Experimental Study on Void Defects Detection of Ballastless Track Mortar Layer Based on FFT and WT

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Abstract. The mortar layer of the ballastless track is prone to generate hidden voiding defects, which seriously affect the performance and safety of high-speed trains. These kinds of defects can be detected in different ways, such as the impact echo method (IE), but the detection accuracy of the different void defects and their locations in the mortar layer is insufficient. In this paper, a full-scale ballastless track model with preset voids was designed and manufactured for IE experimental study. The mortar layer of the model was evenly divided into four zones. Three types of voids of different sizes were designed on the edges of Zone-1 and Zone-2 connected, and the voids on one side were filled with EPS board to simulate the loss-of-cohesiveness void defect for comparison with the unfilled voids to simulate the fragmentation void defect on the other side. The interior of Zone-4 was set two rows of square voids filled with Pykrete ice to simulate the bubble-type void defect. Zone-3 did not set defects as a control group. The impact echo method was used to detect and collect the vibration signal at each point on the surface of the model. Taking into account the non-stationary characteristics of the echo signal of the layered structure, the frequency domain spectrum obtained by the traditional fast Fourier transform (FFT) shows multiple peaks, which makes it difficult to extract the main frequency. Thus, the wavelet transform (WT) is selected because it can realize the multi-scale detailed analysis of signals, which can obtain more accurate information reflecting the characteristics of the defect. The analysis of the study results shows that (1) For the recognition of the three void defects, WT is more accurate and intuitive than FFT in feature extraction. (2) Only combining FFT and WT can complete the identification of small-scale void defects on the board edge. (3) Compared with FFT, WT has more advantages in processing the echo signal of the layered structure.

Keywords: ballastless track, void defects, fast Fourier transform, wavelet transform
1. Introduction

The ballastless track structure is widely used in high-speed railways due to its strong integrity, stable performance, good durability, small deformation, and less demand for maintenance [1, 2]. In the ballastless track structure, the CA mortar layer between the rail slab and the base plate uses cement emulsified asphalt mortar, which is the weakest layer in the ballastless track structure. The CA mortar layer plays an important role in force transmission, vibration reduction, and adjustment [3]. Its quality and performance directly affect the stability and safety of high-speed train operation. Due to the coupling effect of some factors, such as improper construction operation, train dynamic load, uneven foundation sedimentation deformation, and temperature effect, the CA mortar layer is prone to generate structural defects such as cracks, seams, and voids [2, 4]. Since the ballastless track is an integrally closed concrete structure, it is difficult to determine the location and size of the mortar layer defects, so the research on the detection method and analysis method of the mortar layer defects is particularly important.

At present, the detection of concealed defects in ballastless track has gained some development. Liao used ground-penetrating radar technique to carry out a two-dimensional forward numerical simulation of the different filling degrees and hardening process of the CA mortar layer of the ballastless track [1]; Zhan adopted the dynamic stiffness change index of the rail slab under the impact load as the evaluation index to achieve effective assessment of CA mortar layer pulverization and local void defects [3]; Li studied the dispersion characteristics of Lamb wave by establishing a ballastless track equal-scale model, proving that Lamb wave can be used for the interlayer void damage detection of the ballastless track [4]; Tian used the transient shock response characteristics to carry out numerical simulations and entity model tests on the mortar void of the ballastless track, and the characteristics of time-history curve, spectral curve, and admittance variation proved that the transient shock response can accurately identify the defects of mortar layer with the length greater than 0.4m [2]; Liu utilized the impact echo method to identify the seam separation from the bottom of the ballastless rail slab, and comprehensively distinguished the seam defect through the frequency-amplitude spectrum and the excellent frequency intensity reflection spectrum [5]. The impact echo method research has confirmed that it can meet the defect detection of concrete structures, but its feasibility and accuracy need to be further studied [6].

