiffener at different heights. The incident wave and reflected waves can be easily distinguished in the response received at R, while the response received at T is all transmitted waves. This confirms that not only do reflection and transmission occur but also multiple modes are generated via the “T-shape” transformation along with mode conversion when the incident wave encounters the stiffener. Different heights of the stiffener and the difference between the wave velocities of each mode wave lead to the different arrival times of scattered waves reaching R and T. Then, these waves overlap with each other at receivers, which explains the responses presenting different superposition shapes, as shown in Figures 9b–f and 10b–f.

Figure 8. The simulated displacement contour in the z-direction as the AE signal propagates in the cylindrical shell with the stiffener when \( f_c = 150 \) kHz and \( h = 16 \) mm.

Figure 9. The partial reflected waveform in the z-direction acquired by R \( (f_c = 150 \) kHz).
Figure 10. The partial transmitted waveform in the z-direction acquired by T ($f_c = 150$ kHz).

5.2. Propagation Mechanism

According to the proposed multipath propagation model and the group velocity in Figure 1, the arrival time of each mode wave is calculated to identify the received wave packet and mode. The arrival time can be estimated using the numerical simulation ($T_s$) and the theoretical calculation ($T_c$). The results obtained by the two methods are compared to prove the effectiveness and consistency. The arrival times of each interested mode wave scattered from the stiffener with $f_c = 150$ kHz and $h = 32$ mm are marked in Figure 11. The incident L(0,1) mode, reflected L(0,1) mode, and transmitted L(0,1) mode can be easily distinguished in Figure 11, which proves that determining the installation position of sensors based on the proposed model in Section 2.3 is feasible.

Figure 11. Reflection and transmission waveforms with $f_c = 150$ kHz and $h = 32$ mm: (a) reflection; (b) waveform.

As seen in Figure 11a, three modes are identified: the incident L(0,1) mode, the reflected L(0,2) mode (converted from the incident L(0,1) mode, denoted as L’(0,2)/L(0,1)), and the reflected L(0,1) mode from the incident L(0,1) mode (denoted as L’(0,1)/L(0,1)). In Figure 11b, the first group of waves is the converted L(0,2) mode, which is produced when the incident L(0,1) mode interacts with the stiffener, denoted as L(0,2)/L(0,1). Additionally, the second mode is the transmitted L(0,1) mode from the incident L(0,1) mode, denoted as L(0,1)/L(0,1).

Table 3 shows the comparison of the arrival time obtained using both the numerical simulation and the theoretical calculation. The estimated arrival times obtained by the two methods are in close agreement because of the presented less time difference. Accordingly,
the mechanism about the single-frequency AE signal mainly in L(0,1) mode propagating in the cylindrical shell with the stiffener can be summarized, as shown in Figure 12.

Table 3. The comparison about the arrival time of each wave with $f_c = 150$ kHz and $h = 32$ mm.

| Symbol  | Description                  | $T_c/\mu$s | $T_s/\mu$s | $\Delta T = |T_s - T_c|/\mu$s |
|---------|------------------------------|------------|------------|--------------------------|
| $t_{iL(0,1)}$ | Incident L(0,1) mode       | 20.0       | 19.8       | 0.2                      |
| $t_{rL(0,2)}$ | Reflected L(0,2) mode       | 48.6       | 44.2       | 4.4                      |
| $t_{rL(0,1)}$ | Reflected L(0,1) mode       | 58.6       | 56.2       | 2.4                      |
| $t_{tL(0,2)}$ | Transmitted L(0,2) mode     | 57.9       | 57.2       | 0.7                      |
| $t_{tL(0,1)}$ | Transmitted L(0,1) mode     | 77.9       | 72.4       | 5.5                      |

Figure 12. The mechanism of the L(0,1) mode propagates in the cylindrical shell with the stiffener.

