Journal of Architectural Research and Development, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Application Strategy of Ultrasonic Non-destructive Testing Technology in Bridge Engineering

Shulin Tan[1], Xu Meng[1], Lei Chen[2], Zhi Tu[1]

[1]China Merchants Chongqing Testing Center for Highway Engineering Co., Ltd., Chongqing 400067, China
[2]Chongqing Dazu District Transportation Commission, Chongqing 402360, China

Abstract: The purpose of this study is to analyze the application of ultrasonic non-destructive testing technology in bridge engineering. During the research phase, based on literature collection and reading, as well as the analysis of bridge inspection materials, the principle of ultrasonic non-destructive testing technology and its adaptability to bridge engineering are elaborated. Subsequently, starting from the preparation work before inspection until damage assessment, the entire process of ultrasonic non-destructive testing is studied, and finally, a technical system of ultrasonic non-destructive testing for bridge engineering that runs through the entire process is formed. It is hoped that this article can provide technical reference value for relevant units in China, and promote the high-quality development of China's bridge engineering from a macro perspective.

Keywords: Ultrasonic; Bridge engineering; Non-destructive testing; Signal filtering

Online publication: May 30, 2025

1. Introduction

During the construction and operation of bridge engineering, it will be subjected to long-term dynamic loads and environmental erosion. The early identification of internal damage to the bridge engineering structure directly affects the safety and service life of the bridge engineering. Traditional bridge engineering detection techniques, such as visual inspection and hammering methods, are highly dependent on manual experience and have deviations in subjective judgment dimensions. They can only detect surface defects of the structure and cannot effectively detect concealed problems such as internal cavities in the concrete and corrosion of steel bars. Moreover, traditional techniques often require some damage to the structure itself [1]. Ultrasonic non-destructive testing technology utilizes the propagation characteristics of sound and analyzes parameters such as sound velocity and waveform to obtain internal compactness information without damaging the structure's surface. This enables precise positioning and quantitative assessment of internal defects in the bridge structure. Additionally, its non-destructive and rapid detection advantages can reduce interference with the normal use of the bridge and establish a structural health archive for the bridge through periodic inspections, effectively compensating for the deficiencies of traditional detection techniques in dynamic detection, detection depth, and accuracy.

2. Principles of ultrasonic non-destructive testing technology and its adaptability to bridge engineering

2.1. Principles of ultrasonic non-destructive testing

2.1.1. Propagation characteristics of sound waves

Ultrasonic waves, as mechanical waves with a frequency greater than 20 kHz, have propagation characteristics that are closely related to the density of the transmission medium. Based on wave theory, within a medium, the propagation speed (v) of sound waves follows a relationship with the elasticity (E) and density (ρ) of the material, represented by $v = \sqrt{\frac{E}{\rho}}$. The relationship between the propagation frequency (f), wavelength (λ), and wave speed is expressed by $f = \frac{v}{\lambda}$. As the material density increases, the wave speed decreases, the wavelength shortens, and the frequency response changes accordingly. Simultaneously, the attenuation coefficient (α) is directly proportional to the square of the frequency and is associated with the material density and defects in its internal structure. If cracks appear inside the material, the scattering of sound waves will intensify, leading to significant attenuation of energy.

2.1.2. Classification of waveforms

Based on the relationship between the direction of vibration and the direction of propagation, ultrasonic waves can be classified into longitudinal waves, transverse waves, and surface waves. Among them, longitudinal waves have extremely high propagation efficiency in a medium with uniform density, and the wave speed is significantly affected by density. The vibration direction of the particle in a transverse wave is perpendicular to the direction of propagation. When encountering areas with density changes, refraction and mode conversion phenomena are prone to occur, so they are often used to detect internal defects in buildings and bridge structures. Surface waves propagate along the surface of the material, and energy attenuation is related to the surface roughness and near-surface density changes of the material, making them highly suitable for detecting surface damage in bridge structures [2]. The frequency, wavelength, and attenuation characteristics of different waveforms can provide multi-dimensional information for highly complex layered detection of bridge structures.