In the process of using the impact echo method to detect the void defect of the CA mortar layer, due to the mutual interference between p-wave and surface wave in the multilayer structure, it is often difficult to obtain useful information reflecting the characteristics of the defect when the conventional fast Fourier transform (FFT) is used to process the echo signal [7]. Therefore, it is necessary to select a relatively reasonable signal processing method to effectively identify the characteristics of the defect to improve the accuracy of the detection of the void defects of the CA mortar layer. Some papers have done further research on echo signal processing methods. In order to solve the mode overlap problem of Empirical Mode Decomposition (EMD), Jun established an impact echo analysis method based on Variational Mode Decomposition (VMD) and marginal spectrum, which proved that VMD has higher resolution in identifying different defects in concrete structures [8]; Tyler used the wavelet transform (WT) to process the impact signal of large reinforced concrete beams and proves that damage detection based on wavelet transform was better than FFT in efficiency and accuracy [9]. In some papers [10-14], the frequency domain spectrum obtained through FFT and the time domain spectrum obtained by WT were used to analyze the signals and extract defect features.

To realize the detection of various defects in the mortar layer, the study took the full-scale ballastless track model with three types of void defects in the CA mortar layer as the test object and used the impact echo method to extract the signal. Furthermore, FFT and WT were used to process and analyze the echo signals. From the analysis results, it can be determined that IE is accurate and effective to detect the mortar voids and that WT is more suitable for echo signal processing than FFT.
2. Experimental design
In this study, a full-scale ballastless track model with different types and sizes of void defects in the CA mortar layer was designed and manufactured, and the impact echo method was used to extract the signal of each testing point on the board surface and study it.

2.1 Experimental model
To verify the effectiveness of the EI in detecting the void defect of the mortar layer, a full-scale ballastless track model experiment was carried out. The size of the ballastless track model was 6.55×2.55×0.24m, which was composed of a 0.20m thick C50 concrete rail slab and a 0.03m−0.04m thick mortar layer, as shown in Figure 1. In actual engineering, the mortar layer was prone to generate the following three types of void defects: (1) board edge void defect caused by material fragmentation, (2) board edge void defect caused by the loss of cohesive force between the mortar layer and the rail slab, (3) void defect in the board developed by large-area air bubbles. To distinguish them, they were defined in order by fragmentation void defect (FV), loss-of-cohesiveness void defect (LCV), and bubble-type void defect (BTV). According to the position where the above defects were prone to appear, the simulation of the void defects was preset in Figure 2, the FV was simulated with unfilled voids, the LCV with Expanded Polystyrene board and the BTV with Pykrete ice.

![Figure 1. Full-scale model of the ballastless track.](image1)

To determine the influence of the void defects’ position and size, two void defects of size 500×600mm, which were marked as FV-1 and LCV-1, were respectively set at the corners of the board. At a distance of 1337.5mm and 2975mm away from the short edge of the board, two sizes 600×600mm void defects and two sizes 300×600mm void defects were respectively set at the edge of the board, which were respectively marked as LV-2, LCV-2, and LV-3, LCV-3 as shown in Figure 2.

![Figure 2. The layout and mark of different types and sizes of void defects (unit: mm).](image2)
The whole board was equally divided into four zones, as shown in Figure 2. Zone-1 and Zone-2 contained LV-1~3 and LCV-1~3. Zone-3 did not contain any defect. Zone-4 contains eight BTV with a size of 300 ×300mm.

2.2 Impact-echo instrument and testing method
The instrument of the IE is composed of three parts: excitation source, signal receiving sensor, and data acquisition system. Considering the high frequency of elastic wave reflection wave, 411.7g SACL60KE steel hammer was selected as the excitation source, and IEPE type acceleration sensor was selected as the signal receiving sensor, and DHDAS dynamic signal acquisition and analysis system were selected as the data acquisition system, shown in Figure 3.

As shown in Figure 4, to obtain enough echo signals, testing lines with uniform distribution and interval were divided along the surface of the rail slab and many grids with a size of 100×100mm were formed. After completing the testing net division, the impact echo method was used to test each grid point. The first step was to set the sensor on the grid point and connect to the acquisition system which was set the sampling frequency to 50000Hz. The second step was to set the excitation source on the adjacent grid points of the sensor for 2~3 excitations, and finally completed the echo signal collection of 1364 grid points. Two sets of data were collected on each grid point, a total of 2728 sets of data were collected.

