



Study on Ultrasonic Detection Method for Lead Seal Defects in High-Voltage Cable Terminals

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SUMMARY: *The lead seal is an important component of high-voltage cable terminals. Internal defects such as pores or cracks may occur due to poor installation quality or external forces during operation. To mitigate the potential risks to the safe operation of the power grid posed by lead seal defects, this paper proposes an ultrasonic detection method for detecting such defects. Based on the structural characteristics of the cable terminal lead seal, the method in this study adopts COMSOL simulation software to perform ultrasonic simulations on typical defects of high-voltage cable terminal lead seals, revealing the propagation characteristics and patterns of ultrasonic waves in lead seal defects. This study also conducts ultrasonic detection experiments on lead seal samples with artificial defects. The results show that ultrasonic waves reflect and transmit at pore defect locations, and defects at different positions can be accurately identified through defect echo time and amplitude. This method verifies the feasibility of applying ultrasonic detection technology to detect lead seal defects in cable terminals and provides a reference for detecting such defects.*

KEYWORDS: *High-voltage cable; Terminal lead seal; Ultrasonic detection; Defect identification*

1 Introduction

High-voltage cable terminals, being a critical part of transmission lines, are composed of materials such as tail pipes, aluminum sheaths, and lead seals. The lead pouring process, as one of the key techniques in manufacturing high-voltage cable terminal accessories, directly affects the safe and stable operation of high-voltage cables [1, 2].

Currently, the production of high-voltage cable accessories still largely relies on manual on-site operations, including processes like conductor crimping and the sealing of copper tubes to aluminum sheaths with lead seals. Poor installation quality, external forces or vibrations during operation, can lead to cracks and holes in the lead seal of the cable terminal. In severe cases, this may cause unplanned outages in the power grid [3-5]. To ensure the safe and stable operation of cables and their accessories and to detect whether defects exist within the lead seals of high-voltage cable terminals, as well as to identify the types and sizes of these defects, there is an urgent need to develop effective methods to quickly and accurately detect internal defects in cable terminal lead seals.

At present, various detection technologies such as X-ray detection, infrared detection, partial discharge detection, electric field distributed detection, and metal sheath ground-ing current detection have been widely used in diagnosing defects in power cable accessories [6].

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However, the complex structure of actual cable terminal lead seals and the limitations of these methods, such as complex operation, long detection time, unclear imaging, and low detection accuracy, prevent them from being effectively applied to the detection of lead seal defects in cable terminals. Ultrasonic defect detection methods, however, offer significant advantages, including convenient operation, low cost, fast detection speed, and accurate defect location. These methods have been widely used in detecting defects in insulators, pipes, and plate components, yielding good detection results [7, 8].

Xie Congzhen *et al.* [9] used conventional ultrasonic non-destructive testing methods to detect internal pore defects in composite insulators, successfully detecting smaller pore defects and verifying the feasibility of using ultrasonic waves to detect internal defects in complex structures. However, this method cannot achieve good coupling between the ultrasonic probe and objects with large curvatures. Gao Ying *et al.* [10] used the ultrasonic pulse-echo method to detect internal defects in composite insulators submerged in water, detecting small defects in the sheds. This method allows ultrasonic detection of objects with large curvatures but requires immersing the object to be tested in water, which affects its subsequent use. Xue Guanghui *et al.* [11] used ultrasonic detection technology to assess the crimping quality of crimped workpieces, achieving radial and axial detection accuracy of up to 0.1 mm, verifying the feasibility and effectiveness of ultrasonic detection technology for crimp quality assessment. Wang *et al.* [12] established simulation models to analyze the propagation patterns of sound waves under different defect conditions for common defects in spot welding such as indentations, cracks, and shrinkage holes. Cao Jun-ping *et al.* [13] used eddy current detection methods to conduct experiments on cracking defects in high-voltage cable terminal lead seals, achieving good results. However, this method has limitations, as it can only detect cracking defects in lead seals and cannot effectively detect defects within the lead seal or between the lead seal and the aluminum sheath. Given the special nature of the materials and structure of cable terminal lead seals, it is crucial to study the feasibility of using ultrasonic detection technology to achieve non-destructive testing.

