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On-Board Detection of Longitudinal Track Irregularity Via Axle Box Acceleration in HSR

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ABSTRACT Track irregularity detection serves as one of the most essential technologies to interpret the in-service condition of the high-speed railway (HSR) and ensure the comfortability and safety in HSR service. This study newly proposed a novel on-board detection technique integrated with newly developed algorithm for identifying the longitudinal track irregularity to obtain the condition monitoring for further condition based maintenance (CBM). Such on-board detection technique includes data acquisition unit, spatial-time synchronous calibration unit and data processing unit, which can be directly installed in commercial high-speed trains. Via inertial reference method, an algorithm is developed to derive longitudinal irregularity from the acceleration measured in axle box of high-speed train by combining multiple digital filters. A prototype is developed and is installed on a comprehensive inspection train to verify the feasibility and test on multiple HSR lines eventually. The comparison affirms that the detection system has high accuracy and sound repeatability, and certain on-board detection technique enables the real-time online monitoring of track condition.

INDEX TERMS Longitudinal irregularities, axle box acceleration, on-board, on-line monitoring, HSR.

I. INTRODUCTION

In high-speed railway (HSR) system, the maintenance becomes more and more essential due to the high-speed, where a small defect can induce huge economic loss. The track irregularity is a typical unavoidable defect among all defects. Track irregularity is defined as the deviation between the actual line position and the designed line position of left and right rails, and its wavelength, amplitude and periodic characteristics directly affect the safety of vehicle operation and ride comfort. Track condition detection is of great significance to master the characteristics and distribution of track irregularity, to provide track maintenance fundamentals and to restore track smooth state in time. The track irregularity detection is one of the key technologies to master the in-service condition of the railway and ensure the safety operation continuously. Currently, the track geometry inspection of China HSR adheres to the principle of "giving priority to dynamic inspection, combining dynamic and static inspection". In engineering, the comprehensive inspection trains conduct a periodic inspection on the existing HSR lines every ten to 15 days, and static measurement is conducted once or twice a year. The dynamic inspection mainly relies on the results of comprehensive inspection train detection, which will be rechecked by on-site static measurement when any problem is found. Those determined defects would serve for the further maintenance plan.

The detection methods of track dynamic geometric irregularity mainly include chord measurement method and inertial reference method. China's comprehensive detection train employs inertial reference system combined with optical system to detect track dynamic geometric. The track geometry of the same line can merely be detected two to three times per month. The inspection interval is too long to fix the problems of track condition timely. In summer, the amplitude of longitudinal irregularity will increase due to thermal expansion of ballastless track at high temperature. In winter, the frost heaving of subgrade will also increase the amplitude of longitudinal irregularity. These changes have a certain burst, making the encryption detection of longitudinal irregularities

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more essential. The all-weather on-line monitoring of track condition becomes essential for the safety and reliability of intense HSR in the near future. The development, maintenance and scheduling operation of the comprehensive inspection train request lots of investment, and its operation will occupy a certain transport capacity.

On-board equipment is desirable to obtain the track condition; the installation of certain instrument on the commercial high-speed train enables the efficiency and further improvement in the condition monitoring of HSR. Researchers at home and abroad have carried out extensive studies for such goal. Some focused on the complete vehicle dynamic model, which inverted the dynamic response of the carriage body into track irregularity. Alfi S *et al.* [1], [2] deduced the transfer function between the input and output of the two-dimensional vehicle dynamics model. In the frequency domain, the vibration response of the car body, bogie and axle box was inverted into medium and long wave longitudinal irregularity through inverse calculations. In the later stage, the three-dimensional model is used to invert medium and long wave lateral irregularity. Baier M *et al.* [3] started from the transfer function of track irregularity and car body acceleration, and used the analytical inversion method to restore the car body vertical acceleration to longitudinal irregularities in theory. Wei X *et al.* [4] applied multiple acceleration measuring points on the metro car body and bogie, and inverted the acceleration into longitudinal irregularity via the vehicle dynamics model. However, the inversion results are not completely consistent with the real longitudinal irregularities. It needs to define three levels of standards to find out the location of the large value. In addition, Kalman filter can be introduced to solve the track irregularity based on vehicle dynamics model. Based on the two-dimensional vehicle dynamics model, Tsunashima H *et al.* [5]–[8] respectively used Kalman filter, impulse response and dynamic programming filter to inverse the vertical acceleration and pitch angular velocity of car body into longitudinal irregularity and its 10 m chord. Lee j s *et al.* [9], [10] invert the measured lateral and vertical acceleration of axle box and bogie of high-speed train into track irregularity based on Kalman filter, and divide the irregularity into several wave bands through band-pass filter. Compensation filter is used to compensate amplitude and phase, and the effects of inversion by axle box and bogie acceleration is compared and analyzed.

Some focused on the part below the secondary suspension, and track irregularity is inversed from the response of bogie. Weston PF *et al.* [11], [12] respectively integrated and filtered the nodding and swaying angular velocities of the bogie to obtain the longitudinal and lateral irregularities with a wavelength above 6m, and restore the vertical and lateral acceleration of the axle box to track irregularity with a wavelength of 6m. Xing Z *et al.* [13] employed the combined filtering algorithm to invert the bogie pitching angle velocity into a long wave longitudinal irregularity of [6, 300] m. OBrien EJ *et al.* [14] used the measured vertical acceleration and pitch angular velocity of bogies, the cross entropy optimization method to obtain longitudinal irregularity.

Other studies focused on the response of axle box below the primary suspension, avoiding the consideration of the suspension parameters' effect. The track irregularity can be reduced by quadratic integration. The acceleration can also be applied to detect the short wave rail defects. Naganuma Y *et al.* [15], [16] employed two digital processing technologies and one analog processing technology to measure 10m chord longitudinal irregularity from double integrals of vertical axle box acceleration, and developed a track state detection system (RAIDARSS 3) equipped with 'variable frequency differential filter' on commercial Shinkansen trains. Real J I *et al.* [17], [18] performed double integrals on the measured vertical and lateral axle box accelerations of trams, and obtained the longitudinal and lateral irregularities through filter. Li *et al.* [19], [20] applied time-frequency analysis of axle box vibration acceleration to qualitatively detect welds and corrugation.

The existing research can be divided into two directions: to retrieve track irregularity via vehicle dynamics model from the dynamic response of car body and bogie, and to measure irregularity from double integrals of axle box acceleration. The existing high-speed trains are equipped with high performance suspension system, the vibration caused by track irregularity will be greatly attenuated, and the suspension parameters used to input model are difficult to obtain accurately, making it very difficult to reverse the track irregularity from the car body attitude accurately. The track of distinct vehicles on the same line is different, and the repeatability is arduous to be guaranteed. As to measure irregularity from double integrals of axle box acceleration, there are the following problems in the existing research: the method is mainly applied to trams and low speed trains, or high-speed commercial trains with the maximum operating speed of 250km/h. To guarantee the reliability of the detection equipment in the complex environment under the condition of higher speed is also challenging, which requires higher dynamic range and low-frequency sensitivity of the acceleration sensor.