2.1.3. Echo signal analysis

When ultrasonic waves are generated by equipment and encounter interfaces with different acoustic impedances within the material (such as internal defects or internal layers), reflection echoes are produced. By analyzing the arrival time, amplitude, and frequency components of the reflected echoes, the internal structural characteristics of the material can be deduced. Differences in wave speed caused by changes in density will result in changes in echo time delay. Scattering and reflection at defect sites will cause significant attenuation of echo amplitude, and high-frequency components will be preferentially lost. Therefore, combining spectrum analysis and waveform feature analysis can quantify the size, location, and uniformity of internal defects in the material, providing data-level support for structural health evaluation [3].

2.2. Suitability of ultrasonic detection for bridge engineering

2.2.1. Applicable scenarios

In bridge engineering, ultrasonic detection technology, with its unique penetration characteristics, can precisely locate complex defects inside concrete. For voids inside the concrete of bridge structures, when ultrasonic waves encounter voids during propagation, they will scatter and diffract due to the discontinuity of the medium. The sound time at the receiving end will be extended, and the wave amplitude will attenuate. Based on the analysis of these acoustic parameter changes, the location and size of the voids can be determined. For the detection of steel corrosion, corrosion will change the acoustic impedance parameters of the steel and concrete interface. When the equipment emits ultrasonic waves, the reflection signal strength and frequency characteristics of the sound waves at this interface will change accordingly. This can be used to determine whether the steel is corroded and the degree of corrosion [4]. During the crack depth detection stage, based on the principle of ultrasonic diffraction, diffraction occurs when the wave propagates to the crack tip area. By measuring the sound time during which the sound wave bypasses the crack, combined with the analysis of the speed of sound in concrete, the depth of the crack can be calculated.

2.2.2. Technical advantages

The advantages of ultrasonic detection applied to bridge inspection are reflected in its non-contact, high-resolution, and repeatability. Firstly, the non-contact feature allows the technology to be used in bridge inspection without damaging the surface of the structure, effectively reducing the negative impact of inspection work on the normal use of the bridge. This feature is highly suitable for bridge projects that have already been put into operation. Secondly, the high-resolution characteristic of ultrasonic detection enables it to capture millimeter-level defect changes. Both tiny cracks and subtle voids can be clearly presented in the inspection results, greatly satisfying the precision requirements of bridge engineering inspection. Thirdly, ultrasonic detection technology has strong repeatability. The standardized inspection process, combined with advanced equipment, can stably obtain reliable inspection results at different times and with different inspection personnel backgrounds, which is helpful for continuous monitoring of the structural health of bridges [5].

3. Application of ultrasonic non-destructive testing technology in bridge engineering

3.1. Preparation before testing

Before conducting ultrasonic non-destructive testing, multi-dimensional preparation work needs to be completed. Firstly, in terms of testing equipment selection, the inspection team needs to select ultrasonic detectors and probes with appropriate frequencies based on the component size, material characteristics, and inspection objectives of the bridge. For example, for non-destructive testing of large-volume concrete components, low-frequency probes should be preferred to ensure the penetration ability of ultrasonic waves. For the inspection of thin-walled components and near-surface defects, high-frequency probes should be used to improve resolution.

Secondly, before the inspection work, a detailed site survey of the bridge inspection area needs to be carried out, combining survey data to clearly identify the type, size, and appearance damage information of the components. At the same time, key inspection areas such as piers, beam connections, and surrounding areas of prestressed anchors, which are prone to stress concentration, should be determined based on the bridge engineering design drawings. Additionally, special personnel should be arranged to clean the inspection surface, completely removing laitance, oil stains, and loose layer impurities. After grinding and leveling the inspection points, a suitable amount of coupling agent, such as Vaseline or paste, should be applied to ensure that the probe can closely fit the inspection surface and reduce the loss of sound energy during the inspection process [6].

