

Study on the Method of Detecting Voids Behind Subway Tunnel Lining

-- Data Segmentation of Continuous Impact Echo Signal

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Abstract

When using the impact echo method to detect the void behind the tunnel lining, the continuous impact detection scheme helps to improve the detection efficiency, but it also brings a new challenge: multiple impact echo signals are superimposed and mixed during the recording process, which makes it difficult to independently process each impact event in the subsequent time-frequency analysis. In order to improve the accuracy and efficiency of signal processing, this paper proposes and develops a signal segmentation algorithm based on peak feature extraction, and introduces time window constraints to divide the entire signal into several independent sub-segments, thereby effectively reducing the degree of signal mixing. In practical applications, the data processing time of this segmentation method at the same measuring point is about 10 minutes, which is only 30%~50% of the processing time of the entire data segment; and the segmented multiple signal segments can be processed in parallel, and its segmentation processing efficiency is about 2 to 3 times that of the entire signal segment. By independently analyzing each segment of the signal, not only the subsequent time-frequency conversion and other processing procedures are simplified, the signal processing efficiency is improved, but also the accuracy of signal analysis is significantly improved, which provides theoretical and technical support for the application of the impact echo method in the analysis of tunnel segment void inspection data in the future.

Keywords

Void Behind Tunnel Lining; Impact Echo Method; Signal Segmentation; Peak Feature Extraction; Time Window Constraints.

1. Introduction

As the operating mileage of China's subway tunnels continues to increase[1], China has entered a stage of development in which subway tunnel construction and maintenance are carried out in parallel, and subway operation and maintenance are becoming increasingly important. For the voids behind the lining of shield tunnels, the impact echo method, as a new and effective detection method, has gradually been applied to actual detection projects. In order to improve the detection efficiency, the continuous impact echo detection scheme will be the development trend of the impact echo method for inspecting voids behind the tunnel in the future. Therefore, how to separate each independent impact event has become a major challenge to improve the accuracy and efficiency of data analysis. Regarding the research on peak extraction and data segmentation, scholars in different fields have conducted relevant research. Zhang et al. [2] proposed a peak feature extraction algorithm based on

multi-layer narrowband local peak factors, which effectively extracted mechanical fault features based on peak frequency and amplitude. Farrokhi et al. [3] used adaptive threshold and positioning technology to successfully dynamically identify and extract peak features in the electrocardiogram. Jayasanthi et al. [4] proposed an improved fast convergence adaptive independent component analysis to improve the accuracy and sensitivity of R peak detection. Trabelsi et al. [5] studied a posture adjustment clustering algorithm with total variation constraints, which automatically segmented the patient's posture coordination signal into behavioral patterns. Hamza et al. [6] proposed an online or offline change detection algorithm for GNSS signal segmentation, which was used for automatic GNSS signal segmentation and achieved water body detection and edge positioning.

The signal segmentation research of the above scholars is mainly aimed at steady-state signals, and the application scenarios are relatively limited, which is not suitable for peak extraction and signal segmentation of the impact echo method. This paper uses a peak extraction algorithm based on the height function to segment the repeated experimental data to improve data processing efficiency and realize independent processing of each segment of data. The height function can automatically identify all peaks that exceed the set threshold range, and combine the impact frequency of the pulsed laser to calculate the appropriate segmentation time interval to achieve signal segmentation.

2. Data Source

Based on the impact echo method, this experiment carried out an outdoor shield tunnel segment void detection experiment based on a remote nondestructive testing system, as shown in Fig. 1. Instantaneous loads were applied to the segments at an impact frequency of 1 Hz and 5 Hz, respectively, and a Doppler vibrometer was used for data acquisition to simulate continuous impact and echo data detection under inspection conditions.



Fig. 1 Experimental site of continuous detection of voids behind segment based on impact echo method

In the experiment, a single shock echo experiment with an impact frequency of 1 Hz and a continuous shock echo experiment with an impact frequency of 5 Hz were collected respectively. In the continuous shock echo experiment, each measuring point was subjected to continuous shock for 5 s, and the vibration meter took continuous samples within these 5 s.

