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Development and Application of Wheel-set Lateral Displacement Test System in High Speed Railway Turnout Zone

***Abstract**. Turnout is one of important infrastructures in high-speed railway. In order to study the law of wheel-set lateral displacement when a train passes a turnout at high speed, a wheel-set lateral displacement test system is developed by using laser displacement sensors and a corresponding digital data collection system. The test system is verified to be reliable through a field test focusing on turnout No.18 of Hefei-Nanjing high speed railway in China. Meanwhile, the field test reveals the wheel-set lateral displacement law of EMUs(Electric Multiple Units) as they pass the turnout No.18 at different speeds and from different directions: when the EMUs pass the turnout at high speed, in sections of switch rail top width ranging 15～35mm and nose rail top width ranging 45~65mm, the wheel-sets produce lateral displacement rapidly; comparing two conditions, i.e. the EMUs pass the turnout from forward and from reverse direction, the wheel-set lateral displacement under former condition is bigger and it will cause a bigger lateral vibration acceleration.*

***Streszczenie.** Zaproponowano system kontroli rozjazdów w sieci kolejowej wysokiej prędkości. Badane jest boczne odkształcenie rozjazdu w chwili gdy przejeżdża pociąg przy wykorzystaniu czujników laserowych. (**Projekt i zastosowania systemu testowania bocznego odkształcenia rozjazdów w systemie kolei wielkich prędkości**)*

Keywords: High Speed Railway; Turnout; Laser Displacement Sensor; Wheel-set Lateral Displacement; Digital Data Collection System
Słowa kluczowe: koleje wielkich prędkości, rozjazdy, pomiar odkształcenia

Introduction

With the increasing of train’s running speed, carrying weight and transport density, wheel/rail dynamic interaction becomes more prominent and complex. Turnout is one of important infrastructures in high-speed railway. The dynamic optimization of turnout design remains a key problem that needs to be solved because a turnout has complex structure and variable wheel/rail contact geometry. In turnout zone, there is inevitable track irregularity (depends on structural design, as shown in Figure 1 and Figure 2) and lateral impact, uneven distribution of overall track stiffness (along the line), deviation of large movable rail components caused by their deformation, unsustainable stability of ballast bed caused by expansion and severe vibration of jointless turnout---all these reasons result in strong wheel/rail dynamic interaction, thus the turnout is a key structure to restrict running speed of train [1~5].

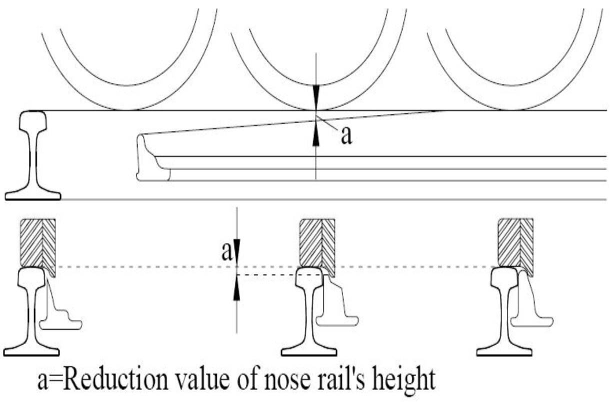


Fig. 1. Vertical structural irregularity of track in turnout zone

Wheel-set displacement is the main manifestation of wheel/rail dynamic interaction when a train is running on railway track. The test of wheel-set displacement can not only estimate the applicability of track system, but also evaluate the vehicle running quality. Especially for the turnout, the rationality of wheel/rail relation design (such as plane connection type, reduction value of switch or nose rail's height, horizontal hiding mode of nose rail's tip, etc.) can be evaluated comprehensively by the wheel-set displacement value. Therefore, the development of wheel-set displacement non-contact test system is important for opening up a new approach to optimize the wheel/rail relation design in high speed turnout. A field test will provide the basis for the selection of wheel/rail dynamic simulation parameters of the turnout.