In addition, it is necessary to strictly establish reference values for inspection parameters before testing. Acoustic parameters such as sound velocity and sound time should be measured for defect-free areas of components, which will serve as a basis for comparative analysis of subsequent inspection results. **Table 1** shows the reference parameters for ultrasonic inspection of common bridge materials:

Table 1. Ultrasonic inspection parameters for bridge structures

Material type	Applicable probe frequency(kHz)	Reference sound speed(m/s)
Concrete	20–500	3000–4500
Steel	500–1000	5900–6100
Stone	50–300	3500–5000

3.2. On-site operation

Key points of on-site operation include designing the scanning path, setting key detection parameters, and real-time signal detection.

3.2.1. Scanning path design

In the scanning path design phase, reasonable planning should be based on the shape of the component and the predicted direction of defects. For regular-shaped components, such as bridge beams and piers, a grid-like scanning pattern is recommended. The grid spacing can be uniformly set based on the detection accuracy, typically ranging from 10cm to 30cm. For areas of the bridge where cracks or voids are suspected, the scanning path should be densified, and cross-scanning and fan-shaped scanning should be used to ensure effective coverage of defective areas. Additionally, during the scanning process, inspectors need to strictly mark the moving direction and starting position of the probe to facilitate subsequent data analysis and tracing [7].

3.2.2. Key parameter settings

During the inspection phase, the reasonable setting of key parameters has a direct impact on the accuracy of the inspection results. In the inspection operation phase, the transmission voltage should be set flexibly based on the sound attenuation level of the material in the bridge inspection area. For example, for high-attenuation materials such as old concrete, the transmission voltage should be appropriately increased to enhance the signal strength. Meanwhile, the sampling frequency should satisfy the Nyquist sampling theorem (the sampling frequency must be at least twice the highest frequency of the signal), and can typically be set to 5–10 times the detection frequency to ensure complete acquisition of the echo signal. **Table 2** provides references for key parameter settings in different inspection scenarios.

Table 2. Key parameter settings for different inspection scenarios

Purpose of detection	Sampling frequency(MHz)	Transmission voltage(V)
Concrete cavity detection	5–10	200–400
Steel corrosion detection	10–20	150–300
Crack depth detection	1–5	100–250

3.2.3. Real-time signal monitoring

During the inspection process, a dedicated person should be arranged to observe the waveform interface of the ultrasonic detector in real-time, monitoring changes in parameters such as sound time, amplitude, and frequency. Once abnormal signals such as a sudden drop in amplitude, prolonged sound time, or multiple occurrences of reflected waves are encountered, scanning should be suspended immediately. Repeated inspections and multi-angle verifications should be carried out for the abnormal areas to ensure the authenticity of the reflected signals. At the same time, a dedicated person should be arranged to record the specific location and signal characteristics of the abnormal signals, providing clues for subsequent deep analysis of the data [8].

3.3 Data processing and analysis of inspection results

The key points of data processing and analysis of inspection results lie in signal filtering, defect localization, and damage evaluation.

3.3.1. Signal filtering

The original ultrasonic signals collected by the equipment are highly susceptible to negative effects caused by environmental noise and instrument interference. Therefore, targeted filtering processing is required for the ultrasonic signals. In this process, a band-pass filter device is first used to adjust the filter's passband range based on the center frequency and bandwidth of the ultrasonic probe used during the inspection. For example, if a 50 kHz probe is used, the band-pass filter can be set to 45–55 kHz to effectively filter out all interference signals outside this frequency band. For other random noise mixed with the ultrasonic waves, such as white noise, a median filtering algorithm can be used. The sampling points within the detected signal are taken as the center of the filtering process, and the window length is reasonably set, such as 5–11 sampling points.