3. Peak Extraction Method based on Height Function

The goal of signal segmentation is to decouple the time-frequency aliasing effect of multiple impacts, and to avoid cross-interference between signals by extracting independent time windows of a single impact and its echo signal. Since the laser Doppler vibrometer continuously collects vibration signals in a non-contact manner, the transient vibration waveform caused by pulsed laser excitation will be fully recorded. Based on the analysis of stress wave propagation characteristics, the amplitude of the

stress wave is significantly higher than the subsequent reflected echo, so the peak moment of the stress wave can be used as the reference point for signal segmentation to achieve accurate separation of impact events.

Experimental data analysis shows that when the incident wave β passes through the interface of different media, it will be partially reflected and transmitted at the interface. Due to the damping effect and geometric diffusion of the medium, the energy of the reflected wave γ and the transmitted wave η will be attenuated, resulting in the shock wave amplitude being much higher than the subsequent echo [7]-[9]. This physical mechanism provides theoretical support for signal segmentation based on peak detection. The principle is shown in Fig. 2.

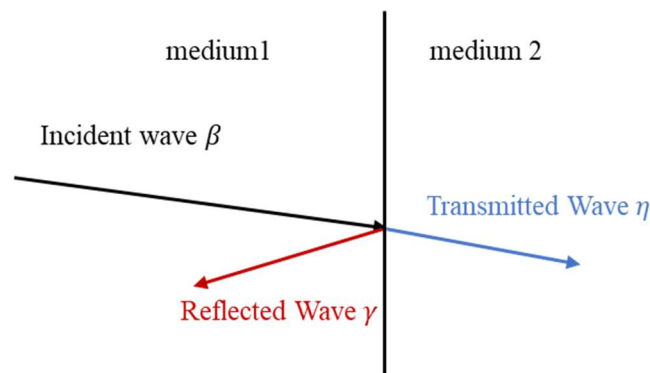


Fig. 2 Reflection and transmission of stress waves at interfaces between different media

Based on the above analysis, this paper adopts a peak feature extraction method based on the height function to mark the peak of the signal time course curve and use it as the identification feature of the signal segmentation. The core purpose of using the height function in this study is to extract the local maximum value in the signal, check each sampling point in the signal, and compare the size relationship between the point and the adjacent points. If the point is larger than the value of the two adjacent points before and after, and the value of the point is greater than the preset amplitude threshold, then the point is considered to be a valid local maximum point, that is, the peak value. The basic principle is as shown in formula (1). Assuming that the signal is, the condition for detecting a valid peak at time i is:

$$\begin{cases} x_i > x_{i-1} \text{ and } x_i > x_{i+1} \\ x_i > h_{min} \end{cases} \quad (1)$$

In the formula x_i --the signal amplitude value detected at time; x_{i-1} --the amplitude value of the left adjacent point of the signal point detected at time; x_{i+1} --the amplitude value of the right adjacent point of the signal point detected at time; h_{min} ---the preset amplitude threshold.

Based on this method, we first take the signal with an impact frequency of 1 Hz as an example, set the amplitude threshold to 12 mm/s, and extract the peak value as shown in Fig. 3. The maximum peak value we need is extracted, and it can be used as the basis for segmentation.