This paper studies the detection of typical defects in cable terminal lead seals using ultrasonic detection technology. COMSOL, a multiphysics simulation software, is utilized to analyze the propagation characteristics and patterns of sound waves under different defect conditions in high-voltage cable terminal lead seals. Simultaneously, samples with typical lead seal defects are fabricated for ultrasonic defect detection experiments. By analyzing the simulation and experimental results, this paper evaluates the feasibility of using ultrasonic detection technology to detect defects in cable terminal lead seals. Sensor design

2 Principle of Ultrasonic Testing and Model Establishment

2.1 Ultrasonic Testing Theory

Ultrasonic waves are elastic vibration waves with frequencies higher than 20 kHz. The frequency range commonly used in ultrasonic non-destructive testing is 0.5 to 10 MHz. The propagation process of ultrasonic waves follows Newton's second law, the law of conservation of energy, and the law of conservation of momentum. Due to differences in the acoustic properties of different materials, when ultrasonic waves pass from one medium into another with a different acoustic impedance, refraction and reflection occur at the heterogeneous interface. The greater the difference in acoustic impedance between the two media, the stronger the reflection.

As shown in Figure 1, when a sound wave from medium I is incident perpendicularly into medium II, the acoustic impedances of medium I and medium II are Z_1 and Z_2 , respectively.

Part of the incident wave I_o becomes a transmitted wave with an intensity I_t , and another part of the energy is reflected back from the interface between medium I and medium II, forming a reflected wave with an intensity I_r . According to the law of conservation of energy [14]:

$$I_o = I_t + I_r \tag{1}$$

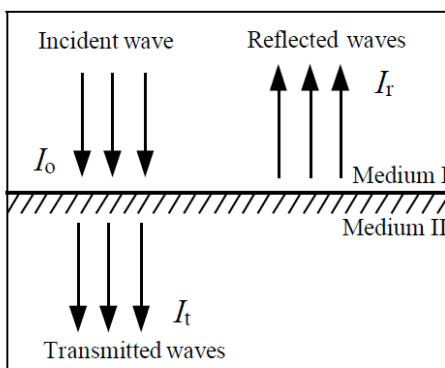


Figure 1: Reflection and Transmission of Sound Waves at Normal Incidence

In actual field tests, the sound pressures of the reflected wave, incident wave, and transmitted wave are represented as P_r , P_o , and P_t respectively. The sound pressure reflection coefficient R and sound intensity transmission coefficient T at the interface can be expressed as follows:

$$R = \frac{P_r}{P_o} = \frac{z_2 - z_1}{z_1 + z_2} \tag{2}$$

$$T = \frac{P_t}{P_o} = \frac{2z_2}{z_1 + z_2} \tag{3}$$

The ultrasonic transmission parameters of the materials involved in lead seal defect testing are shown in Table 1. When the ultrasonic beam is reflected at the interface between the lead seal and the aluminum sheath, its sound pressure reflection coefficient R is 0.18, indicating that the reflection coefficient is very small and the ultrasonic beam is not easily reflected at this interface. When the ultrasonic beam is reflected by a defect containing air, since the acoustic impedance value of air is almost zero, its sound pressure reflection coefficient $R = -1$

Table 1: Ultrasonic Transmission Parameters

Material	Velocity/ ($m \cdot s^{-1}$)	Density/ ($g \cdot cm^{-3}$)	Acoustic impedance/ ($g \cdot cm^{-3} \cdot s^{-1}$)
Plumbum	2200	11.34	2.46×10^6
Aluminium	6300	2.7	1.7×10^6
Air	340	1.29×10^{-3}	0.0004×10^6

In this paper, a transient driving pulse is used to simulate ultrasonic waves, studying the propagation characteristics of ultrasonic waves vertically loaded on the model surface. The driving signal is modulated using a corresponding Gaussian window function. The driving signal function is:

$$f(t) = e^{\left\{-\left[\frac{(t-T_0)}{(T_0/2)}\right]^2\right\}} \times \sin(2\pi ft) \quad (4)$$

where f is the center frequency of the transducer, t is the time variable, and T_0 is the period of the driving signal. When the center frequency of the signal is set to 5 MHz, the excitation signal waveform is shown in Fig.2.