3. Data analyse and discussion
Aiming at the layered structure composed of concrete and mortar, two signal processing methods, fast Fourier transform (FFT) and wavelet transform (WT), were adopted for the echo signal to extract the defect features. The mainly characteristic frequency and the maximum amplitude which were obtained from the amplitude spectrum transformed by FFT can reflect defects features. However, FFT uses harmonic components, which shows that it is suitable for relatively stable signal analysis [11]. For non-stationary signals, the decomposition result will increase non-existent frequency components.
which is called the Gibbs phenomenon [7, 12]. When the IE is used to detect the multi-layered structure, the frequency domain spectrum is prone to generate multiple repeated peaks under the effect of the FFT time-shifting characteristics and the overlapping interference of the elastic wave signal, which affects the determination of the largest peak and the true main frequency in the amplitude spectrum [7, 12]. Different from FFT, the signal processed by WT can retain time and frequency information at the same time. It uses the movement of the variable window to refine the signal in multiple scales, which can highlight the local features of the signal and obtain the outstanding features of various diseases [12-14]. The multi-scale analysis feature of WT can effectively improve the resolution of the signal. The results of this experiment using WT and FFT are as follows.

3.1 FFT frequency domain spectrum

According to the impact-echo method in Section 2 for testing and sampling, the echo data signals of 1364 testing points are obtained. Considering that the manual excitation intensity of each testing point is not completely consistent, each sampling signal is normalized to map the signal data to (-1,1) through linear change before the spectrum analysis. Thus, the amplitude is dimensionless. FFT is used to process the normalized data of all the testing points within the range of different types of void defects and defect-free zone to obtain the amplitude-frequency domain spectrogram.

From all results, it can be found that there are obvious differences in amplitude spectrums of the testing points in the middle and the edge of each void defect. Therefore, using the CR and EG to mark the centre and the edge of the defect, and selecting representative testing points in CR and EG of each defect for analysis. The amplitude spectrums of the representative testing points of LV-1~3, LCV-1~3, BTV, and Zone-3 are respectively shown in Figure 5-8.

The multi-peak distribution with no significant difference in amplitude can be seen in these amplitude-frequency domain spectrograms. As can be known from the multi-layer structure of the ballastless track model and elastic wave propagation characteristic, the P-wave will be reflected when it transmits the interface of different materials, and the reflection intensity varies with the material, which causes the different time of the P-wave to reflect from different interfaces to the sensor. To obtain more signal features, the maximum amplitude, the primary and the secondary frequency, the dominant peaks which are composed of the top ten peaks in amplitude are analyzed. The frequency range corresponding to the dominant peaks is defined as the main frequency band. The relevant analysis as follows.

By comparing Figure 5(a) and Figure 5(b), it can be seen that, compared with the LV-1-CR, the amplitude of the main peak of the LV-1-EG decreases, and its main frequency band becomes wider, and both high-frequency and low-frequency components of LV-1-EG increase. The main frequency band of the LV-1-CR is 2000~3400Hz, but the LV-1-EG is 1000~4000Hz, which indicates that the main frequency band under the influence of edge effect is more concentrated in the detection of void defect within a certain range at the corner of the board. As can be seen from Figure 6(c)-(f), both the LV-2-CR and the LV-3-CR are the larger main peak amplitude similar to LV-1-CR, but they have more low-frequency components compare to the LV-1-CR and as the size of the defect decreases, the amplitude of the low-frequency component decreases. Both the LV-2-EG and the LV-3-EG are lower main peak amplitude than the middle of their respective defect, which shows that FFT is affected to a certain extent by the edge of the board.

As presented in Figure 6, for the loss-of-viscosity void defect, the maximum amplitude at the corner of the board is larger than at the board edge. In the main frequency band distribution, the LCV-1-EG is wider than LCV-1-CR, similar to LV-1-EG than LV-2-CR. In low-frequency distribution characteristics, LCV-2-CR and LCV-3-CR are similar to LV-2-CR and LV-3-CR. From the above analysis, the following three conclusions can be obtained: (1) The location and size of the void defects are the factors that determine the feature of the frequency band distribution in the amplitude spectrums, and the void type is the factor that determines the boundary of the amplitude. (2) At the corner of the board, due to the edge effect, the internal amplitude changes and the concentration of the main frequency band in the defect spectrums are related to the distance to the edge. (3) For the voiding
defect at the edge of the board, the amplitude around the defect is slightly lower than that at the center, which may be affected by the boundary of the mortar layer.