Subsequently, the median value within the window replaces the original sampling value, preserving the edge characteristics of the signal while effectively suppressing noise. Additionally, if there is periodic interference in the ultrasonic signal, the LMS (Least Mean Squares) adaptive filtering algorithm can be used. By comparing the reference signal with the original signal, the algorithm automatically adjusts the filter coefficients to dynamically cancel the interference signal. After processing the ultrasonic signal, a spectrum analysis tool should be used to verify the effectiveness of the filtering treatment, ensuring that the defect characteristic frequency components in the signal are completely preserved [9].

3.3.2. Defect localization

Defect localization can be achieved through the use of the "time-of-flight to distance" method combined with geometric calculations. For internal voids in the concrete of bridge components, the first step is to measure the sound velocity (v) in a non-defective area of the component. Then, test points are set up in suspected defective areas to send ultrasonic waves, and the time (t) it takes for the sound wave to travel from emission to reception is measured. If the measurement results show that the sound travel time at a certain measurement point is greater than that in the normal area, the coordinates of that point are recorded. Subsequently, that point is used as the center for sound travel time measurements in multiple directions. Based on the increase in sound travel time (Δt), the additional propagation distance of the ultrasonic wave after bypassing the void is calculated. This, combined with geometric triangular relationships, allows for the confirmation of the boundary position and size of the void.

During the detection of crack depth in bridge components, the single-sided measurement method can be adopted. Measurement points are arranged on both sides of the crack, and the first wave sound travel time and distance are measured. Then, crack depth calculations are performed using Equation 1:

$$h = \frac{\sqrt{(vt_2)^2 - L_2^2} + \sqrt{(vt_2)^2 - L_1^2}}{2} \tag{1}$$

In Equation 1, v represents the sound velocity of concrete. For complex cracks, the position of the measurement points should be changed multiple times to cross-validate the detection results.

3.3.3. Damage assessment

The main basis for damage assessment is the type of defect and quantitative assessment of inspection data. For concrete voids in bridge structures, the detected void volume can be compared to the total volume of the component. If the proportion of void volume exceeds 3%, it can be judged as severe damage. A level of 1% to 3%

can be judged as moderate damage, and below 1% can be judged as minor damage. For the detection of corrosion of internal steel bars in bridge components, the level of corrosion can be assessed based on the attenuation of the reflected signal amplitude of ultrasonic waves at the steel bar-concrete interface. If the attenuation exceeds 50% of the original signal, it indicates significant loss of steel bar cross-sectional area, requiring special attention. If the attenuation is in the range of 20% to 50%, it can be judged as moderate corrosion, and below 20% can be judged as minor corrosion. For crack damage assessment, the length, width, and depth of the crack need to be comprehensively considered. If the crack length is greater than 1m, the width is greater than 0.3mm, and the depth penetrates through the component, this situation should be regarded as a crack that seriously affects structural safety. If the crack length is 0.5 to 1m and the width is 0.1 to 0.3mm, the crack can be judged as moderate damage. Cracks with a length less than 0.5m and a width less than 0.1mm can be judged as minor damage [10].

4. Conclusion

This study explores the application of ultrasonic non-destructive testing technology in bridge engineering. After introducing the principles of ultrasonic non-destructive testing and its suitability for bridge engineering inspection, the key points of the application process are discussed in detail. Ultrasonic non-destructive testing can effectively compensate for the deficiencies of traditional bridge engineering inspection techniques, enabling precise detection and evaluation of internal defects in bridges without disrupting their normal operation. In the future, with the development of technology, it is believed that ultrasonic non-destructive testing technology will gradually achieve deep integration with artificial intelligence, big data, and other technologies, further enhancing the level of intelligent inspection. Therefore, relevant enterprises should strengthen research on technology application, actively explore the combination with other advanced technologies, further leverage the technical advantages of ultrasonic non-destructive testing, and achieve new breakthroughs in the field of bridge engineering inspection.

Disclosure statement

The authors declare no conflict of interest.

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