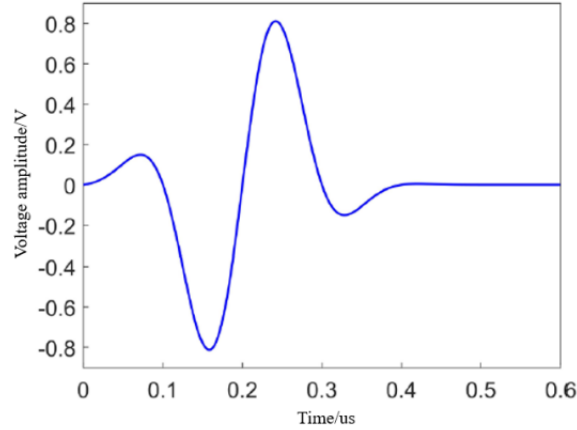


Figure 2: Excitation Signal Waveform

2.2 Ultrasonic Sound Field Simulation Model

The structure of the cable terminal lead seal is complex, with an arched surface, large curvature, and difficult ultrasonic coupling. Therefore the propagation of sound waves within it is quite intricate. To better understand the propagation of sound waves inside the lead seal, COMSOL's acoustic-solid coupling field is employed for ultrasonic simulation calculations on the cable terminal lead seal defects. In the simulation model, the probe, terminal lead seal, and defect structures are appropriately simplified, and a two-dimensional model with proper boundary conditions is utilized to simulate the three-dimensional calculations. The model is shown in Fig.3. The lead seal has a bottom length of 10 cm, a maximum thickness of 3 cm, an internal defect diameter of 1 mm, and a defect diameter of 3 mm at the interface between the lead seal and the aluminum sheath layer.

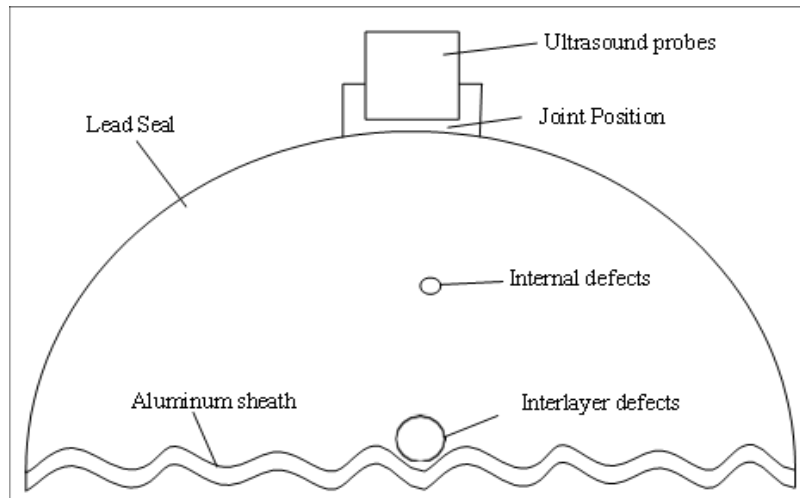


Figure 3: Simulation Model of Cable Terminal Lead Seal

3 Acoustic Field Characteristics of Cable Terminal Lead Seal Defects

3.1 Internal Defects in Lead Seals

Ultrasonic detection simulations were performed to study the effect of lead seal defects on the propagation characteristics of ultrasound. When an internal defect in the lead seal is located 1 cm from the upper surface, the transient distribution simulation results of the internal sound field are shown in Figure 4. As the ultrasonic wave propagates within the lead seal, reflection and transmission occur at the defect. At $2.7 \mu\text{s}$, the sound wave reaches the defect location. The defect reflection echo reaches the coupling point between the probe and the lead seal surface at $5.4 \mu\text{s}$, and the defect transmission wave reaches the bottom aluminum sheath at $7.06 \mu\text{s}$. Fig.5 illustrates the internal defect echo. At one-third of the echo position, a significant internal defect reflection echo appears, which matches well with the position of the internal defect in the simulation model. The bottom aluminum sheath of the lead seal is corrugated, which affects ultrasonic reflection and scattering, causing significant attenuation of the bottom surface reflection echo.