As exhibited in Figure 7(a)(b), an obvious primary peak can be seen in the middle and edges of the bubble-type void defect. Two peaks with similar frequencies appear in the BTV-CR, which may be caused by frequency-domain scattering. Same as the distribution of the maximum amplitude of all defects, the BTV-EG is lower than BTV-CR.

Through statistical analysis of the main feature values of all testing points of LV-1~3, LCV-1~3, and BTV, we found most of the main frequency band in amplitude spectrums of fragmentation void defect and loss-of-viscosity void defect are 1000~4000Hz, and that of the bubble-type void defect is 1000~3000Hz. The more concentrated frequency band indicates that the voids caused by multiple bubbles may have a greater interaction influence. At the maximum amplitude, all testing points of BTV are greater than 0.2. Considering the primary and the second frequency values, the LV-1 and
LCV-1 mainly contain around 2000Hz, 2500Hz, and 3000Hz, and the LV-2 and LCV-2 mainly contain around 2000Hz, 2500Hz, 3100Hz, and 3500Hz, and the LV-3 and LCV-3 are irregular. Considering the average value of the primary frequency of the testing points of each defect, LV-1, LV-2, and LV-3 take 2479Hz, 2954Hz, 2756Hz respectively, and LCV-1, LCV-2, and LCV-3 take 2592Hz, 2842Hz, 2765Hz respectively, and the BTV is 2592Hz.

As can be seen from Figure 7(c), the maximum amplitude in Zone-3 which simulates the defect-free situation is relatively lower than the defected location. The maximum amplitude of 58% of the testing points in Zone-3 is below 0.1, and none of that exceeds 0.2. In the amplitude spectrums, it is difficult to determine the primary frequency and secondary frequency. Most of the main frequency bands are distributed between 2000Hz and 4200Hz, and there are many high-frequency components. The average value of the primary frequency of the testing points of Zone-3 is 3232Hz.

From the above analysis, the following conclusions can be obtained: (1) It is possible to distinguish defected and defect-free zones from the amplitude, but the amplitude distribution of Lo and defect-free is relatively close, making it difficult to identify them; (2) For multi-layer structure, it is difficult to determine the type of defect based on the dominant frequency of a certain testing point, but in the case of a large number of statistics (more than 10 testing points), the average frequency of the defected zones is lower than that of the defect-free zones; (3) It can be seen from the amplitude spectrums of BTV and Zone-3 that for the defects in the board, both have significant differences in maximum amplitude and dominant frequency. (4) For BTV and Lr, there is a clear difference from the dominant peaks, and for BTV and Lo, there is a clear difference from the maximum amplitude.

3.2 WT time domain spectrum

To obtain more effective information, the wavelet transforms with the mother wavelet cmor3.3 is selected to obtain the time-frequency spectrums of the testing points of the various defects and Zone-3, taking the representative testing points for the following analysis. CR and EG represent the center and edge of the defects, as described in section 3.1.

Figure 8-10 shows the time-frequency spectrum of typical testing points for a series of defects FV, LCV, BTV, and Zone-3, from which we can see the obvious bright band distribution. To facilitate analysis and feature value extraction, the spectral range greater than 60% of the maximum power amplitude is highlighted by a solid black rectangular frame and named it Part M. The spectral range greater than one-third of the maximum amplitude is marked by a red dashed rectangular frame and named it Part N. The frequency range represented by Part M is regarded as the main frequency band of the testing point, and the time range represented by it is regarded as the main response time of the signal. The time range represented by Part N is regarded as the total response time of the signal. The frequency corresponding to the maximum power amplitude is regarded as the primary frequency. Extracting the above values from Figure 8-10 as Table 1.

| The main frequency (Hz) | The main frequency (Hz) | The main frequency (Hz) | The main frequency (Hz) |
|------------------------|------------------------|------------------------|------------------------|
| CR                     | 1856-2930              | 1759-2539              | 1586-2490              |
| EG                     | 2246-3230              | 3846-4318              | 3125-3930              |
| FR                     | 2246-3711              | 1953-3809              | 1598-3418              |
| LM                     | 2051-3320              | 1856-2930              | 1759-2539              |
| LG                     | 1172-3027              | 1856-3125              | 1759-2539              |
| Zone-3                 | 1856-4688              | 1856-4688              | 1856-4688              |

