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Progress on wheel-rail dynamic performance of railway curve negotiation

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Abstract: Recent advances on wheel-rail dynamic performance of curve negotiation are reviewed in this paper. There are four issues, the mechanism and calculation method of curve negotiation, the analysis and assessment of dynamic performance of vehicle, the effect of vehicle parameters on dynamic performance, and the influence of railway parameters on dynamic performance. The promising future development of wheel-rail coupled dynamics theory is analyzed in the research of curve negotiation. The framework and technique matching performance of wheel-rail dynamic interaction on the curved track are put forward for modern railways. In addition, the application of performance matching technique is introduced to the dynamic engineering, in which the wheel load is reduced obviously when the speed of train is raised to 200-250 km/h.

Key words: railway; curved track; dynamic interaction; wheel-rail system; performance matching

1 Introduction

Due to the change of alignment and geometric size, the moving path of wheelset and the state of wheel-rail contact will change obviously when a vehicle passes through a curved track, which can aggravate the wheel-rail interaction, intensify the wheel-rail vibration, and affect the running safety and comfort. On the small-radius curved track, this phenomenon would be more serious. Therefore, it is very important to carry out researches on mechanism and dynamic performance of curve negotiation. Since the wheel-rail dynamic performance on the curved track has been one of the focuses of vehicle dynamics, there are a large number of theoretical and experimental studies on the curve negotiation in the international and domestic domain. There are four issues, including the mechanism and the calculation method of curve negotiation, the analysis and assessment of vehicle dynamic performance, the effect of vehicle parameters on dynamic performance, and the influence of railway parameters on dynamic performance. However, because the curved track is a weak link on the railway and the mechanism of wheel-rail interaction on curved track is complex, there are many engineering problems closely related to the interaction, such as, the

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rail corrugation appearing on the small-radius curves of existing railway and on the big-radius curves of high-speed railway, the rail side abrasion and the plastic flow appearing on the curved track of heavy-haul railway, etc. It can be seen that studies on the wheel-rail dynamic interaction of curved track are not deeply and systematically performed yet. It has not been investigated from the view of system engineering. More detailed researches, including theoretical models, principles and techniques of performance matching and so on, should be carried out. In this paper the advance and achievement in these studies are reviewed and discussed. From the view of system dynamics, the framework and technique matching performance of wheel-rail dynamic interaction on the curved track are put forward for modern railways.

2 Mechanism and calculation method of curve negotiation

A quasi-static method was introduced into the study on the mechanism of curve negotiation (Newland 1968; Boocock 1969). Subsequently, lots of studies on the steady-state curving performance of locomotives and rolling stocks have been performed (Wickens 1975; Elkins and Gostling 1977; Piotrowski 1988; Sheffel et al. 1993). The dynamic interaction between vehicle and curved track cannot be figured by means of quasi-static method. Then, the dynamic performance of curve negotiation was presented. A quasi-static model and a dynamic model of curve negotiation were established (Zboinski 1998), and the curving performance and stability of motion on curved track were analyzed. By establishing a bond graph model of curve negotiation, some dynamic rules which cannot be discovered by the conventional method were found (Banerjee et al. 2009). Two types of calculation method of wheel-rail contact were developed (Sugiyama and Suda 2009), one was the table look-up that can be effectively used for the tread contact, and the other was the real-time online when the contact point jumped to the flange region. If there are two contact points in curve negotiations, the latter method is used to determine the contact configuration. By means of the software SIMPACK, a dynamic model of metro vehicle passing through small-radius curved track was established (Kurzeck 2011). The relationship between wheel-rail dynamic interaction caused by the resonance and rail corrugation on curved track was analyzed. The wheel-rail longitudinal creep forces, lateral creep forces and spin creep moments were calculated when a vehicle passing through the curved track, and the formulas of the friction power were obtained (Tudor et al. 2009). Under traction condition, the characteristics of wheel-rail dynamic interaction on the curved track were analyzed (Grassie and Elkins 2005). Results indicated that, under the traction condition, the lateral wheel-rail dynamic interaction would be larger to certainly cause the rail oblique crack. In recent years, the stability motion on the curved track has been studied (Dukkipati and Swamy 2001; Cheng et al. 2009; Zboinski and Dusza 2010). The most prominent research was conducted (Cheng et al. 2009), in which, a vehicle model with 21 DOFs was established, and another model with fewer DOFs was obtained, and the stability motion of vehicle with different DOFs was analyzed by the simplified model.