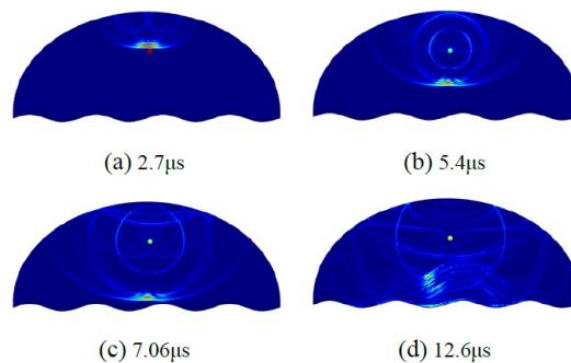


Figure 4: Transient Acoustic Field Distribution of Internal Defects

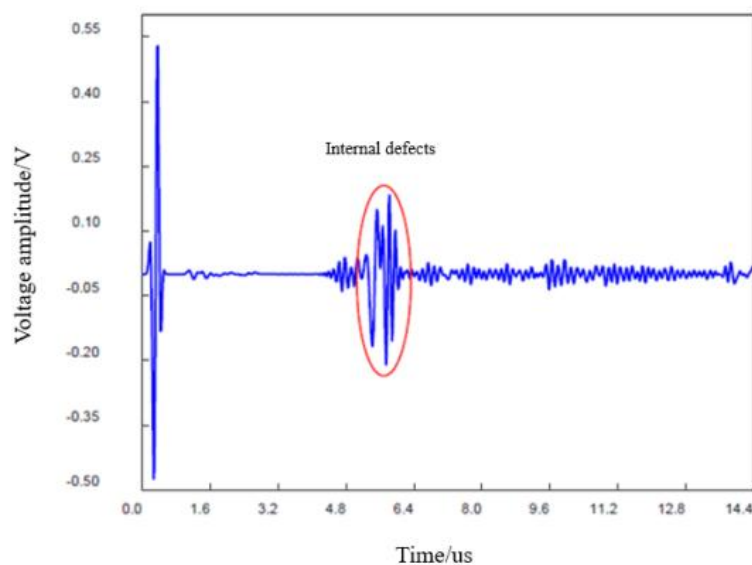


Figure 5: Simulation echo of internal defects in the lead seal

3.2 Interlayer Defects in Lead Seals

The interlayer defect is located at the junction between the lead seal and the aluminum sheath. The transient simulation results of the internal sound field are shown in Fig. 6. At $6.5 \mu\text{s}$, the sound wave reaches the defect location, causing partial reflection. The defect echo reaches the coupling point between the probe and the lead seal surface at $12.58 \mu\text{s}$ and is received by the probe. The interlayer defect echo is shown in Fig.7. A significant amplitude interlayer defect echo appears before the echo from the bottom surface of the aluminum sheath, which matches well with the position of the interlayer defect in the simulation model.