To meet the need of on-line monitoring of track geometry by carrying equipment under high speed conditions, and to monitor and maintain railway condition in time, this study proposes an on-board detection system for longitudinal irregularity via axle box acceleration signal is developed, which can be applied to commercial trains. The system consists of three parts: data acquisition unit, spatial-time synchronous calibration unit and data processing unit. The system relies on the acceleration signal collected on the axle box and the mileage and speed information from the train comprehensive system to restore the longitudinal irregularity. Last, a prototype is developed to carry out verification and testing on multiple high-speed railway lines. This study tries to solve the problems of high development, maintenance cost and long testing period of the existing comprehensive inspection train, and to provide technical support for the continuous safety and stable operation of HSR lines.

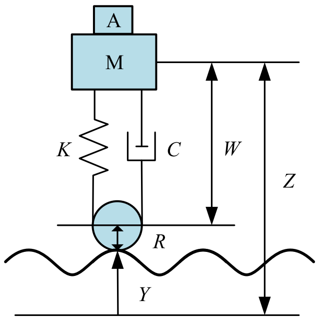

FIGURE 1. Principle of inertial reference method.

II. ON-BOARD DETECTION SYSTEM

A. PRINCIPLE OF TRACK GEOMETRY DETECTION SYSTEM APPLIED ON COMPREHENSIVE INSPECTION TRAIN

The GJ-6 track geometry detection system via inertial reference method is adopted for the comprehensive detection train to measure the track irregularity. The principle is shown in **Fig. 1.** M means the vehicle body; K and C represent equivalent stiffness and damping, respectively. The displacement meter measures the relative displacement W between the vehicle body and the axle. The displacement Z of the car body relative to the inertial reference is obtained by quadratic integration of the acceleration signal a collected by the accelerometer. The longitudinal track irregularity Y is calculated as

$$Y = Z - W - R \tag{1}$$

The amplitude of wheel irregularities is very small. Therefore, the wheel radius R can be considered to be constant. The actual measurement time in **Equation (1)** can be simplified as

$$Y = Z - W = \iint a dt dt - W \tag{2}$$

The maximum allowable error of the system is ± 1mm when the wavelength range is [1.5, 42] m. In the same railway line and under the same condition, the repeatability index requires that the absolute value of the difference between the two detection results should not exceed 0.4mm.

B. PRINCIPLE OF THE ON-BOARD DETECTION SYSTEM

Regarding to the inertial reference method, the on-board detection system for longitudinal irregularities is shown in **Fig. 2**. The vertical acceleration of the axle box is hereinafter integrated twice to obtain its vertical displacement trajectory, that is, the longitudinal irregularity along the line direction, expressed as

$$z = \iint \ddot{z} dt dt \tag{3}$$

where z means the vertical axle box displacement, dt represents the integration interval.

The value of transfer function in inertial reference method equals '1' in theory, as expressed in **Equation (4)**. The track irregularity can be truly characterized with the accurately measured axle box acceleration. The reduction effect of this method highly relies on the accuracy of measured acceleration. In terms of selecting the accelerometer used in measuring the acceleration of the axle box, sufficient accuracy in the wavelength range should be desired especially for the medium and long wavelength irregularity with low frequency excitation since the axle box behaves large dynamic response range. Acceleration signal is required to have higher measurement accuracy in the low frequency range. In addition, the acceleration signal collected at low speed is weak, and its active component might be submerged in the interference signal. Therefore, the method has the limit of the lowest detection speed.

$$H = H(\lambda)\left(\iint \ddot{z} dt dt\right) H(\lambda) \equiv 1 \tag{4}$$

where H means transfer function, λ means wavelength.

C. PARADIGM OF THE ON-BOARD DETECTION SYSTEM

According to the inertial reference method, the on-board track longitudinal irregularity system consists of data acquisition unit, space-time synchronous calibration unit and data processing unit. The system is shown in **Fig. 3**.

The data acquisition unit mainly completes the synchronous data acquisition of each axle box acceleration response channel. The main hardware module is an acceleration-measuring instrument, which introduces the signal collected by the acceleration sensor and the distance pulse of the train comprehensive system into the collection device. A prototype equipment is developed and carried on a comprehensive inspection train, as shown in **Fig. 4**. To solve the anti electromagnetic interference, moisture-proof sealing and component reliability of the detection system of EMU under high-speed conditions, a kind of glass fiber reinforced equipment tooling is designed, and the acceleration sensor is fixed in it. Fixing the two groups of the tooling on the left and right axle boxes connecting plates of the same wheel set with bolts to facilitate installation and replacement, as shown in **Fig. 5**. The sensor range selection should consider the vibration acceleration amplitude range in the frequency band that needs to be analyzed, and the vibration acceleration amplitude range in the frequency band that the sensor itself can sense, and take into account the impact of the vibration environment under the condition of the high-speed train operating speed of 350 km/h. The range of a capacitive accelerometer is 200g, the frequency response is [0, 3000] Hz, and the resolution is 0.05g.

A train comprehensive system can obtain uniform information such as speed, time and mileage, and its precise location is realized by GPS, radio frequency tag, high precision encoder and so on. The spatial-time synchronization unit is used to receive the spatial-time synchronization information of the comprehensive system, label the collected data with time mileage, and transmit the detected data to the central processing computer through the network.

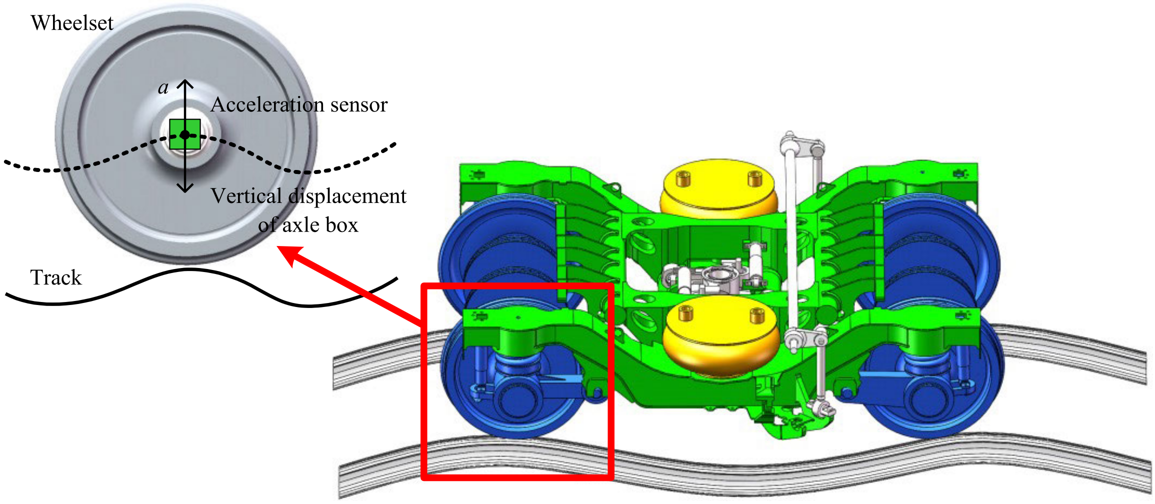

FIGURE 2. Principle of inertial reference detection method.