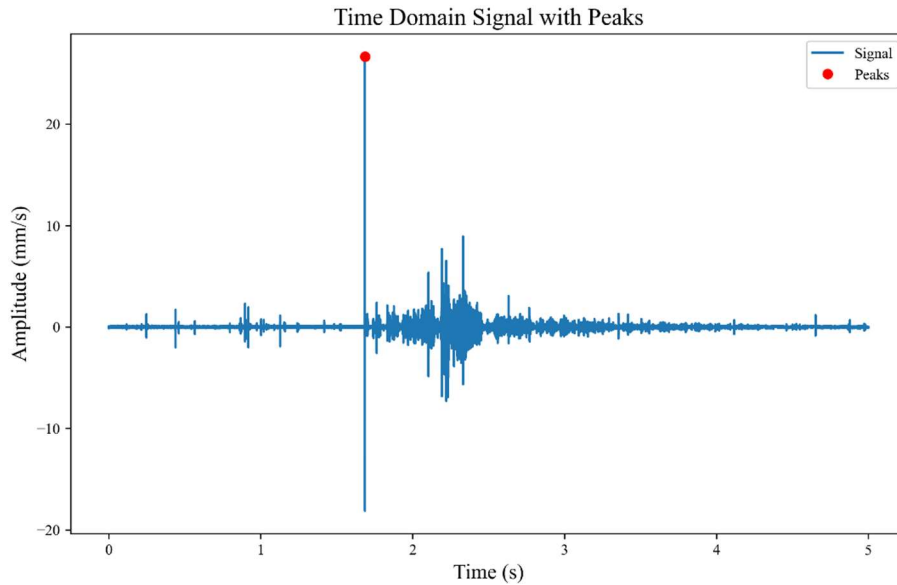


Fig. 3 Peak marker of the time domain diagram of the signal with a shock frequency of 1 Hz

However, if the threshold is set too low or the signal dynamic range is too large, it is impossible to extract effective peaks with a uniform threshold, and peak over-detection will occur, as shown in Fig. 4. At this time, all peaks cannot be used as the basis for segmentation.

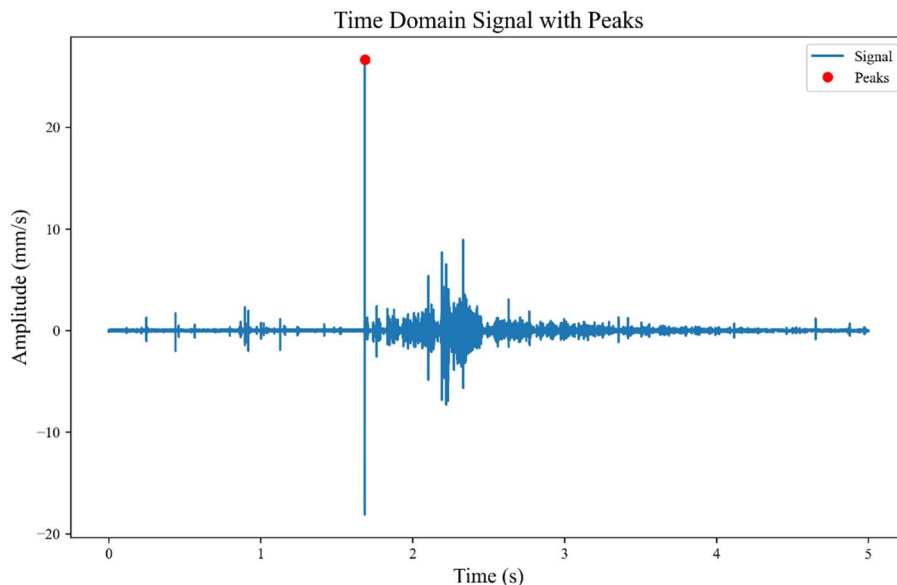


Fig. 4 Peak over-detection in time domain

4. Time Window Constraint Introduction

Since the height function is prone to over-detection or under-detection, other constraints need to be added to help optimize the signal segmentation algorithm to make it more accurate and reliable. Since the pulse laser shock frequency is set to 5 Hz in this experiment, the time interval between each shock is 0.2 s, that is, in the time history curve of the 5 Hz shock experiment, the time interval between each peak is approximately 0.2 s, as shown in Fig. 5. The time interval between each shock is equal, so the time window can be added as a constraint condition to combine the peak value for signal segmentation.