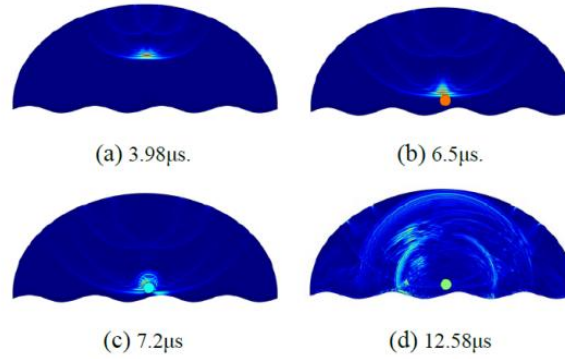


Figure 6: Transient Acoustic Field Distribution of Interlayer Defects

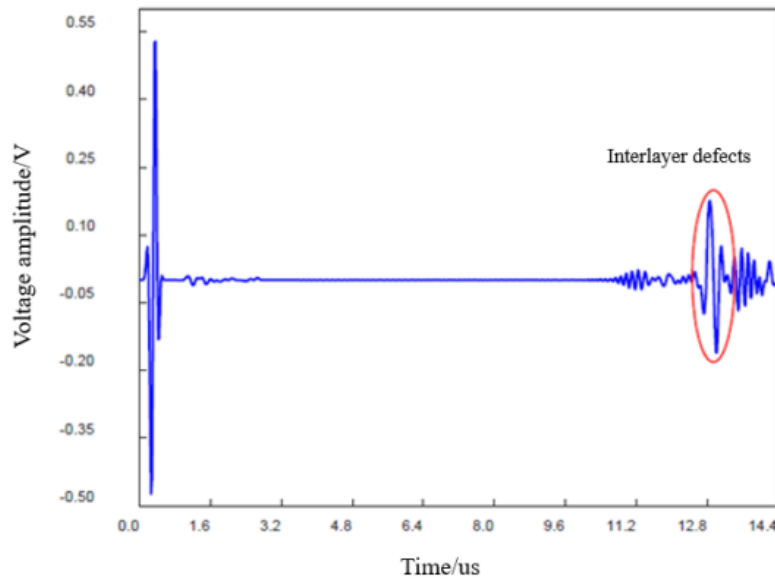


Figure 7: Simulation echo of defects in the lead seal layer

3.3 Internal and Interlayer Defects in Lead Seals

To further investigate the impact of multiple defects within the lead seal on the propagation characteristics of ultrasound, a model with both internal defects and interlayer defects is established to observe their impact on ultrasonic defect detection. Fig. 8 shows the transient distribution of the internal sound field, where reflection and transmission occur at the two defect locations. Fig. 9 presents the ultrasonic defect echo diagram. In the entire defect echo waveform, two distinct defect echoes appear. The positions of these echoes are identified to be from the internal defect and the interlayer defect, respectively. This indicates that as the position of the

lead seal defect changes, the defect reflection echo shifts accordingly, which matches well with the positions of the lead seal defects in the simulation model.

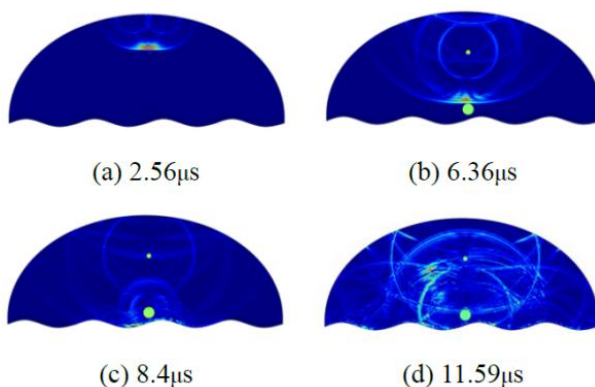


Figure 8: Transient Acoustic Field Distribution of Internal and Interlayer Defects