It can be noticed that the L(0,1) mode wave propagating to the bottom of the stiffener has a “T-shaped” transformation to result in the reflected wave (L′(0,1)/L(0,1)), the transmitted wave (L(0,1)/L(0,1)), and the wave propagating alongside the stiffener. In contrast, mode conversion appears and produces a little L(0,2) mode wave when the incident L(0,1) mode wave interacts with the stiffener. The produced L(0,2) mode wave mainly propagates in two directions, namely the reflected wave (L′(0,2)/L(0,1)) and the transmitted wave (L(0,2)/L(0,1)). These mode waves also propagate alongside the stiffener, while their energy is negligible. The wave propagating alongside the stiffener is reflected at the stiffener’s end and then goes back into the cylindrical shell where mode conversion appears again to produce the reflected waves (L′′(0,1)/L(0,1) and L′′(0,2)/L(0,1)) and transmitted waves (L′′′(0,1)/L(0,1) and L′′′(0,2)/L(0,1)) with less energy.

5.3. Reflection and Transmission Coefficients

Simulations have been performed for each case with different excitation frequencies ($f_c$) and different stiffener heights ($h$), and the scattering coefficient in each case can be computed using Equations (3) and (5). The obtained scattering coefficients of the incident L(0,1) mode are reported in Figure 13 for different frequencies and stiffener heights, which are calculated by the scattering coefficients presented in Section 2.2. It can be observed that the reflection and transmission coefficients are displayed as a function of the excitation frequency and the height of the stiffener. Figure 14 extracts the scattering coefficients calculated at different frequencies, including 110 kHz, 130 kHz, 150 kHz, and 170 kHz, to further study the underlying characteristics.

From Figure 14, it should be noted that the reflection coefficient shows a special trend with respect to $f_c$ and $h$, while the trend of the transmission coefficient is roughly the opposite. The reflection coefficient for the incident A0 mode reaches the maximum value of around 0.4 when $h$ is about 5 mm, while the transmission coefficient acquires the minimum value of around 0.2 for the same $h$. Regarding the stiffener with larger heights, the effect of stiffeners on the coefficients decreases gradually, and both coefficients appear to be stable.
Moreover, the reflection coefficient and the transmission coefficient can be considered in three portions in terms of the rate of change versus $h$, namely the sensitive part, the fluctuation part, and the stable part, as shown in Figure 14. The corresponding regions are region I, region II, and region III. It is a noticeable phenomenon that the reflection coefficient and the transmission coefficient in region I present linear variations with the increase in $h$. The difference is that the reflection coefficient increases monotonously to the maximum as $h$ increases, but the transmission coefficient, which monotonously reduces to the minimum value, shows the opposite in this region. With the increase in $h$ in region II, the reflection coefficients fluctuate and show a downward trend. Conversely, the transmission coefficient fluctuates oppositely but has a slight upward trend, and the rate of change is relatively high. This intuitively indicates that both the reflection coefficient and the transmission coefficient change with respect to $h$ are nonlinear. Both the reflection coefficient and the transmission coefficient remain basically unchanged in region III. It can be reasonably deduced that the reflection coefficient and transmission coefficient are not very sensitive to the height of the stiffener increasing after $h$ exceeds a certain value.

Additionally, for different $f_c$, the rate of variation of the reflection coefficient and transmission coefficient versus $h$ differs a little. If the frequency increases, critical points between the three parts shift to smaller $h$ regions, that is, the sensitivity to the presence of $h$ increases. Maximum values of the reflection coefficient under different $f_c$ all appear at smaller $h$ regions (around $h = 5$), but minimum transmission coefficients appear at the same $h$. Although the critical points between region I and region II under different $f_c$ are located within a small range, it can still be observed that the $h$ corresponding to the critical point has a slight decreasing trend as $f_c$ increases. However, the $h$ corresponding to the critical points between region II and region III clearly reveals a decreasing trend with an increase
in $f_c$. As for $f_c = 100$ kHz, both the reflection coefficient and the transmission coefficient present stable trends with a slight fluctuation when $h > 33$ mm. However, for $f_c = 170$ kHz, the both coefficients stabilize after $h$ exceeds about 25 mm. It can be indicated from the above that, with the increase in $f_c$, not only the sensitivity of the signal to the variation of stiffener’s height increases but also the critical point between regions appears earlier.