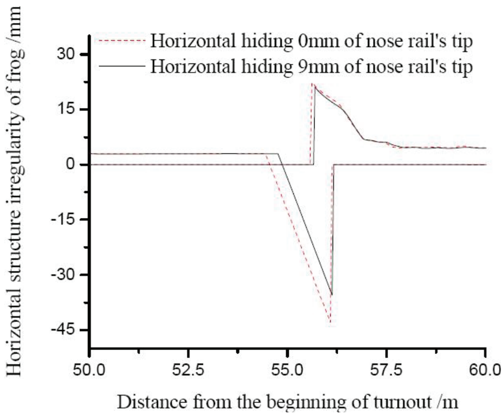


Fig. 2. Horizontal structural irregularity of track in turnout zone

Development of Wheel-set Lateral Displacement Test System

There are two types of laser displacement measuring system, contact and non-contact. And the non-contact one is adopted in this test because of the high-speed and motion characteristics of the train. The short effective test time requires high resolution, high-precision, and high-frequency measurements of the test system, thus OPTONCDT 1700 series displacement sensor manufactured by German Micro-Epsilon Company is adopted. And a corresponding digital data collection system is also used to establish the wheel-set lateral displacement test system.

Basic Principles

The principle of the wheel-set lateral displacement test is shown in Figure 3. The sensors are set outside the railway line; distance between a wheel-set and the sensor is measured, and according to the geometric relation between wheel-set, rail and sensor, the formula of wheel-set lateral displacement Δt is expressed as follows:

$$\Delta t = \frac{T}{2} + T_w + D_w - (\frac{S}{2} + W_r + D_r) \qquad (1)$$

where, S is the gauge of corresponding measuring point; Wr is the width of rail head; T is the inner distance of wheel back; Tw is the thickness of the wheel; Dw is the distance between the side surface of measured wheel-set and the sensor; Dr is the distance between rail outer side and sensor.

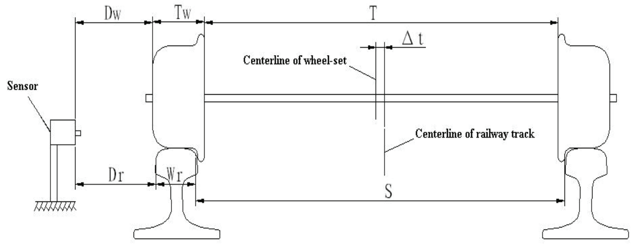


Fig. 3. Principle of wheel-set lateral displacement test system

If Δt is positive, it means the wheel-set deviates to the side that is away from the sensor; if Δt is negative, it means the wheel-set moves laterally to the side that is close to the sensor; if Δt is 0, it means the wheel-set centerline coincides with track centerline, and there is no wheel-set lateral displacement.

Main Equipments of Test System

(1) Laser displacement sensor based on position sensitive detector (PSD)

PSD laser displacement sensor is the core part of the test system. Its basic theory is triangulation reflection principle of laser. The sensor emits a laser beam, which through the lens forms a tiny light spot on the surface of the measured object. Then the light diffuses and through an imaging light microscope it is projected on a quite sensitive linear film, which can recognize position changes of laser reflection point. Then these raw data is calculated by digital signal processor (DSP) and the position of measured object is output in the form of analog signals, as seen in Figure 4.

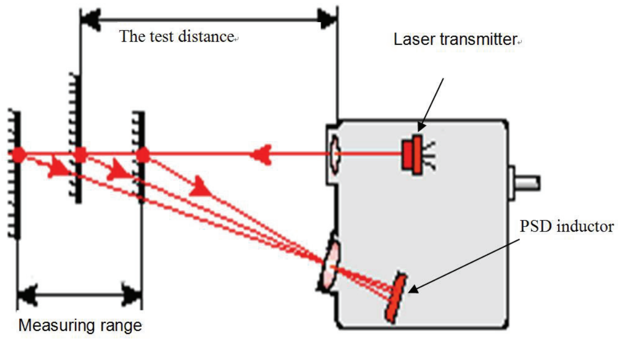


Fig. 4. Triangulation reflection principle of PSD laser displacement sensor

When EMUs pass the turnout at high speed, the wheel-set side surface will reflect the emitted laser to the sensor, which can determine its distance from the wheel-set side surface through angle of the reflected light. Then according to the formula (1) the wheel-set lateral displacement can be calculated. The distance between railhead work face and the sensor can be obtained through static calibration.

Laser displacement sensor type adopted in the system: OPTONCDT1700; number: 20. Its main technique parameters:

Effective range: 170-270mm;

Absolute measurement error < ±0.08%;

Resolution: 0.005% (5 um);

Measurement frequency range: 100-10000 Hz (be adjusted according to actual situations);

Output signal is analog signal.