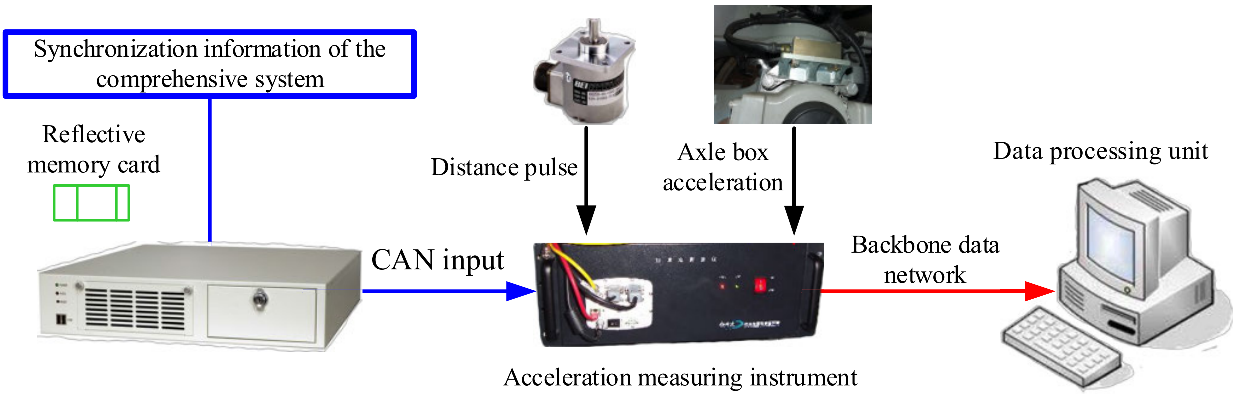

FIGURE 3. Components of the on-board track longitudinal irregularity detection system.

FIGURE 4. Test train equipped with on-board detection system.

FIGURE 5. Accelerometer and its installation on axle box.

The data processing unit can accurately reduce the axle box acceleration to the longitudinal irregularity, and display the information of mileage, speed, irregularity waveform and so on. The algorithm used in the data processing unit is described in section III.

III. AXLE BOX ACCELERATION SIGNAL PROCESSING METHOD

The processing of axle box acceleration is illustrated in **Fig. 6**, which is mainly divided into five steps.

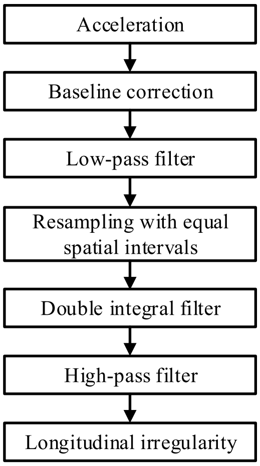

FIGURE 6. Axle box acceleration responses processing paradigm.

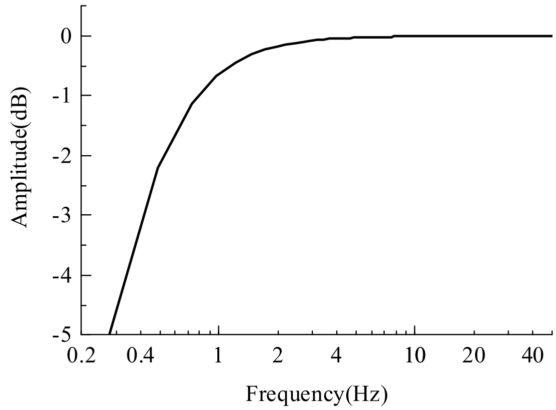

FIGURE 7. Amplitude frequency features of the high-pass filter.

Step1: The direct-current (DC) component in the acceleration response is removed by a high-pass filter with a very low cutting-off frequency to reduce the drift generated by double integrals;

Step 2: The low-pass filter is used to remove the high frequency components outside the effective frequency band of the acceleration responses, which will prevent the low frequency aliasing phenomenon of the acceleration responses in the further resampling process;

Step 3: The mileage and speed information are introduced to resample the acceleration responses from time domain to spatial domain;

Step 4: The acceleration responses are transformed into displacement responses by a double integral filter based on the isometric interval responses;

Step 5: The longitudinal irregularity of the specified wavelength range is hereinafter extracted by high-pass filter.

A. BASELINE CORRECTION

Acceleration integration will amplify low frequency and suppress high frequency, and low frequency signal is likely to cause integral saturation. It is necessary to avoid the presence of DC components in acceleration responses. Before integration, a high-pass filter with a very low cutting-off frequency can remove the extremely low frequency components. It is obtained in the frequency domain by means of zero-pole configuration. The transfer function is expressed as

$$H(z) = \frac{(1-\rho)\left(1-z^{-1}\right)}{1-(1-\rho)z^{-1}} \tag{5}$$

where ρ is determined through experiments, it determines the attenuation characteristics and transition bandwidth of the filter. The smaller the value of ρ is, the more favorable the amplitude-frequency feature will be flat and the transition band will be narrower. However, too small ρ will make the attenuation of low frequency components insufficient. The amplitude-frequency features of the high-pass filter are shown in **Fig. 7**.

B. RESAMPLING OF ACCELERATION RESPONSES AT EQUAL SPATIAL INTERVAL

1) FREQUENCY VARIATION RELATION OF TIME DOMAIN TO SPATIAL DOMAIN

Assuming the typical track irregularity wavelength of a certain section to be λ, when the train passes through this section at a speed v, the disturbance frequency of the wheelset is $f = v/\lambda$, the signal frequency sensed by the accelerometer installed on the axle box will also be f, and the mapping from spatial domain to time domain is linear. When the train passes with a varying speed, the frequency of the responses received by the accelerometer also change with time. While at this time, the spatial domain to time domain mapping is nonlinear, the spatial wavelength of the responses does not change accordingly. In addition, track irregularity can also be characterized by spatial responses. In order to eliminate the influence of speed changes on the collected responses, it is necessary to resample the time domain acceleration responses at equal spatial intervals, and use the spatial signal to characterize the track irregularity.

2) INFLUENCE OF RESAMPLING ON ACCELERATION RESPONSES

In this study, the sampling frequency of acceleration response is 5000 Hz. To reduce data redundancy and calculation, resampling at equal spatial interval will reduce the sampling frequency. In the process of down sampling, the frequency spectrum of digital signal will be extended periodically, which may lead to signal aliasing at low frequency. This phenomenon will be discussed in theory below.