Further analysis was carried out to gather statistics on the scattering coefficient in all regions for $f_c = 150$ kHz, as shown in Figure 15. The top and bottom lines in Figure 15, respectively, represent the maximum value and the minimum value of each data group. The top and bottom lines of the box are the 25th and the 75th percentile, the line inside the box indicates the median, and $\times$ indicates the mean of the data. Figure 15 shows information about the center, extension, and distribution status of several batches of data. The transmission coefficients in each region have more obvious advantages than the reflection coefficients in statistical parameters such as the mean, median, and distribution range. The distribution of both reflection and transmission coefficients in each region shows that the transmission coefficient is more widely distributed than the reflection coefficient. This means that the transmission coefficient varies more within the same range of the stiffener height. Consequently, it can be concluded that the transmission coefficient is more sensitive to the variation in the stiffener’s height than the reflection coefficient. In addition, the reflection and transmission coefficients in region I are more widely distributed and the data are more dispersed than those in regions II and III. It can be inferred that the reflection coefficient and the transmission coefficient in region I are most sensitive to the change in $h$ among the three regions.

![Figure 15. Distribution of reflection and transmission coefficients in different regions with $f_c = 150$ kHz.](image.jpg)

### 5.4. Experimental Results

Experiments on the unstiffened cylindrical shell are used as a reference signal for different $f_c$. Several minutes are maintained between each measurement to allow the experimental results to not be interfered by previous signals. It is noteworthy that the sensor attached at the reflection measuring point should be removed to avoid the influence of the sensor on the transmission signal when collecting the transmission waveform. The reflection waveform and the transmission waveform are received by following a similar procedure on the stiffened cylindrical shell. The experimental results are depicted in Figures 16 and 17.
Figure 16. Reflected waveforms collected experimentally on specimen 1 (blue curves) and specimen 2 (red curves) under different $f_c$.

Figure 17. Transmitted waveforms collected experimentally on specimen 1 (blue curves) and specimen 2 (red curves) under different $f_c$.

Figure 16 shows a comparison between the reflection waveforms collected from specimen 1 and specimen 2, while Figure 17 focuses on a comparison of the transmitted waves. The results show that the incident L(0,1) mode, the reflected L(0,1) mode, and the transmitted L(0,1) mode can be successfully distinguished and recognized based on the sensor arrangement, which confirms that arranging sensors based on the proposed model
in Section 2.3 is feasible. Figure 18 compares the experimentally calculated reflection and transmission coefficients related to the incident L(0,1) mode with the simulated reflection and transmission coefficients as well as the errors between them.

![Graphs of reflection and transmission coefficients](image)

**Figure 18.** Comparison of scattering coefficients obtained from simulations (solid lines) and experiments (dashed lines): (a) reflection; (b) transmission.

It can be seen from Figure 18 that the experimental points are always close to the predicted points, which demonstrates that scattering coefficients curves are satisfactorily verified within the acceptable margin of errors. These results are encouraging in that the simulation characterizing the propagation of the AE signal in a cylindrical shell with a stiffener has been demonstrated.

6. Conclusions

This paper investigates the interaction of an AE signal with a stiffened cylindrical shell. The following conclusions can be drawn.

1. The multipath propagation model for the signal propagating in a stiffened cylindrical shell is established, and the constraint conditions for the position of sensors are derived. Numerical simulations and experiments are employed to verify the proposed signal multipath propagation model. The model has the ability to separate and identify the signals of interest in the time domain, which paves the way for further research.

2. The mechanism of the AE signal mainly in L(0,1) mode interacting with the stiffener is summarized. When the incident signal interacts with the stiffener, the signal uses a “T-shaped” transformation to produce reflected waves, transmitted waves, and waves propagating alongside the stiffener. Additionally, mode conversion takes place to produce new modes. The first reflected and transmitted waves are dominant, and the mode conversion waves are negligible.