(2) High-speed data collection system

Hardware of data collection system includes sensor power supply equipment, all cables and connectors linked with the sensor, controller, data collection instrument and computer. The sensors and controllers set at each measuring point are linked with the data collection instrument by shielded cables and connectors. Data collection card of the instrument transforms the analog signal into digital signal, which is then transferred to the computer. Because the data collection instrument is portable and can be linked with notebook computer to record the data, it is convenient for field operation. It ensures not only reliability of data transmission but also convenience of measurement.

Data Collection Process

When EMUs pass a turnout, the wheel-sets move fast relatively to the sensor. Thus relative position of the wheel-set and sensor at different times should be collected and recorded quickly. Figure 3 shows the data collection process: at first, analog signal from the laser displacement sensor is transferred from the controller to data collection instrument, where the signal is transformed into digital ones, and then the final data of wheel-set lateral displacement will be presented and stored in computer through the data cables.

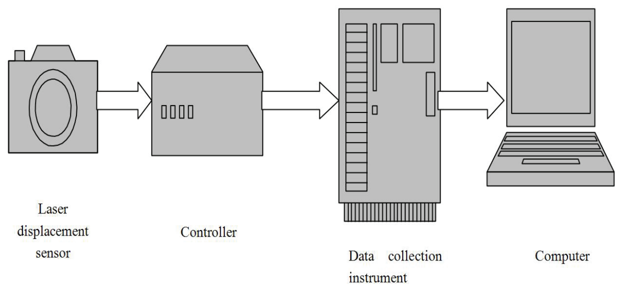


Fig. 5. Data collection process of the test system

The data is recorded immediately as the EMUs pass the turnout. The wheel-set lateral displacement waveform of a single measuring point is shown in Figure 6. As seen in the figure, horizontal axis represents the data collection time, while vertical coordinate represents the distance between wheel-set and sensor. One vertical line at 220mm of the vertical coordinate represents one wheel-set. When there are no wheel-sets passing the measuring point, the laser emitted by the sensor will spread to the infinity. At this time the system feedback value is over the range, namely 170mm.

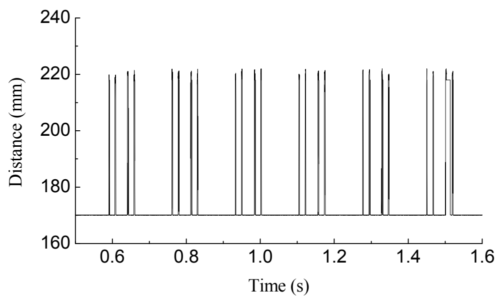


Fig. 6. Wheel-set lateral displacement waveform of a single measuring point

Application of the Test System

Layout of Measuring Points

Figure 7 shows the layout of measuring points. There is twelve points in switch section, two points at guide curve, six points at the frog, and in all there is twenty points in turnout zone. Figure 8 and Figure 9 show the field installation of laser sensor and field layout of all measuring points respectively.

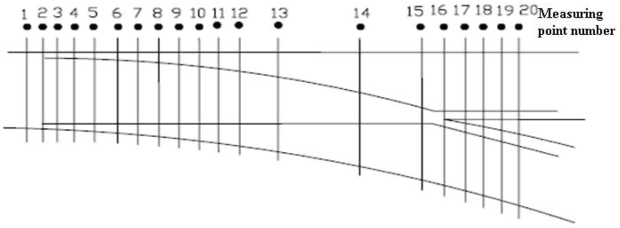


Fig. 7. Measuring point layout in turnout zone

Fig. 8. Field installation of PSD laser displacement sensor

Fig. 9. Field layout of measuring points

Table 1. Correspondence between measuring point and sleeper number

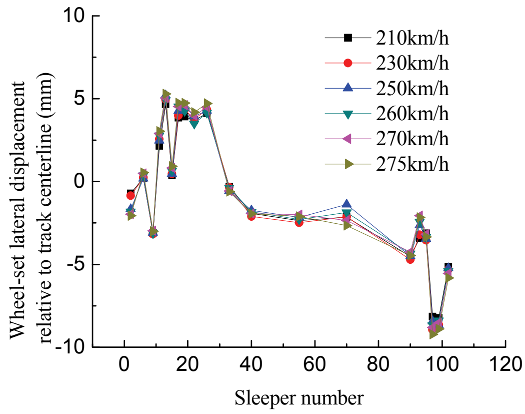
Measuring point No.	Sleeper No.	Measuring point No.	Sleeper No.
1	2	11	33
2	6	12	40
3	9	13	55
4	11	14	70
5	13	15	90
6	15	16	93
7	17	17	95
8	19	18	97
9	22	19	99
10	26	20	102

All measuring points are set at sleeper end of outer side of straight stock rail. Correspondence between each measuring point and sleeper number is shown in Table 1. The location of each measuring point is determined under the following conditions: (1) wheel load transition section, especially the wheel/rail contact point where lateral mutation is produced; (2) switch rail and nose rail sections where reduction value of rail height changes.