At the domestic level, researches on the mechanism of curve negotiation have been performed relatively late. The study of steady-state curving performance began in 1970s. The formula to calculate displacement of the centre plate on curved track was deduced (Sha 1979). According to the safety running condition of vehicle, an integrated graph was given to describe the restricted relationship among the loading gauge, the goods, and the multi-oriented vehicle. Taking a locomotive with two bogies as an example, a simplified calculation method of nonlinear negotiation performance was proposed (Shen 1982). Formulas were deduced to calculate the longitudinal, lateral and spin creep rates. According to the principle of steady-state curve performance, the design principle of force-steering bogie was studied (Mao et al. 1985). The mechanism and calculation method of steady-state performance were analyzed by developing different simplified linear models (Huang 1981; Shen 1998; Shu 1999; Lu et al. 2002). Afterwards, with the evolution of the dynamic model and the computer technology, the investigation on the mechanism of curve negotiation was performed. Research on the experiment method of curve negotiation was carried out using a roller rig (Xian 2004) and by means of the dynamic software SIMPACK and the dynamic performance of curve negotiation was investigated. The phenomenon of wheel-rail multipoint contact on the curved track was studied (Ren and Jin 2010). The dynamic characteristics of curve negotiation of radical bogie were analyzed (Li et al. 2003). Based on the theory of vehicle-track coupled dynamics, the mechanism of curve negotiation under the traction condition was investigated (Wang et al. 2006).

Generally speaking, there are two methods being used for studying the mechanism of curve negotiation of railway vehicle, which are steady-state and dynamic-state methods. The simplified linear models were established to analyze the geometric relationship and the mechanism of curve negotiation in the steady-state method, while the dynamic models were established to investigate the wheel-rail dynamic interaction of curve negotiation in the dynamic-state method.

3 Analysis and assessment of dynamic performance of vehicle

Using a simplified linear model, an optimal design method of hunting stability and curving performance of vehicle was introduced (De Pater 1987). In order to investigate the dynamic performance of curve negotiation of vehicle, a coupled model for a quarter car and track was established (Yugat et al. 2009). In this model, the motion of each component caused by curved track was described by the rolling motion. There are serious limitations, and the pitch motion of vehicle cannot be described by this model. By means of the software NUCARS, a dynamic model of locomotive was established and the dynamic performance of curve negotiation was analyzed (Delorenzo 1997). The dynamic performance and stability motion of curve negotiation of an asymmetric bogie were analyzed (Dukkipati and Swamy 2001). Model, calculation, and bench test of performance of curve negotiation were introduced (Iwnicki 2006). The dynamic performance of curve negotiation of low-floor vehicle with independently rotating wheels was analyzed (Sugiyama et al. 2010b). Later, a dynamic model of bogie with independently rotating wheels was also established (Sugiyama et al. 2010a), and the dynamic performance of curve negotiation of this bogie was simulated. The dynamic performance of vehicle was introduced systematically, and the dynamic performance of curve negotiation of self-steering bogie was simulated (Sebesan 2011).

At the domestic level, a lot of studies on curve negotiation of vehicle have been done. The curving performances of controllable and radial bogie were analyzed (Shu et al. 1996; Liu et al. 2001; Li et al. 2004). The curving performances of rigid and flexible system with single wheelset were studied (Lu and Zhao 2004). The performances of different types of vehicles, such as the vehicle with magneto-rheological fluid coupled wheelsets, the metro vehicle mounted linear motor, the bogie with independently rotating wheels, and the bogie with rubber-tired wheelsets, were analyzed (Chi et al. 2002; Long et al. 2007; Huang et al. 2001; Wang et al. 2003). The curving performance of heavy-haul train was studied (Tian et al. 2009). The experimental study of freight train on small-radius curved track at low speed was investigated (Wang and Chen 2009). Based on the theory of vehicle-track coupled dynamics, the curving performance of locomotives on elastic track was analyzed (Wang et al. 2004). Based on the modern bifurcation theory, the lateral stability of wheelset on the curved track was investigated (Luo and Lei 2005). The nonlinear stability of freight wagon on the curved track was analyzed and a limit cycle of hunting motion was given (Wang and Liu 2011).