Suppose an analog signal to be $x_a(t)$, its digital signal is $x(n) = x_a(nT_s)$, $-\infty < n < \infty$. By reducing the sampling frequency M times to form a new sequence $y(n)$, the sequence relation before and after the sampling is

$$y(n) = x(Mn) \tag{6}$$

To discuss the spectral relation between $y(n)$ and $x(n)$, define an intermediate sequence as $x'(n)$

$$x'(n) = x(n)p(n) \tag{7}$$

$p(n)$ represents the pulse sequence, $p(n) = \sum_{i=-\infty}^{\infty} \delta(n - Mi)$, $i = 0,\pm1,\pm2,\pm3,\ldots$, The sampling frequency of $x'(n)$ and $x(n)$ is f_s, and that of $y(n)$ is $f_s' = f_s/M$. So $y(n) = x'(Mn)$, by using discrete Fourier transform, one can get following results

$$\begin{aligned} Y\left(e^{j\omega}\right) &= \sum_{n=-\infty}^{\infty} x'(Mn)\, e^{-j\omega n} \\ &= \sum_{n=-\infty}^{\infty} x(Mn)\, p(Mn)\, e^{-j\omega n} \\ &= \sum_{n=-\infty}^{\infty} x(n)\, p(n)\, e^{-j\omega n/M} \\ &= \sum_{n=-\infty}^{\infty} \left[x(n)\left(\frac{1}{M}\sum_{k=0}^{M-1} e^{j2\pi nk/M}\right)\right] e^{-j\omega n/M} \\ &= \frac{1}{M}\sum_{k=0}^{M-1}\left[\sum_{n=-\infty}^{\infty} x(n)\, e^{-j(\omega-2\pi k)n/M}\right] \\ &= \frac{1}{M}\sum_{k=0}^{M-1} X\left(e^{j(\omega-2\pi k)n/M}\right) \end{aligned} \tag{8}$$

where the spectrum of $y(n)$ is the spectrum of $x(n)$ on the ω axis with M-fold expansion, and linear superimposition after every 2π/M frequency shift.

Assuming that the spectrum range of analog signal $x_a(t)$ is $[-f_{max}, f_{max}]$ and the amplitude is 1, the spectrum characteristics are shown in**Fig. 8(a)**. The spectrum characteristics of its digital signal $x(n)$ are shown in **Fig. 8(b)**. The spectrum period is f_s and the amplitude is $1/T_s$. The spectrum features of the down sampled signal $y(n)$ are shown in **Fig. 8(c)**. The spectrum period is f_s/M and the amplitude is $1/MT_s$. Spectrum aliasing occurs near f_s/2M.

To avoid the above aliasing phenomenon, it is necessary to filter the signal anti aliasing before resampling, that is, low-pass filtering. The $x(n)$ frequency band of the original signal should be limited to less than f_s/2M, but the effective components for the restoration of irregularities should be included in the frequency band. Let $h(n)$ be an ideal low-pass filter,

$$H\left(e^{j\omega}\right) = \begin{cases} 1 & |\omega| \le \pi/M \\ 0 & \text{other} \end{cases} \tag{9}$$

The output of $x(n)$ is $x_1(n)$ through low-pass filter, and the spectrum characteristics are shown in **Fig. 8(d)**.

$$x_1(n) = \sum_{k=-\infty}^{\infty} h(k)\, x(n-k) \tag{10}$$

where $x_1(n)$ is down sampled to get $y_1(n)$.

$$y_1(n) = x_1(nM) = \sum_{k=-\infty}^{\infty} h(k)\, x(nM-k) \tag{11}$$

The discrete Fourier transform of $y_1(n)$ is shown in **Equation (12)**, and the spectrum characteristics are shown in **Fig. 8(e)**. After low-pass filtering, low-frequency aliasing will not occur in down sampling.

$$Y_1\left(e^{j\omega}\right) = \frac{1}{M}\sum_{k=o}^{M-1} X\left(e^{j(\omega-2\pi k)/M}\right) H\left(e^{j(\omega-2\pi k)/M}\right) \tag{12}$$

3) LOW-PASS FILTER

The low-pass filter is designed to ensure that the acceleration signal does not aliasing during resampling. On the other hand, it is also designed to determine the lower wavelength limit of the reduction irregularity. The filter uses equiripple linear phase FIR filter, which is realized by Remez switching algorithm based on Chebyshev approximation criterion. It can achieve the best match between the expected frequency response and the actual filter, and avoid signal distortion.

The cut-off frequencies of passband and stopband are selected according to the maximum speed and the wavelength range of concern. In addition, the stopband cut-off frequency also needs to meet the frequency requirements of anti-aliasing filter. For example: Longitudinal irregularity caused by deformation of standard simply supported beam bridge is one of the important components of track irregularity. The characteristic wavelength is 32.6 m. When the speed is 250 km/h. The disturbance frequency to the vehicle is about 2.1 Hz. Therefore, the passband cut-off frequency ω_p of the filter is 2.5 Hz. Optional a minimum wavelength of 1.5 m, of concern an exciting frequency of about 46 Hz, for vehicles. Therefore, the stopband cut-off frequency ω_s of the filter is 50 Hz. Passband ripple R_p and stopband wave attenuation R_s determined by experiments. The amplitude-frequency characteristic curve of the filter is shown in **Fig. 9**.

4) ACCELERATION SIGNAL RESAMPLING

The filtered acceleration is mapped from the time domain to the spatial domain by using the **Equation (13)**. When the vehicle is running at variable speed, the spatial signal is of unequal interval sampling signal, and the next step is to resample with equal space interval before integration.

$$l_{i+1} = l_i + v_i \Delta t,\ i = 1, 2, 3, \ldots \tag{13}$$

where l_i means the mileage of the vehicle at i moment, v means the speed at i moment, Δt means the sampling interval of acceleration signal.

Because of the Runge phenomenon in the interpolation process of high-order interpolation resampling, the data near the ending point fluctuates greatly, but piecewise linear interpolation does not have this problem. Therefore, piecewise linear interpolation is used to approximate the original function, and the **Equation (14)** is a first-degree interpolation polynomial between any two points. Select the appropriate resampling interval Δl to ensure the accuracy of the fitting and reduce the amount of subsequent processing calculations.