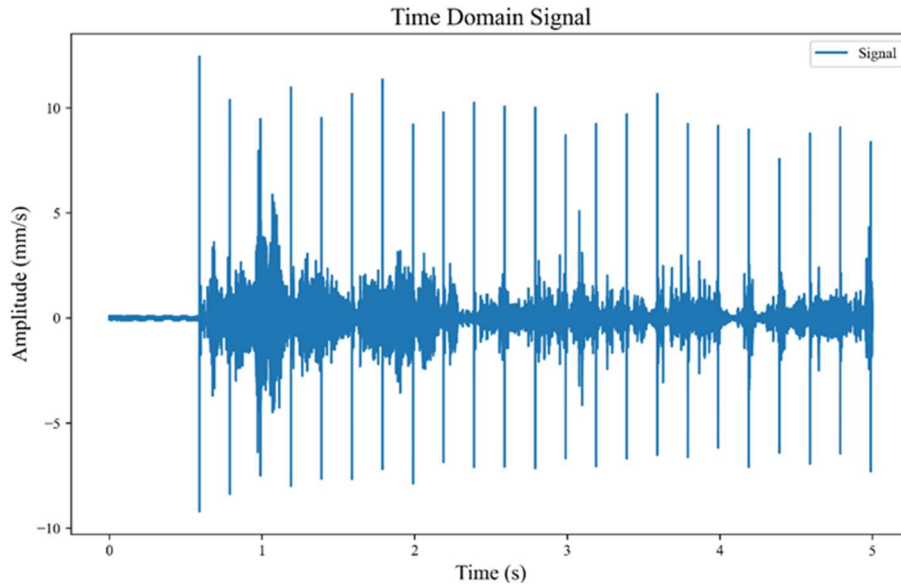


Fig. 5 Time domain diagram of the signal with an impulse frequency of 5 Hz

When dividing the time interval, we first determine the locality and uniqueness of the peak. If there are multiple valid peaks in each time interval, it will still lead to over-detection of the height function. However, if only the highest or some of them are selected as valid peaks during the entire detection time, it will lead to missed detection of the height function. To avoid this situation, we set the peak time point as the median point of the time window, that is, 0.1 s before and after the peak, so we set a 0.2 s time window, and then refer to the principle of sliding time window. In the original time domain data, the window sliding size is set to 0.1 s. In each 0.2 s, only the maximum peak is marked as a valid peak. The marking result is shown in Fig. 6.

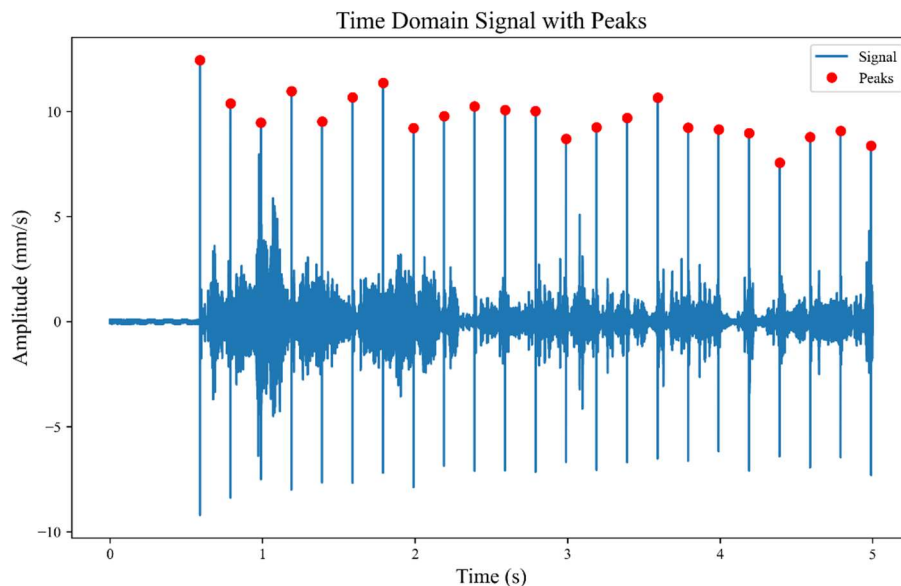


Fig. 6 Time domain diagram of the signal with an impulse frequency of 5 Hz

When segmenting the signal, we need to consider not only the time interval for selecting the effective peak, but also the propagation speed of the stress wave in concrete to ensure that the echo signal is contained in the time window as much as possible, while avoiding the time window being too wide, which will cause the local signal characteristics to be covered. The propagation speed of the stress wave in concrete is about 4000 m/s, and the thickness of the pipe segment is 0.3 m, which means that

it takes about 1.5×10^{-4} s for the stress wave to pass through the pipe segment and return. The stress wave will also attenuate during the propagation process. Therefore, in order to better analyze the detailed characteristics of the echo signal, each segmented signal finally selects only the time range of 1×10^{-3} s before and after the peak.