In summary, a lot of theoretical and experimental analyses of curve negotiation have been performed. The assessment of curve negotiation has been analyzed for different types of railway vehicles and urban vehicles, which provides the theoretical and technical support for the modern rail transportation. It is worth noting that many studies are based on the theory of vehicle system dynamics, in which the effect of track structure vibration has not been taken into account yet.

4 Effect of vehicle parameters on dynamic performance

The effect of suspension and structure parameters of vehicle on curving performance were introduced systematically (Garg and Dukkipati 1984). The influence of parameters of wheelset coupling connector of freight wagon on curving performance was studied (Ahmed and Sankar 1988). The effect and rule of active control technology of secondary suspension on curving performance were analyzed (Goodall and Kortum 1983; Conde et al. 2009). The influence of parameters of anti-hunting damper on wheel-rail force was investigated (Michalek and Zelenka 2011). The effects of vertical and rolling movements of bogie frame on stability motion of vehicle were analyzed (Lee and Cheng 2006). The influence of vertical stiffness of secondary suspension on ride comfort was investigated (Karim and Khan 2011).

The influences of suspension and structure parameters on curving performance have been conducted by many domestic scholars. Some dynamic models of curve negotiation of locomotives and rolling stocks based on the theory of vehicle system dynamics were established (Dong et al. 2006; Gu 2011; Wang et al. 2010; Ren and Sun 2003; Ni et al. 2007; Luo et al. 2007). The effects of parameters of wheel tread, difference of wheel diameter, anti-hunting damper, and air spring on curving performance were studied. The effect of assembly error on dynamic performance of vehicle was analyzed by means of software MEDYNA (Wang and Li 1996). The coupled relationship between locomotive and vehicle was established (Yang et al. 2008). The influences of curve radius, length of carbody, length of coupler, and lateral displacement of carbody on the coupler angle were derived. Also, the effect of coupler angle on lateral displacement of carbody was analyzed.

Generally speaking, many researches on the influence of vehicle parameters on curving performance have been done. The matching parameters were proposed, which could provide a theoretical basis and reference for the vehicle design.

5 Influences of parameters of railway track on dynamic performance

By using software GENSYS, the influences of radius and superelevation of curved track on stability motion were analyzed (Lindahl 2001). Taking Swedish railway for an example, the values of radius and superelevation were proposed for three kinds of freight wagon at different speeds, and parameter values of planar and vertical sections on high-speed railway were given with a speed range from 200 km/h to 350 km/h. Three types of track models were established (Gialleonardo et al. 2012), including a rigid track model, a simplified sectional model, and a detailed finite element model. The author analyzed the influences of track models on curving performance, and the results showed that the wheel-rail interaction force would be overestimated if the effect of elasticity was ignored. A freight wagon model with 78 DOFs was established (Sun and Simson 2008), in which the track was considered as a discretely supported model with one layer. The authors analyzed the influence of parameters of radius and superelevation on the rail corrugation, and the results showed that the influence of radius was larger, while the influence of superelevation was not obvious. By means of the software RACING, the influence on the rail corrugation was investigated (Oyarzabal et al. 2009), in which the parameters included the interval of sleepers, the mass of sleeper, the vertical and lateral stiffness of rail pad, and ballast stiffness. Using the software UM, the effects of track irregularity, track superelevation, rail profile, and gauge on the safety performance of curved track were analyzed (Cherkashin et al. 2010; Pevzner and Petropavlovskaya 2010).