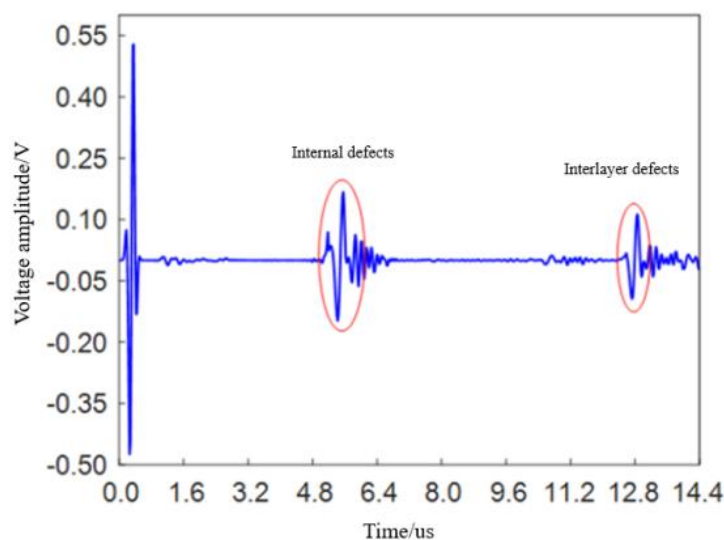


Figure 9: Simulation echo of Internal and Interlayer Defects in Lead Seal

4 Cable Terminal Lead Seal Defect Experiment

4.1 Test Samples

Common terminal lead seal failures in high-voltage power cable systems during operation are shown in Fig.10.

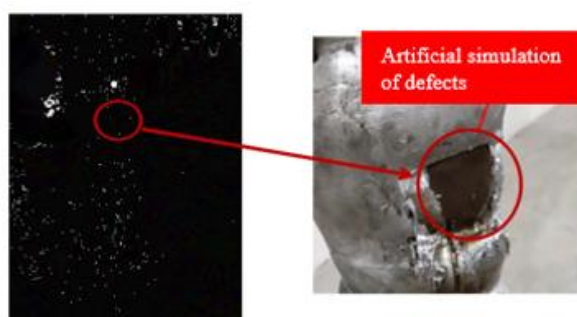


Figure 10: Failures in High-Voltage Cable Lead Seals

To simulate defects that might occur in the lead seals of cable terminals during power grid operation, three types of artificial defect samples were fabricated: internal defect samples, interlayer defect samples, and samples with both internal and interlayer defects.

Method for Fabricating Defects

The lead seals at cable terminals are manufactured using lead pouring or lead touching methods. During the making of defect samples, it is challenging to artificially simulate defects such as pores, cracks, and delamination directly. Therefore, materials with significantly different acoustic impedances compared to lead are used to simulate pores. Fig.11 shows the fabrication of lead seal defects, the schematic diagram of defect locations, and the appearance of the samples.



(a) Drawing of seal defects



(b) Sample appearance of cable termination seal

Figure 11: Cable Terminal Lead Seal Sample

4.2 Experimental Platform

The test setup for detecting defects in cable terminal lead seals, as shown in Fig.12, consists mainly of the cable terminal lead seal samples, ultrasonic probe, power supply, digital controller, and display system. During the detection process, the ultrasonic probe is in direct contact with the lead seal surface through a couplant. The ultrasonic waves penetrate the lead seal sample, and the reflected signals are processed by the digital controller, which converts them into waveforms displayed on the system interface.