5. Signal Segmentation Optimization and Independent Processing Strategy Application

The comprehensive evaluation of 5 Hz continuous detection data helps to reduce the impact of errors. Therefore, the main research object of this paper is 5 Hz repeated experimental data, and an example is shown in Fig. 7.

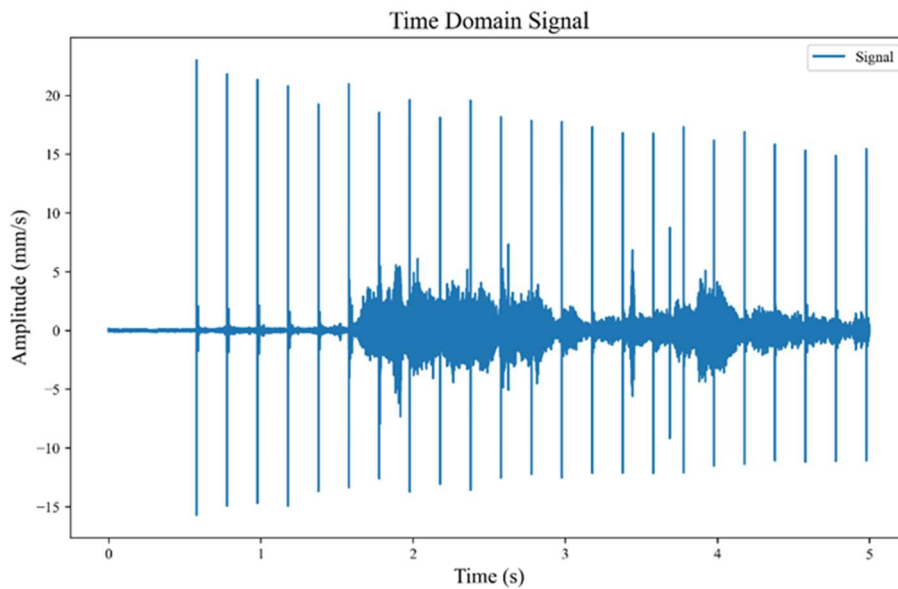
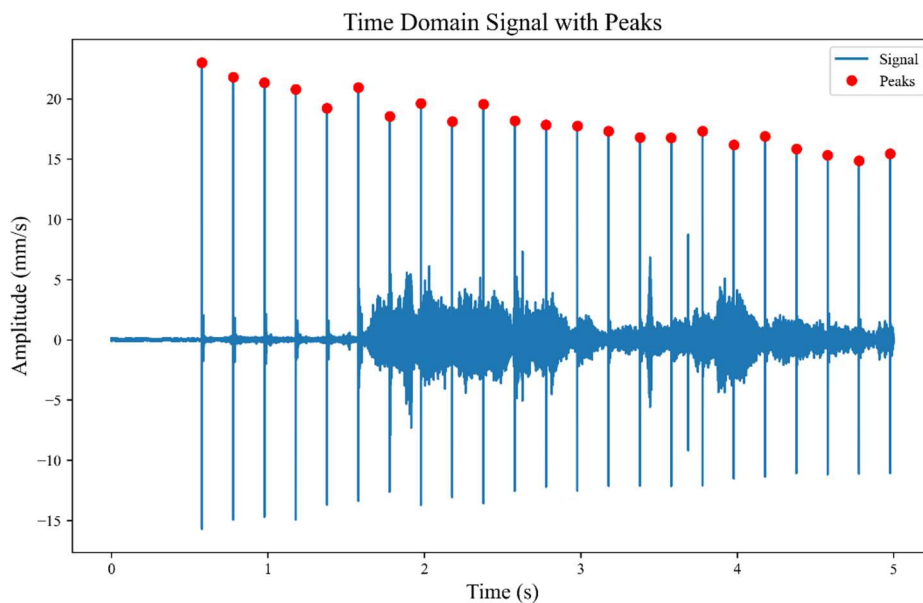
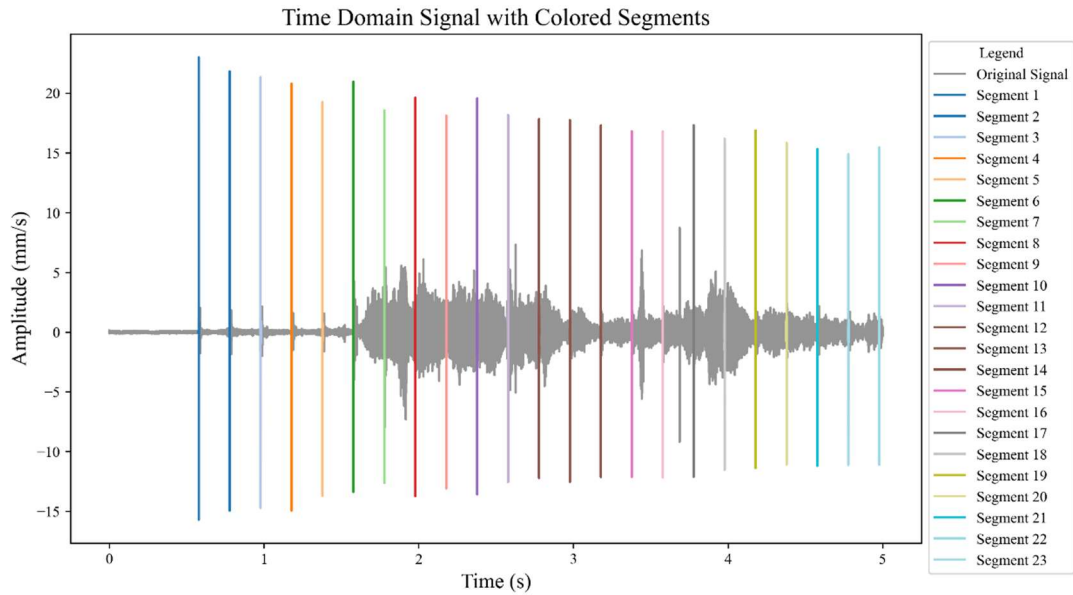