3. The variation in scattering coefficients is calculated for different excitation frequencies and for a range of heights of the stiffener in the simulations. Then, the accuracy of the scattering coefficient is verified by the experiment. The results show the dependence of reflection and transmission coefficients on the stiffener’s height and the center frequency of the excitation signal. Additionally, at the same excitation frequency, the transmission coefficient has a higher sensitivity to the variation in the stiffener’s height than the reflection coefficient.

This paper characterizes the characteristics of the AE signal propagating in the stiffened cylindrical shell. The results of this paper lead to a better understanding of the propagation mechanism about the AE signal in a complicated structure. The proposed model provides a reference for guiding and optimizing the installation of sensors in AE monitoring.
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**References**

1. Solodov, I.; Bernhardt, Y.; Kreutzbruck, M. Resonant Airborne Acoustic Emission for Nondestructive Testing and Defect Imaging in Composites. *Appl. Sci.* 2021, *11*, 10141. [CrossRef]

2. Si, K.; Cui, Z.; Peng, R.; Zhao, L.; Zhao, Y. Crack Propagation Process and Seismogenic Mechanisms of Rock Due to the Influence of Freezing and Thawing. *Appl. Sci.* 2021, *11*, 9601. [CrossRef]

3. Ebrahimkhlanou, A.; Dubuc, B.; Salamone, S. A generalizable deep learning framework for localizing and characterizing acoustic emission sources in riveted metallic panels. *Mech. Syst. Signal Pr.* 2019, *130*, 248–272. [CrossRef]

4. Li, G.; Liu, S. An overview of the development of acoustic emission signal analysis technique. In Proceedings of the 10th China Acoustic Emission Symposium, Daqing, China, 30 July 2004; pp. 52–62.

5. Chen, Y.; Ding, X.D.; Fang, D.Q.; Sun, J.; Salje, E.K.H. Acoustic emission from porous collapse and moving dislocations in granular Mg-Ho alloys under compression and tension. *Sci. Rep.-UK* 2019, *9*, 1330. [CrossRef]

6. Chen, Y.; Gou, B.Y.; Fu, W.; Chen, C.; Ding, X.D.; Sun, J.; Salje, E.K.H. Fine structures of acoustic emission spectra: How to separate dislocation movements and entanglements in 316L stainless steel. *Appl. Phys. Lett.* 2020, *117*, 262901. [CrossRef]

7. Jiang, Y.; Wang, G.H.; Kamai, T. Acoustic emission signature of mechanical failure: Insights from ring-shear friction experiments on granular materials. *Geophys. Res. Lett.* 2017, *44*, 2782–2791. [CrossRef]

8. Salje, E.K.H. Friction in ferroelastic and martensitic materials. In Proceedings of the 1st International Conference on Rheology and Modeling of Materials, Miskolc, Hungary, 7–11 October 2013. [CrossRef]

9. Salje, E.K.H.; Wang, X.; Ding, X.; Sun, J. Simulating acoustic emission: The noise of collapsing domains. *Phys. Rev. B* 2014, *80*, 064103. [CrossRef]

10. Casals, B.; Dahmen, K.A.; Gou, B.Y.; Rooke, S.; Salje, E.K.H. The duration-energy-size enigma for acoustic emission. *Sci. Rep.* 2021, *11*, 5590. [CrossRef] [PubMed]

11. 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]

12. Demma, A.; Cawley, P.; Lowe, M.J.S.; Roosenbrand, A.G.; Pavlakovic, B. The reflection of guided waves from notches in pipes: A guide for interpreting corrosion measurements. *NDT E Int.* 2004, *37*, 167–180. [CrossRef]

13. Lowe, M.J.S.; Alleyne, D.N.; Cawley, P. The mode conversion of a guided wave by a part-circumferential notch in a pipe. *J. Appl. Mech.* 1998, *65*, 649–656. [CrossRef]

14. Zheng, M.; Lu, C.; Chen, G.; Men, P. Numerical modeling of ultrasonic guided wave testing in hollow cylinder using ABAQUS. In Proceedings of the 4th Nondestructive Testing Higher Education Development Forum and Electromagnetic Ultrasonic Nondestructive Testing Technology Symposium, Qingdao, China, 30 July 2011; Volume 33, pp. 70–74.