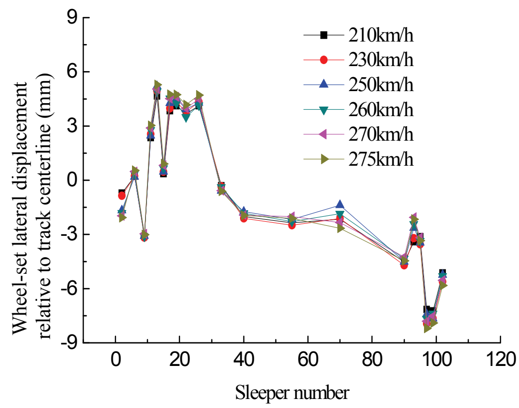
Test Results and Analysis

(1) Wheel-set lateral displacement variation law as EMUs pass the turnout through the main line

As seen in Figure 10, the lateral displacement of each measuring point varies as the EMUs pass the turnout at different speeds. Table 2 shows the maximal wheel-set lateral displacements at the switch and frog.



(a) Passing turnout from forward direction



(b) Passing turnout from reverse direction

Figure 10. Wheel-set lateral displacement variations as EMUs pass the turnout through the main line

Table 2. The maximal wheel-set lateral displacement at the switch and frog (mm)

Passing Speed and direction		Switch part	Frog part
210 km/h	Reverse	5.12	-8.93
	Forward	5.34	-9.13
230 km/h	Reverse	5.37	-9.11
	Forward	5.41	-9.24
250 km/h	Reverse	5.63	-9.22
	Forward	5.68	-9.41
260 km/h	Reverse	5.87	-9.42
	Forward	6.14	-9.63
270 km/h	Reverse	6.12	-9.69
	Forward	6.25	-9.79
275 km/h	Reverse	6.31	-9.83
	Forward	6.44	-9.98

As seen in Figure 10 and Table 2:

① When the train passes the turnout from either direction, the snaking motion of wheels at guide curve is small; with the increasing of train speed, the wheel-set lateral displacement increases greatly.

②When EMUs pass the turnout from reverse direction, from sleepers No.9~13 at switch part (switch rail top width: 15~30mm), the wheel-sets move laterally from straight stock rail to straight switch rail, with a displacement of 8mm; after that the wheel-sets move laterally from straight switch rail to straight stock rail, with a displacement of 5mm. When the switch rail top width is less than 30mm, the height of switch rail lowers, so the wheel tread only contacts with curve stock rail and the wheel contract point moves laterally to the curve stock rail, which results in lateral displacement of the wheel-sets. When the switch rail top width is close to 32mm, the reduction value of rail's height decreases, so the wheels begin to contact with the switch rail and produces a big lateral force that points to the straight stock rail. This force makes the wheel-sets move laterally to the straight stock rail, and consequently the lateral displacement changes rapidly in the section with switch rail top width ranging 15～35mm. This indicates that when EMUs pass the turnout from reverse direction, the lateral acceleration produced in the section with switch rail top width ranging 15～35mm is bigger than those in other sections.

③When EMUs pass the frog from reverse direction, as the wheel-sets pass sleepers No.95~97 (nose rail top width ranging 45～65mm), they move laterally from nose rail to straight stock rail rapidly, with a displacement of 6.5mm, which is slightly smaller than the maximum at the switch. This indicates that when EMUs pass the turnout from reverse direction, big lateral acceleration will be produced in the section with nose rail top width ranging 45～65mm.

④When EMUs pass the turnout from forward direction, the lateral displacement variation is on the whole similar to descriptions in ②&③. The difference is that the lateral displacement change is bigger when the train passes the turnout from forward direction. In the section with switch rail top width ranging 15～35mm, when EMUs pass the turnout from reverse direction, the wheel-set lateral displacement amplitude is 8mm; and the amplitude is 10mm when EMUs pass the turnout from forward direction, which indicates the lateral acceleration is bigger when the EUMs pass the turnout from forward direction.

(2) Wheel-set lateral displacement variation as EMUs pass the turnout through branch line

Table 3 shows average lateral displacement of the wheel-sets as EMUs pass the turnout from branch line. Compared with the average, the maximum of each measuring point increases no more than 0.5mm. The EMUs speed is 90km/h. As the speed increases, the wheel-set lateral displacement will increase a little.