Fig. 7 Time domain diagram of experimental data with an impact frequency of 5 Hz



a) Time domain plot of a 5 Hz repeated experiment with peaks



b) Segmented 5 Hz continuous experiment time domain diagram

Fig. 8 Time domain diagram of experimental data with an impact frequency of 5 Hz

The maximum peak value is selected in each interval, and a signal segment of a fixed time length is intercepted with the peak value as the center. The segmentation result is shown in Fig. 8 a). The separate processing of each segmented signal can effectively reduce the demand for computer memory and computing power. According to the characteristics of the experimental data, this study sets the peak extraction threshold of the height function to 3 and the segmentation time interval to 0.2 s. At the same time, in order to specifically study the data area of interest, combined with the needs of the target time domain interval, only the time range of 1×10^{-3} s before and after the identification peak is intercepted, as shown in Fig. 8 b).

The study found that when the time domain data before segmentation is processed by denoising and wavelet transform, due to the huge amount of data, a large amount of computer memory is occupied during the data processing, resulting in a long time or even failure. After the data is segmented, each segment of data is processed independently, which greatly reduces the complexity of data processing and memory usage, and significantly improves the data processing efficiency. For example, when processing a 23-segment measurement point data, it takes about 20-30 minutes to process the measurement point before segmentation, provided that the operation is successful. After segmentation, it only takes 15 seconds to process each independent data segment, and it takes no more than 10 minutes to process a measurement point.

6. Conclusion

In view of the characteristics of detection data, this paper proposes a signal segmentation algorithm based on peak feature extraction. The algorithm uses the height function to automatically extract the peak value in the signal data, and solves the problem of peak over-detection and under-detection by introducing the time window constraint. According to the actual situation of the data and the signal characteristics, the signal is segmented in the time domain. The segmentation processing efficiency is about 2 to 3 times that of the whole signal, which significantly improves the data processing efficiency and ensures that the echo signals generated by each impact do not overlap, thereby realizing independent segmented signal processing and analysis.

The impact echo signal segmentation strategy proposed in this paper provides theoretical and technical support for the processing and analysis of void echo data behind tunnel lining in the future.

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