$$z''(l) = x_1(i) + \frac{x_1(i+1) - x_1(i)}{l_{i+1} - l_i}(l - l_i) \tag{14}$$

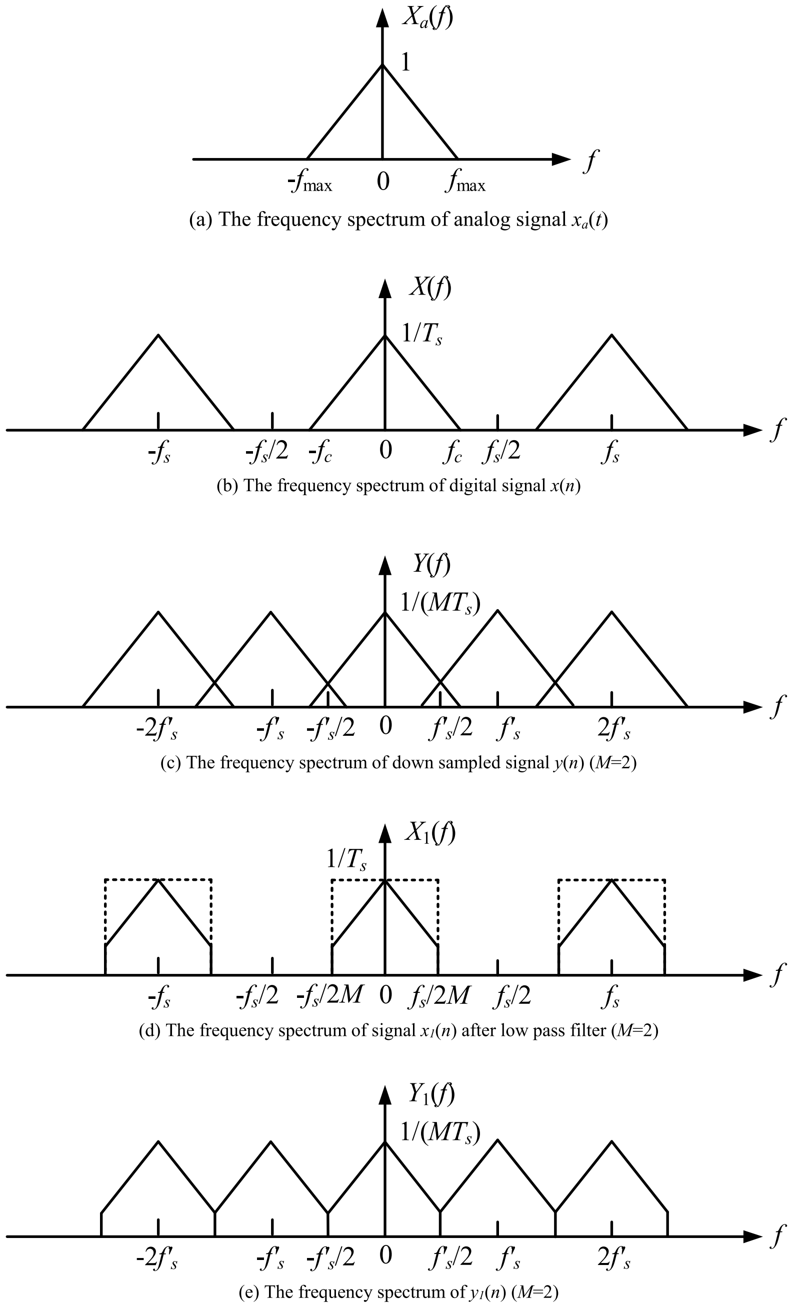

FIGURE 8. **Influence of down sampling on frequency spectrum.**

where $z''(l)$ means the vertical axle box acceleration after equal space resampling at mileage l.

C. DOUBLE INTEGRAL FILTER

The spatial trajectory of train axle box is obtained by double integrals of measured acceleration, which can be realized in time domain or frequency domain. In order to realize the continuous calculation, the transfer function of the double integral filter is derived based on the rectangular integral method, and the filter realizes the double integrals. The displacement variation of any mileage in the rectangular integral method is calculated as follows. If the vehicle speed is too low, the T_n will increase and the integral error will be greater with constant resampling space interval.

$$\Delta z(n) = z(n) - z(n-1) \approx z'(n-1)\,T_n \tag{15}$$

where $T_n = \Delta l / v_n$ represents the time interval between the current and the previous sampling points, which changes as the train speed changes. $z(n)$ means the n^{th} value of vertical axle box displacement. $z'(n)$ denotes the n^{th} value of vertical axle box velocity.

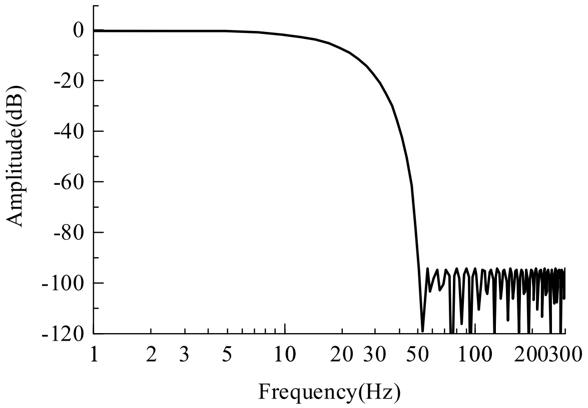

FIGURE 9. Amplitude frequency characteristics of equiripple linear phase FIR low-pass filter.

In **Equation (15)**, the displacement of any mileage is obtained as follows

$$z(n) = \sum_{i-1}^{n} \Delta z(i) \approx z(n-1) + z'(n-1)T_n \quad (16)$$

The results are as follows

$$z(n) - z(n-1) = z'(n-1)T_n \quad (17)$$

The speed variation of any mileage can be calculated as follows

$$z'(n-1) - z'(n-2) = z''(n-2)T_{n-1} \quad (18)$$

From **Equations (15)** to **(18)**, the transfer function of the double integral filter is expressed by

$$H(z) = \frac{z^{-2}\Delta T_{n-1}\Delta T_n}{1 - \left(1 + \Delta T_n / \Delta T_{n-1}\right) z^{-1} + \left(\Delta T_n / \Delta T_{n-1}\right) z^{-2}} \quad (19)$$

Because of the train speed does not change fast, one can obtain $\Delta T_n / \Delta T_{n-1} = 1$, the transfer function of the double integral filter can be simplified as

$$H(z) = \frac{z^{-2}\Delta T_n \Delta T_{n-1}}{\left(1 - z^{-1}\right)^2} \quad (20)$$

D. EXTRACT THE LONGITUDINAL IRREGULARITIES IN THE SPECIFIED WAVELENGTH RANGE

Track irregularity waveform is a random function in spatial distribution, and its wavelength range covers a wide range. In order to extract the wavelength components that are meaningful to guide the maintenance of track, it is necessary to eliminate the low-frequency components and eliminate the drift caused by integral. The main processing methods include high-pass filtering, polynomial fitting and wavelet transform. Butterworth high-pass IIR digital filter is used in this paper. The passing band of Butterworth high pass IIR digital filter has the maximum flat frequency characteristic, and it decreases monotonically with the increase of frequency.

The amplitude squared frequency response of the low-pass Butterworth filter is shown in **Equation (21)**, and the high-pass filter performs frequency transformation on it.

$$|H(\Omega)|^2 = \frac{1}{1 + \left(\Omega / \Omega_c\right)^{2N}} \quad (21)$$

where N is the order of the filter and Ω_c is its cutting-off frequency.

Assuming that the maximum wavelength of interest for track irregularity detection is λ_{max}, the effective component of the displacement obtained by integration mainly locates in the high frequency band. So the cutting-off frequency of the high-pass filter is taken as $1/\lambda_{max}$. When the maximum wavelength is 42 m, the amplitude-frequency characteristics of the high-pass filter are shown in **Fig. 10**.

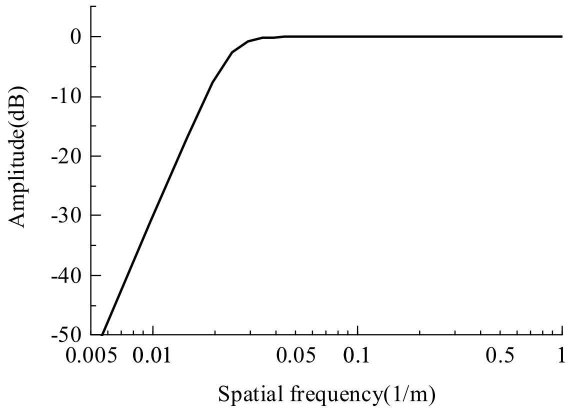

FIGURE 10. Amplitude-frequency characteristics of Butterworth high-pass IIR digital filter.