The influences of parameters of track structure on curving performance have been largely investigated by domestic scholars. The influences of curve radius, rail superelevation, and rail cant on operation performance of vehicle were analyzed (Long et al. 2009; Lian 1990; Shen and Zhang 1994). Using the software SIMPACK, a model of freight wagon was established (Si et al. 2010; Chen 2009), the curving performance of vehicle was analyzed with two kinds of rail cant, and the effect of rail profile on the rail corrugation of curved track was also investigated. With the help of software ADAMS/rail, a dynamical model of curve negotiation for high-speed track was established (Zhang 2009). Under the situations of different radii and superelevations, the dynamic performances of high-speed train at different speeds were investigated. The parameters of existing speed-raised railway were proposed. The method of safety assessment on different curved track was proposed (Zeng and Liu 1997). A more perfect model of vehicle-track dynamic interaction was established to analyze the effects of design parameters of planar and vertical sections on dynamic performance, in which the basic principles of design parameters of high-speed railway were initially obtained (Long 2008). By studying the technology of existing speed-raised railways and combining with the actual conditions of the Chinese railways, the key standards of planar and vertical sections were presented (He et al. 2007), which could be adaptive to passenger train at a speed of 200 km/h, freight train at a speed of 120 km/h, and double-deck container train with the axle load of 25 t. The value and adopting rules for technical parameters, such as the radii of planar and vertical curves, the length of transition line, the minimal length of tangent line between circles, the minimal length of circle, the maximum grade, and the minimal length of grade, were recommended (Gong and Feng 2007). By means of the software ADAMS/rail, a model of vehicle-lines spatially vibration was established (Zhou 2010; Zhou and Xiang 2009). The influences of railline parameters on dynamic response were analyzed to obtain the reasonable parameter values, which could verify the reasonability of planar and vertical sections of Guangzhou-Zhuhai intercity railway. Based on the theory of vehicle-track coupled dynamics, the characteristics of dynamic matching of planar and vertical sections were investigated (Wang et al. 2005; Wang and Zhou 2005; Zhai et al. 2010). The wheel-rail dynamic interaction performances of vehicle on planar and vertical sections were studied, which could propose the method of dynamics assessment of planar and vertical sections of high speed railway.

In conclusion, the effects of parameters of track structure on curving performance have been largely done. There are three main methods. For the first method, a comprehensive model of vehicle is established on the basis of the theory of vehicle system dynamics, which is used to analyzing the effect of planar curve, vertical curve, and planar and vertical sections alignment on running quality of the vehicle. The second method is optimizing the design parameters of planar and vertical sections from a static point of view. For the third method, the effects of parameters of planar and vertical sections on dynamic performance are investigated on the basis of vehicle-track dynamic interaction.

6 Promising future development of the theory of vehicle-track coupled dynamics in research of curve negotiation

During the period from April 1, 1997 to April 18, 2007, there were six large-sized running speed raise of Chinese train. After that, the highest speed of passenger train on existing railway is 250 km/h, the maximum speed of freight train is 120 km/h, and the running speed of train on mountain railway is 70 km/h or more. In order to meet the rapidly growing demands of passenger transport, Chinese railway has started the construction prelude of high-speed railway. Since 2008, the first passenger dedicated line (Hefei-Nanjing) for trains at a speed of 250 km/h has been built successfully, and the first intercity high-speed railway (Beijing-Tianjin) for trains at a speed of 350 km/h has been used. By the end of 2011, the mileage of the new high-speed railways invested in Chinese is 6467 kilometers. The mileage of the high-speed railway for the speed of 200 km/h or more is nearly 10000 kilometers. In 2012, more than 6000 kilometers of high-speed railway, such as Harbin-Dalian, Beijing-Shijiazhuang, Shijiazhuang-Wuhan, went into operation. The backbone network of high-speed railway is basically formed in China.