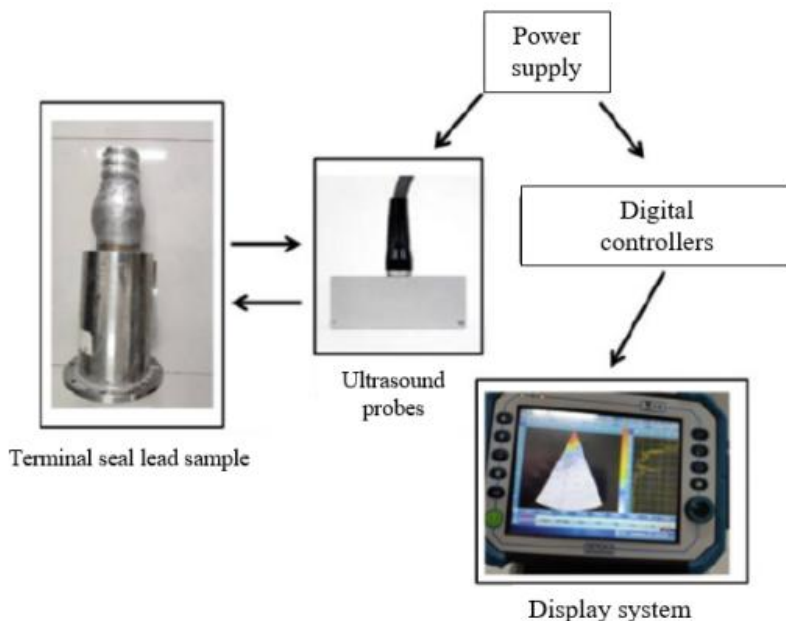


Figure 12: Experimental Setup for Detecting Cable Terminal Lead Seal Defects

Due to the large curvature of the lead seal surface, directly contacting the ultrasonic probe with the lead seal surface results in poor coupling. Therefore, this study uses the water immersion technique, placing the ultrasonic probe in a device sealed at the bottom with a silicone rubber membrane. Compared to the traditional water immersion method, where the sample is directly placed in water, placing the ultrasonic probe in water for defect detection does not affect the sample. In actual testing, water is injected into the device as a couplant, and the device is placed over the sample to be tested. The silicone rubber membrane has excellent elasticity, allowing good coupling between the water in the device and the lead seal. Magnetic field distribution of sensor antenna coils in different environments

5 Waveform Identification and Analysis of Typical Lead Seal Defects

5.1 Internal Defects in Lead Seals

Using ultrasonic equipment, the internal defect sample of the lead seal was detected, and the A-scan echo is shown in Figure 13. A distinct defect echo signal appears at 14.4–18.0 mm, which can be identified as an echo from an internal defect in the lead seal. Some clutter appears before the defect echo, mainly because the horizontal ultrasonic probe cannot completely adhere to the curved surface of the lead seal.

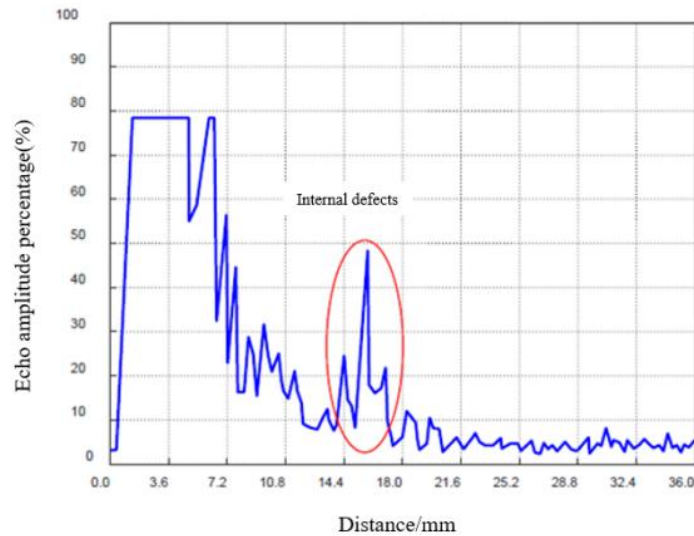


Figure 13: Detection echo of Internal Defects in Lead Seal

5.2 Interlayer Defects in Lead Seals

When the defect is located between the lead seal and the aluminum sheath, the corresponding A-scan ultrasonic echo is shown in Figure 14, with the defect echo located at 25.2–28.8 mm. It can be observed that as the distance between the defect and the ultrasonic probe changes, the position of the defect echo imaged by the ultrasonic equipment also changes accordingly. Compared to the internal defect echo, the distance from the interlayer defect echo to the ultrasonic probe is farther than that of the internal defect echo, which matches the actual situation. This indicates that the defect location can be identified by the defect echo.