IV. RESULTS OF THE PROTOTYPE OF ON-BOARD DETECTION SYSTEM

Based on the system architecture of the above-mentioned inspection technology, a prototype device was developed and was mounted on a comprehensive inspection train. Verification tests have been carried out on several high-speed railways.

A. COMPARISON WITH THE TEST RESULTS OF COMPREHENSIVE INSPECTION TRAIN

GJ-6 track geometry detection system of comprehensive inspection train is selected as reference. Under the same detection speed and line direction, the two systems have been compared on several HSR lines. Two systems have been tested twice in a certain section. The interval between the two tests was three months. The comparison of longitudinal irregularity test results with the wavelength range [1.5, 42] m is shown in **Fig. 11** to **Fig. 14**. The correlation coefficient between the two system results was 0.81. The test results of the on-board detection system and GJ-6 track geometry detection system have good correspondence in time domain and frequency domain. From **Fig. 11** that the maximum peak values of longitudinal irregularity measured by the on-board

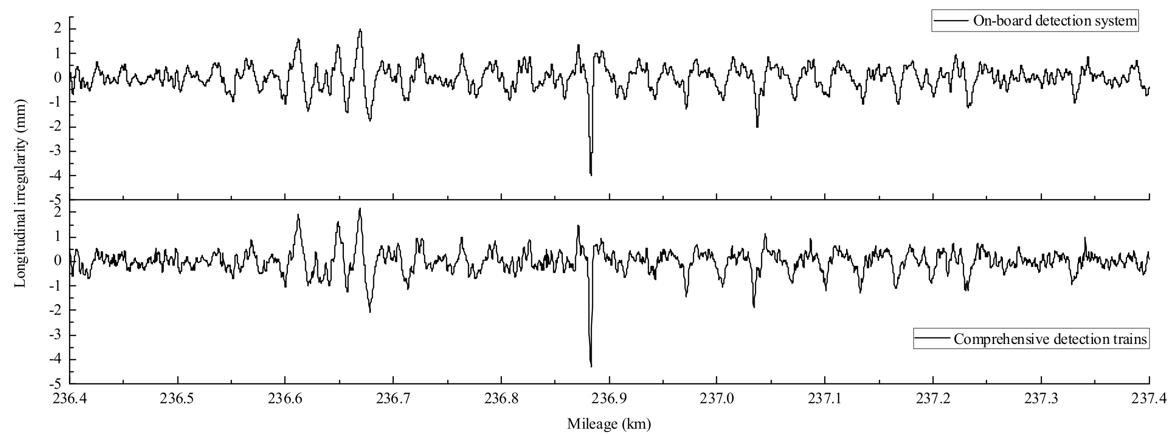

FIGURE 11. Waveform comparison of longitudinal irregularities.

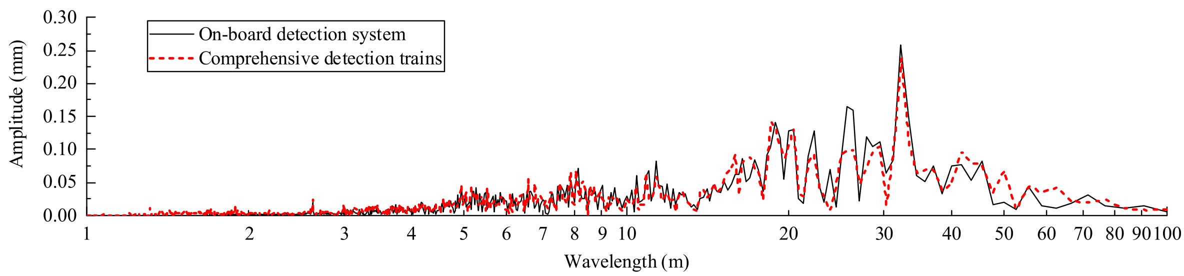

FIGURE 12. Longitudinal irregularity spectrum comparison.

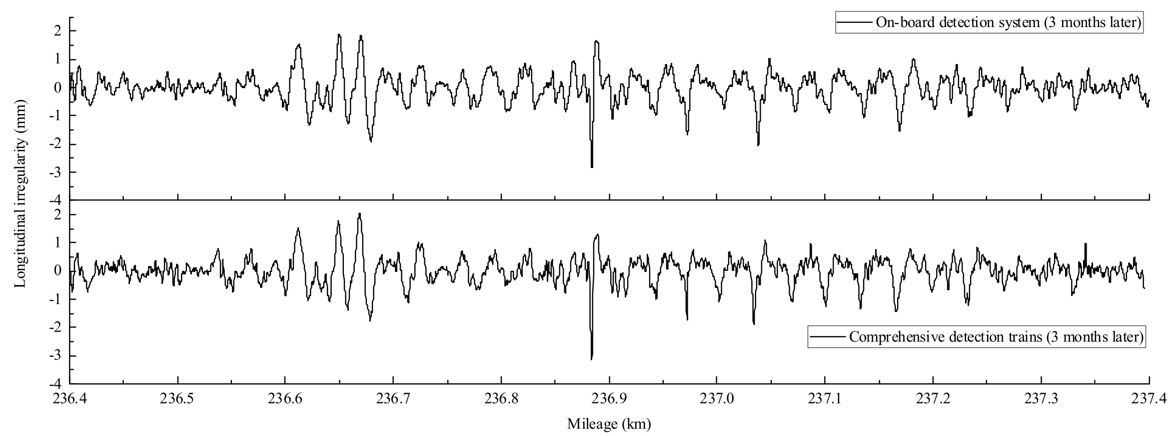

FIGURE 13. Waveform comparison of longitudinal irregularities (3 months later).

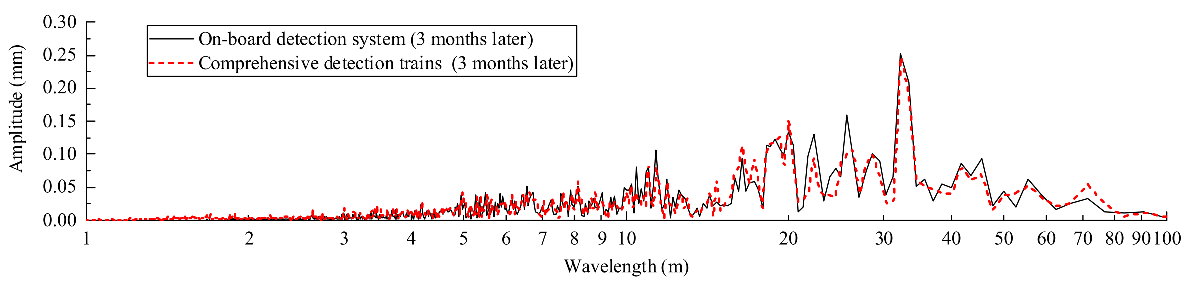

FIGURE 14. Longitudinal irregularity spectrum comparison (3 months later).

detection system and GJ-6 track geometry detection system at K236+880 are −4.0 mm and −4.3 mm respectively, with a difference of only 0.3 mm. In **Fig. 13**, the maximum peak values of longitudinal irregularity measured by the two systems at the same place after 3 months are −2.8mm and −3.1mm respectively, with a difference of 0.3mm.