Table 3. Wheel-set lateral displacement variation as EMUs pass turnout from branch line (mm)

Sleeper number corresponding to measuring point	Passing from Reverse	Passing from Forward
2	-5.4	-6.7
6	-2.78	-7.33
9	-4.09	-7.69
11	-7.33	-8.39
13	-8.72	-8.78
15	-8.38	-8.86
17	-8.82	-9.84
19	-9.15	-9.46

The following results can be concluded from Table 3:

① When EMUs pass the turnout branch line from reverse direction, the wheel-sets move laterally to curve switch rail; at sleeper No.11 (switch rail top width: 22mm), the wheel flange start to cling to the railhead work face; at sleeper No.13 (switch rail top width: 30mm), the wheel-sets move laterally to curve switch rail for more than 8mm, and from then on the wheel flange clings completely to the curve switch railhead.

②When EMUs pass the turnout through branch line from forward direction, the wheel-sets move laterally to curve switch(wheel flange sticks to the work face of curve switch railhead) in the range from guide curve to sleeper No.11 (nose rail top width 22mm); from sleeper No.11 to the tip of nose rail, the wheel-sets lateral displacement decrease gradually. On the whole, under two conditions that EMUs pass the turnout from forward direction and from reverse direction, the wheel-sets lateral displacement under former condition is bigger than that under the latter, which indicates that in former condition the flange contacts with curve switch rail in a wider range and the contact pressure is bigger, so it is easier to cause side wear to the curve switch rail.

Wheel back distance of the EMUs used in the test is 1353mm, and the wheel flange width is 32mm, so the wheel-set width is 1419mm under normal condition; gauge in turnout zone is 1435mm and the clearance between wheel flange and gage line is 16mm. Due to this clearance, when the wheel-sets move laterally to one side in 8mm, the flange will contact with the railhead work face; when the lateral displacement is smaller than 8mm, the wheel flange will not cling to the railhead. As for 1435mm track gauge, after the wheel-sets move laterally to the track centerline for 8mm, the wheel flange will contact with the railhead work face; at this time the wheel-set lateral force is big and the rail produces dynamic lateral displacement. According to dynamic simulation analysis[6~11], if the dynamic gauge increases no more than 4mm, the lateral stability of the EMUs can be satisfied, which means the rail dynamic lateral displacement should be no more than 2mm. After the wheel-sets move laterally for 8mm and cling to railhead work face, the rail together with the wheel-set will produce dynamic lateral displacement. The wheel-set lateral displacement relative to the track centerline is the sum of 8mm and the rail dynamic lateral displacement. According to dynamic simulation results, the wheel-set lateral displacement should be no more than 10mm in order to satisfy the stability. Thus, for Hefei-Nanjing high speed railway, in its turnout zone, if the wheel-sets move laterally to the track centerline for less than 10mm, the safety of EMUs can be satisfied.

Combining the criteria mentioned above and the test results, the maximal wheel-set lateral displacement of each measuring point is less than 10mm. This indicates that for turnout No.18 in Hefei-Nanjing high speed railway, the safety can be satisfied if the EMUs pass the turnout at speed of 210～275km/h from either forward or reverse direction.

Conclusions

A wheel-set lateral displacement test system is developed by using laser displacement sensor and a corresponding data collection system. The test system is verified to be reasonable through a field test of wheel-set lateral displacement focusing on turnout No.18 of Hefei-Nanjing high speed railway. Meanwhile, the field test reveals the wheel/rail contact law in turnout zone.

(1) When EMUs pass the turnout at high speed, in sections of switch rail top width ranging 15～35mm and

nose rail top width ranging 45~65mm, the wheel-sets produce lateral displacement rapidly; comparing two conditions, i.e. the EMUs pass the turnout from forward direction and reverse direction, the wheel-set lateral displacement under former condition is bigger and it will cause a bigger lateral vibration acceleration.

(2) As for turnouts of Hefei-Nanjing high speed railway, the running safety can be satisfied if the EMUs pass the turnout at speed of 210～275km/h from either forward or reverse direction.

(3) When the EMUs pass the turnout through the branch line, the wheel-sets mostly cling to the curve switch rail from sleeper No.13 (switch rail top width: 30mm) and guide curve. Lateral displacements of all wheel-sets are less than 10mm.

Acknowledgment

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