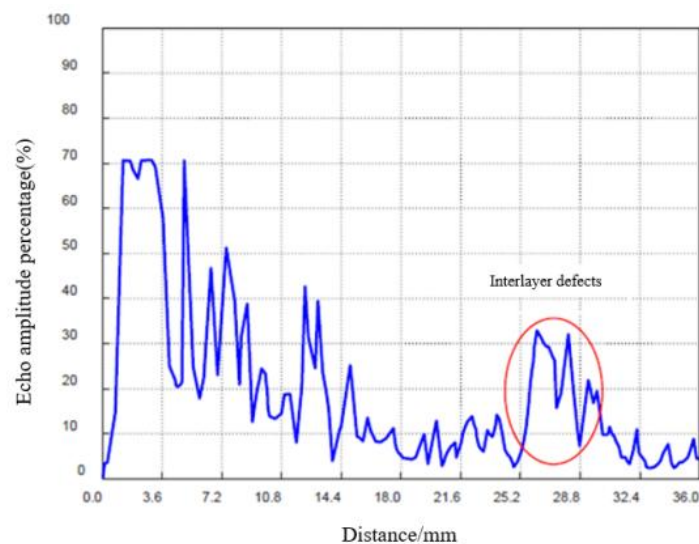


Figure 14: Detection echo of Interlayer Defects in Lead Seal and Aluminum Sheath

5.3 Internal and Interlayer Defects in Lead Seals

When the cable terminal lead seal sample has defects at both its internal and interlayer positions, as shown in Figure 15, the A-scan echo shows two high-amplitude defect echoes at the 18.0–21.6 mm and 25.2–28.8 mm positions.. Compared with the previous two tests, the two defect echoes correspond to the internal defect and the interlayer defect echoes, respectively. This

demonstrates that as the distance between the defect and the probe changes, the position of the defect echo detected by the ultrasonic equipment also changes accordingly.

Simulation and detection experiment results suggest that when defects are present simultaneously in different locations within the lead seal, ultrasonic detection methods can accurately determine the presence and type of defects in the lead seal through defect echoes. This also confirms that defects in different locations do not affect the ultrasonic detection results.

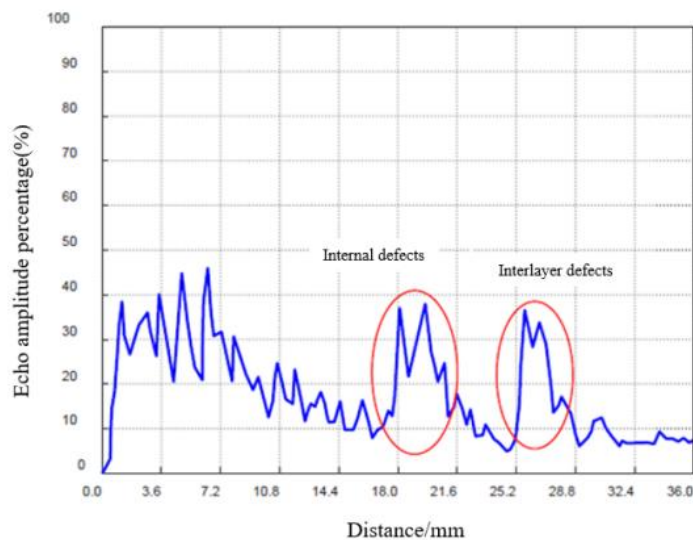


Figure 15: Detection echo of Internal and Interlayer Defects in Cable Lead Seal

6 Conclusion

1. By using COMSOL Multiphysics software to simulate the detection of lead seal defects with pores at the cable terminal, this study examines the impact of lead seal defects at different locations on ultrasonic wave propagation characteristics. The results demonstrate that ultrasonic waves reflect and transmit at the defect location, with the defect echo dynamically shifting in accordance with the defect's position.

2. This study also employs ultrasonic detection methods to test the lead seal defects at the cable terminal, identifying internal and interlayer defects in the lead seal. The defect echoes were clear, allowing for the simultaneous distinction of defects at two different locations.

3. By using ultrasonic detection methods to overcome the difficulties in detecting lead seal defects, this study validates the feasibility of this method for lead seal defect detection through testing on lead seal defect samples, making online detection of cable terminal lead seal defects possible.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest regarding the publication of this paper. The authors have no financial or personal relationships that could have inappropriately influenced this work.

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