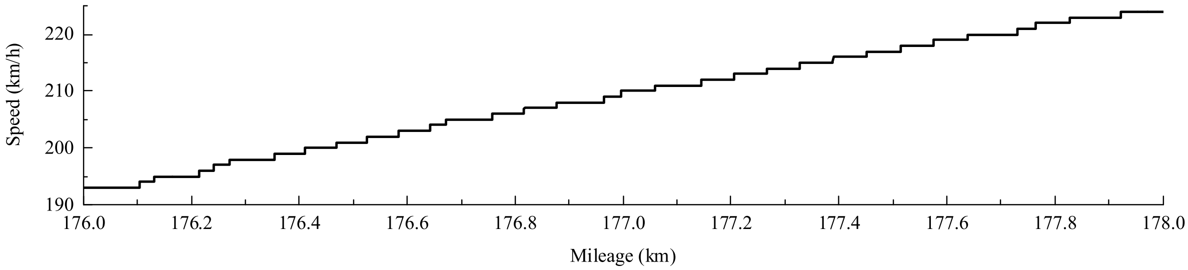

FIGURE 15. Train speed.

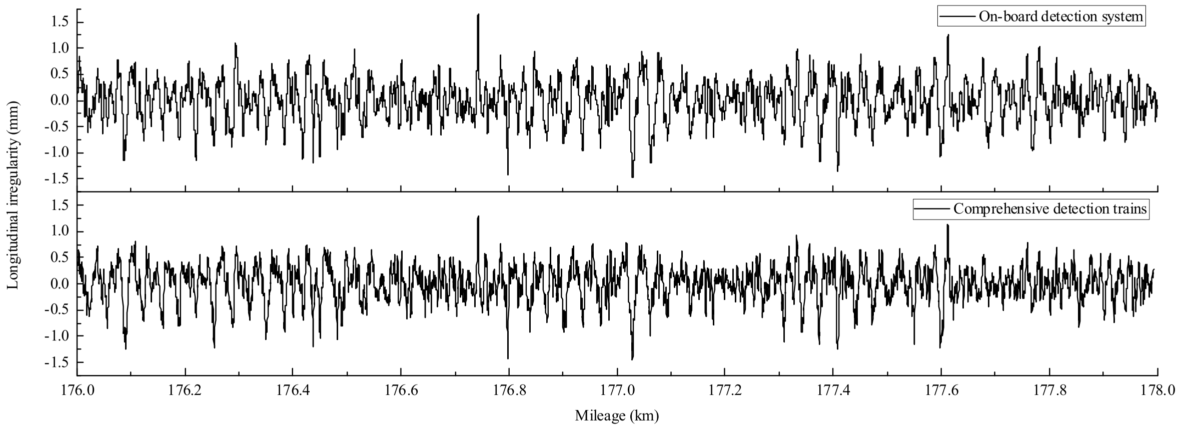

FIGURE 16. Waveform comparison of longitudinal irregularities.

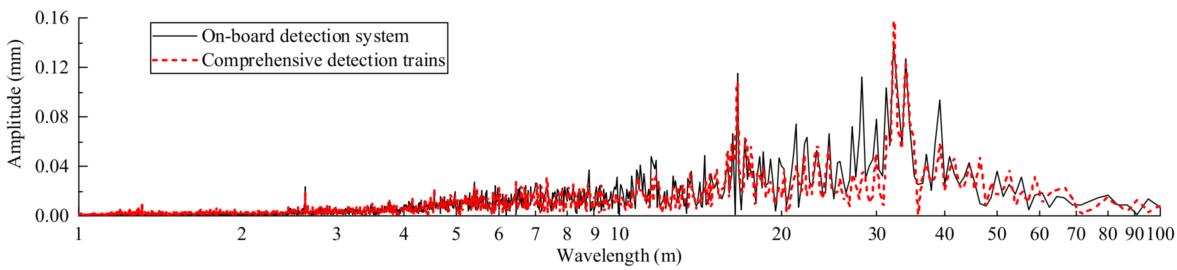

FIGURE 17. Longitudinal irregularity spectrum comparison.

The correlation coefficient between the two system results was 0.87. The 95th percentile of the absolute value of the difference between the two test results was used to describe the comparability of detection system. The 95th percentile is about 0.2mm, less than 0.7mm specified in the specification [21]. The comparative test results of the two systems under variable speed condition are shown in **Fig. 15** to **Fig. 17**. The vehicle speed increased from 193 km/h to 224 km/h. The 95th percentile of the absolute value of the difference between the two systems is about 0.3mm, which is also less than 0.7mm specified in the specification [21]. In **Fig. 16,** the correlation coefficient between the two system results was 0.83. The change trend and amplitude of waveform measured by the two detection systems are in good agreement within the whole section. The corresponding mileage has no obvious deviation. The result shows that the on-board detection system is suitable for vehicle speed change operation.

B. COMPARISON WITH GEODETIC MEASUREMENTS USING SOME FIXED-POINTS

The consistency between the test data of on-board detection system and geodetic measurements using some fixed-points is compared. In China, track static geometry detection data is measured by track inspection instrument, which is equipped with total station, high-precision distance sensor and tilt sensor and other equipment. The internal track geometric parameters are measured including gauge, lateral irregularity, longitudinal irregularity, cross level, twist and so on. The relative error is controlled in submillimeter level. On the other hand, external track geometric parameters are measured by CPIII (Geodetic measurements control fixed-points)

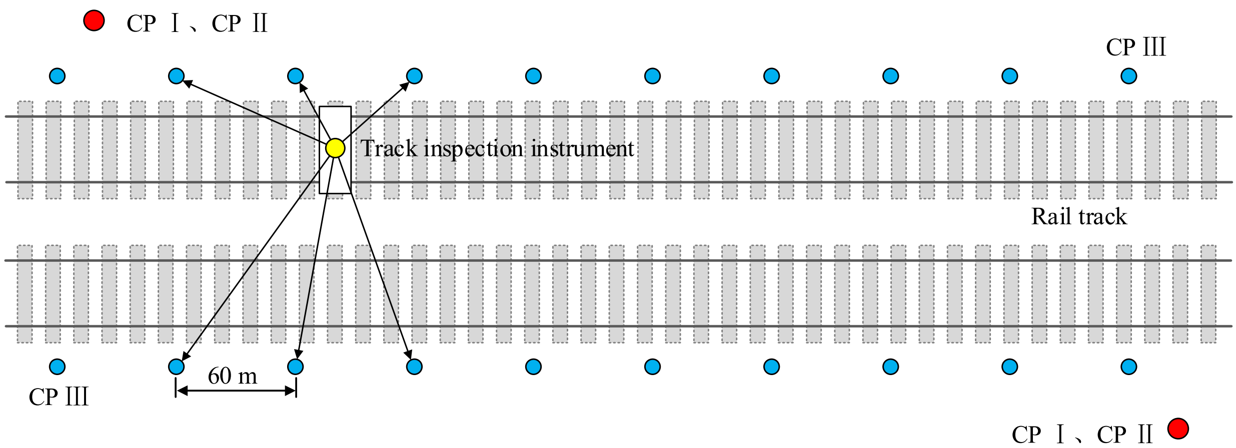

FIGURE 18. Geodetic measurements using some fixed-points.