15. Xiao, Y.; Lu, W.; Chu, F. Propagation characteristics of acoustic emission in different structural shafts. *J. Vib. Shock* 2014, *33*, 76–81. [CrossRef]

16. Li, Y.; Wang, Z.; Rui, X.; Qi, L.; Liu, J.; Yang, Z. Impact Location on a Fan-Ring Shaped High-Stiffened Panel Using Adaptive Energy Compensation Threshold Filtering Method. *Appl. Sci.* 2019, *9*, 1763. [CrossRef]

17. Sun, L.; Li, Y.; Jin, S.; Liu, T.; Wang, W. Study on propagation and attenuation characteristics of acoustic emission wave propagation along fluid loaded pipeline. *Piezoelectrics Acoustooptics* 2008, *30*, 401–403. [CrossRef]

18. Li, S.; Wang, P.; Yan, D.; Wang, P.; Huang, X. Leak location in gas pipelines with time-frequency analysis of modal acoustic emission using smooth pseudo Wigner-Ville distribution. *Chin. J. Sci. Instrum.* 2016, *37*, 2068–2075. [CrossRef]

19. Reusser, R.S.; Holland, S.D.; Chimenti, D.E.; Roberts, R.A. Reflection and transmission of guided ultrasonic plate waves by vertical stiffeners. *J. Acoust. Soc. Am.* 2014, *136*, 170–182. [CrossRef]

20. Reusser, R.S.; Chimenti, D.E.; Roberts, R.A.; Holland, S.D. Guided plate wave scattering at vertical stiffeners and its effect on source location. *Ultrasonics* 2012, *52*, 687–693. [CrossRef] [PubMed]
21. Pau, A.; Achillepoulou, D.V.; Vestroni, F. Scattering of guided shear waves in plates with discontinuities. *NDT E Int.* 2016, 84, 67–75. [CrossRef]

22. Liu, Z.; Pang, B.; Liu, G. Hypervelocity impact induced AE wave mode conversion in a plate with vertical stiffeners. *J. Vib. Shock* 2014, 33, 114–118. [CrossRef]

23. Yin, Z.; Hou, X.; Guo, J.; Liu, Y.; Hao, P. Experimental study on transmission characteristics of acoustic emission signal caused by hypervelocity impact on manned spacecraft with stiffened panel. *ACTA Acust.* 2017, 42, 281–289. [CrossRef]

24. Mohammad, F.H.; Yeasin, B.M.; Banibrata, P.; Bin, L.; Victor, G. Analytical and experimental investigation of the interaction of Lamb waves in a stiffened aluminum plate with a horizontal crack at the root of the stiffener. *J. Sound Vib.* 2018, 431, 212–225. [CrossRef]

25. Li, Y.; Liu, Y.; Rui, X. Effects of stiffeners on transmission of lamb waves in plate-like structures. *ACTA Acust.* 2019, 44, 231–240. [CrossRef]

26. Qi, L.; Yue, G.; Shao, R.; Sun, L.; Rui, X.; Sun, W. Research on propagation characteristic of leakage acoustic emission signal in spacecraft stiffened plate and its effect on leakage location method. *Manned Spacefl.* 2021, 27, 34–39. [CrossRef]

27. Han, C.; Yang, G.; Wang, J.; Guo, X. The research on propagation characteristics of acoustic emission signals in stiffened plates based on the multipath propagation model. *Ultrasonics* 2020, 108, 106177. [CrossRef] [PubMed]

28. 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]

29. Lowe, M.J.S.; Alleyne, D.N.; Cawley, P. Defect detection in pipes using guided waves. *Ultrasonics* 1998, 36, 147–154. [CrossRef]

30. Bijudas, C.R.; Mitra, M.; Mujumdar, P.M. Time reversed Lamb wave for damage detection in a stiffened aluminum plate. *Smart Mater. Struct.* 2013, 22, 105026. [CrossRef]

31. Santhanam, S.; Demirli, R. Reflection of Lamb waves obliquely incident on the free edge of a plate. *Ultrasonics* 2013, 53, 271–282. [CrossRef]