Table 1. Time-frequency spectrum feature values extraction.
As shown in Figure 8, compared to LV-1-EG, the LV-1-CR’s main frequency band shifts to the low-frequency region, and its total response time is longer, which may be affected by the edge of the mortar layer. For LV-2, the difference in feature values between the edge and the middle of the defect...
is very small. Comparing LV-2 with LV-3, it can be found that their total response time is the same, about 8.5ms, but their main response time is quite different and a longer band appears outside Part M in the LV-2. LV-3 is more than twice that of LV-2 in the main response time, which may be affected by the void size. In the distribution of the main frequency band, the fragmentation void defect at the board corner is significantly narrower than at the board edge. The wider red areas of LV-2 and LV-3 indicate that their high-frequency components have increased.

As presented in Figure 9, the main frequency band of LCV-1-EG shifts to low frequency compared with LCV-2-CR, which is different from LV-1. It can be seen from Figure 9(b)-(d) that a long bright line appears along the frequency direction around 0.04s. Compare LCV-1, LCV-2 and LCV-3 have obvious high-frequency components. In the main response time and the total response time, the fragmentation void defect and loss-of-cohesiveness void defect have the same distribution features under the influence of defect size and location.

Figure 10(a)(b) displays the time-frequency spectrums of bubble-type void defect, the difference in feature values between the edge and the middle of the defect is very small as the other two types of defects. In the Part M of BTV, not only does a wide range of high-frequency components and low-frequency components appear but also there are disconnected bright spots along the time axis, which can be used as a distinguishing feature of the bubble-type void defect.

For the defect-free Zone-3, as shown in Figure 10(c), compared with the defected zone, we can see that its main frequency band is distributed widely, the main time response and total time response are both shorter, and there are relatively more high-frequency components in Part M. In Part N, a clear bright band distribution along the frequency direction can be seen.

From the above analysis, the following conclusions can be obtained: (1) By comparing the total response time in the time-frequency spectrums, it can be found that the defect-free zone is significantly lower than the defected zone. Especially, WT has a higher resolution accuracy than FFT in the recognition of the loss-of-cohesiveness void defect and bubble-type void defect. (2) For the identification of void defects of different sizes at the board edge, the main response time in the time-frequency spectrums is quite different, which is more advantageous than using the FFT to identify defects of different sizes. (3) The identification of LV-2 and LCV-2 can be determined by the length of the bright band along the frequency direction in the time domain diagram, but it is difficult for LV-3 and LCV-3 to distinguish only through the time domain spectrums. (4) The primary frequency value in the time-frequency spectrums of each testing point is irregular, so it is difficult to use the primary frequency value to distinguish defects.

4. Conclusions
The study focuses on the impact echo experiment of the ballastless track structure with different types of void defects in the CA mortar layer. The echo signals are processed by WT and FFT, and the following conclusions are obtained by analyzing its spectral features:

(1) The impact echo method can effectively detect the location of the void diseases in the CA mortar layer of the ballastless track. The types of void diseases can be further determined by extracting the characteristic values after FFT and WT processing.

(2) The void diseases at the corner of the board are easier to detect, but difficult to determine their types through FFT and WT. WT is more accurate than FFT in identifying large voids at the edge of board. Combining FFT and WT can detect the defects effectively: determine the existence of the disease by the total response time of the time-frequency spectrums, and then judge the void disease types by the amplitude of the amplitude spectrums.

(3) Both FFT and WT can identify the bubble-type void disease, while the ballastless track is a layered structure, the amplitude spectrums obtained by FFT are prone to multiple peaks, which can only be evaluated from the single factor of amplitude. But WT can realize the multi-scale judgment from signal response time to a frequency band, which has higher resolution accuracy. This also provides a new reference for the analysis of multi-layer structures.
Acknowledgments

The work presented in this article was supported by the Science and Technology Commission of Shanghai Municipality (Grant No.18DZ1205902), the National Natural-Science Foundation of China (Grant No.52078377), and Key Field Science and Technology Project of Yunnan Province (Grant No. 202002AC080002).

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