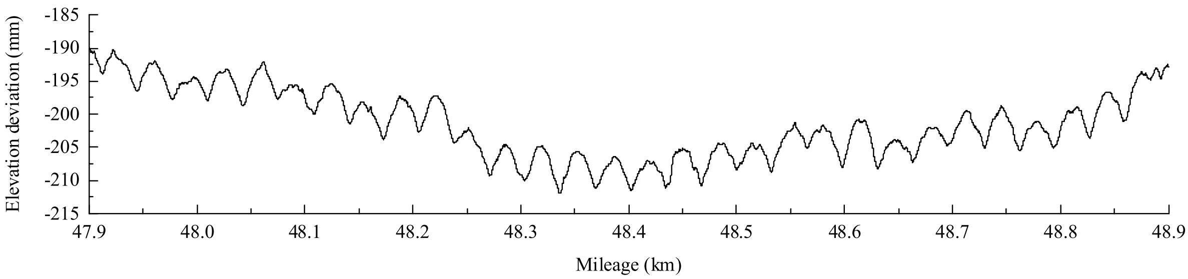

FIGURE 19. Elevation deviation of geodetic measurements using some fixed-points.

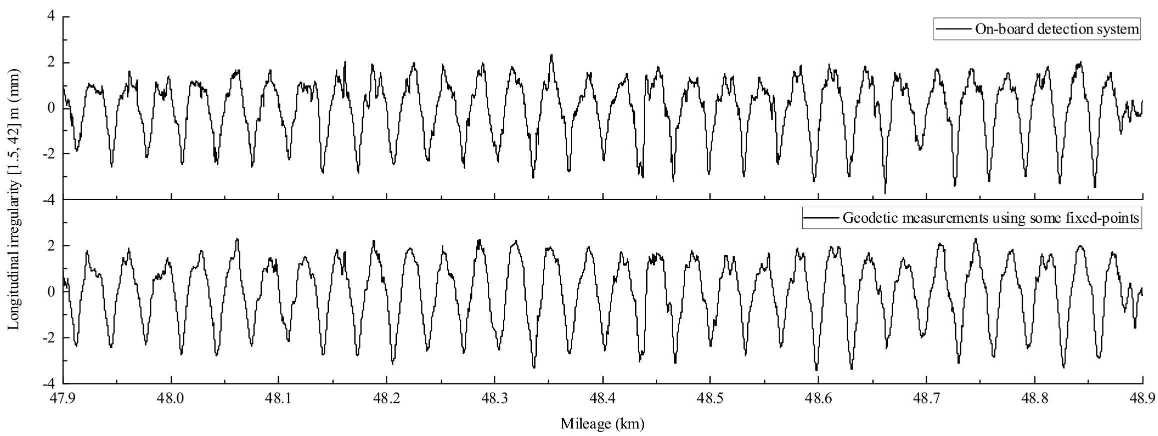

FIGURE 20. Waveform comparison of longitudinal irregularities.

control network, including the plane (lateral) deviation and elevation (vertical) deviation of the track center line and the left and right rails relative to the design line position, as shown in **Fig. 18**. The absolute error is controlled in millimeter level. The horizontal control network of China's high-speed railway engineering survey is divided into three levels, namely CPI, CPII and CPIII. CPI is the basic horizontal control network, which mainly provides Coordinate Datum for survey, construction, operation and maintenance, and uses satellite positioning measurement method for measurement. CPII is the line plane control network, which mainly provides control datum for survey and construction. CPIII is the track control network, which provides control basis for laying and operation maintenance of ballastless track. CPIII control network is laid out on the basis of CPI and CPII control network. CPII control points are deployed on fixed stakes on both sides of subgrade along the line. The distance between a pair of CPIII control points is about [50], [70] m, and the relative accuracy of adjacent points is better than 1mm.

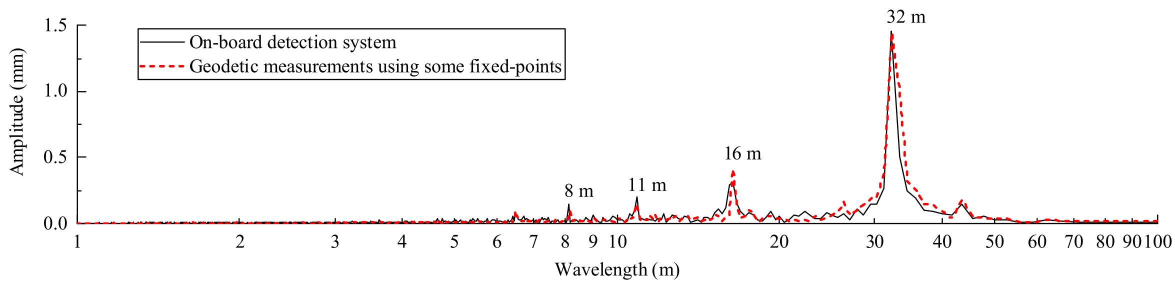

FIGURE 21. Longitudinal irregularity spectrum comparison.

The elevation deviation of geodetic measurements using some fixed-points of a HSR line measured by the above method is shown in **Fig. 19**. The minimum elevation deviation between the actual line position and the designed line position is 190 mm, and the maximum elevation deviation is 212 mm. The elevation deviation is filtered according to the same detection frequency band of the onboard detection system (wavelength range: [1.5, 42] m). The comparison of filtered results is shown in **Fig. 20** and **Fig. 21**. In **Fig. 20**, the waveform characteristics of the detection results of the two methods have a good corresponding relation. The correlation coefficient between the two system results was 0.87. The 95^{th} percentile of the absolute value of the difference between the two methods is about 0.6 mm, which is within the allowable range of error. In **Fig. 21**, there are four obvious peaks in both static and dynamic detection results, and their characteristic wavelengths and amplitudes are basically the same. The wavelength of 32m is the most obvious. This is because the foundation under the rail in this section is a continuous simply supported beam bridge, and the length of a simply supported beam bridge is about 32m.

V. CONCLUSION

This study proposes a new on-board detection technology for longitudinal track irregularity that can be applied to commercial high-speed trains. Based on the inertial reference method, the acceleration of the axle box of the high-speed train is restored to longitudinal irregularity through a combination of multiple digital filters. Certain technology can predict rapid changes in track geometry in a short period of time through high-frequency measurement, and realize the condition monitoring and potential maintenance of railway lines. Concluding remarks can be summarized as follows:

(1) A three-unit on-board detection system is newly designed, in which the data acquisition unit synchronously collects the acceleration response of multiple axle boxes, and the space-time synchronization unit labels the time and mileage of the collected data. The data processing unit accurately reduces the axle box acceleration to longitudinal irregularity;

(2) The axle-box acceleration-processing algorithm composed of multiple filters is newly designed, which can restore the longitudinal irregularity of the acceleration signal collected on the axle-box and the mileage and velocity information from the comprehensive inspection train system;

(3) The prototype of the detection system is mounted on a comprehensive inspection train and verified on multitudinous HSR lines. Comparing the test data of the on-board detection system with the comprehensive detection train and geodetic measurements using some fixed-points respectively, the results show that on-board detection system has high accuracy.

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