However, the running safety and comfort are key elements of modern transport. It needs a technological breakthrough for the rapid development of Chinese railway. It is a major challenge to ensure the running safety and comfort of high-speed and speed-raised railways. As for the wheel-rail dynamics, with the increase of running speed, the dynamic interaction will be greatly strengthened. On the planar curved track, the vertical curved track, and the planar and vertical section of speed-raised and high-speed railways, the wheel-rail dynamic interaction produced by the change of alignment will be more obvious. So the curved track is a weak link on railway line. On one hand, the damage to the curved track caused by train is aggravated. On the other hand, the effects of track structure and track parameters on running safety and ride comfort are more and more noticeable. Some problems related to the wheel-rail dynamics on curved track were exposed at the beginning of speed-raised railway. Taking the experimental result for example, when a certain type of train with CRH ran on the vertical curved track or plane curved track at a speed of 200 km/h, the maximum value of wheel-load reduction ratio was more than 0.8, which was the dynamic limited value. Fig. 1 shows the measured results of the wheel-load reduction ratio. Furthermore, the carbody often vibrates at high frequency of 10 Hz or more, which would affect the ride comfort. Thus, for an example, at the beginning of train speed raising on mountain railway (Fig. 2), the wheel-rail dynamic interaction is more intense, because the radius of curved track is small and the technical standards of track structure are low. So it is the most urgent task to ensure the running safety at that time, otherwise, it would affect the developing plan of Chinese railway. As for the high-speed railway, there is a clear corrugation on the inner rail of curved track (Fig. 3), which is a serious threat to safety of high-speed railway. In addition, when a high-speed train passes through the planar and vertical sections (Fig. 4), the alignment and parameters of these sections have great influences on the safety and ride comfort of train. So the matching problem of parameters of planar and vertical sections should be solved at the stage of design, because it will be difficult to rectify after construction. Thus, for the curved track on high-speed and speed-raised railways, there are many engineering problems, including the wheel-rail dynamic interaction and the performance matching.

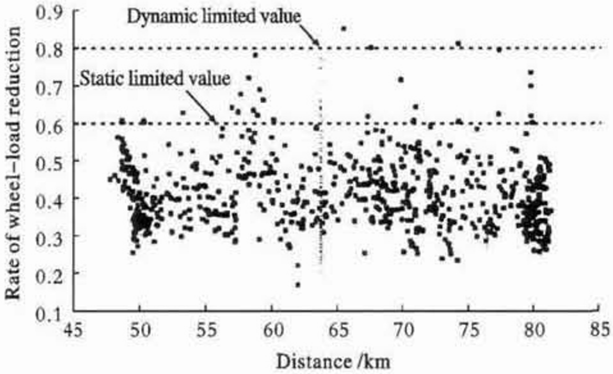


Fig. 1 Measured results of wheel-load reduction on speed-raised railways

(a) Continuous small-radius curve

(b) Track with wooden sleeper

Fig. 2 Small-radius curved track on mountain railway

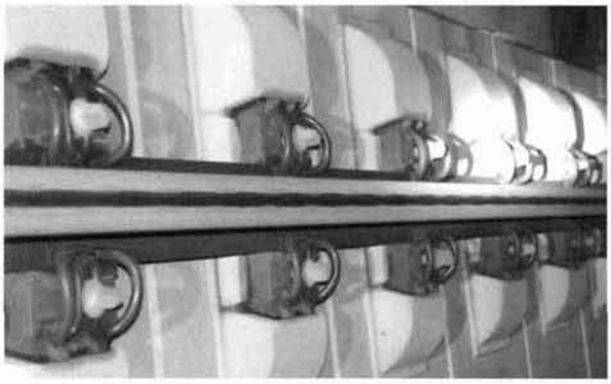


Fig. 3 Rail corrugation on high-speed railway

Fig. 4 Planar and vertical sections on high-speed railway

A new technology for performance matching is needed to solve the problem of wheel-rail dynamic interaction caused by high-speed and raising-speed vehicles. On one hand, it is difficult to reveal the mechanism of wheel-rail dynamic interaction existing on the curved track from the view of vehicle dynamics or track dynamics separately. A theoretical and experimental research must be carried out on the basis of vehicle-track coupled system. Only by knowing the rules of wheel-rail dynamic interaction deeply, can it be likely to minimize the wheel-rail dynamic interaction and achieve optimum design of dynamic performance matching between the vehicle and track. And then the safety and stability can be ensured. On the other hand, the traditional design method for Chinese railway is quasi-static, which only meets the design demands of planar and vertical sections of low running speed railway, but not for high-speed and raising speed railways. For the quasi-static design method, a simple traction calculation is used to check the climbing ability and the unbalanced centrifugal acceleration is adopted to check key parameters, including the minimum radius and superelevation of curved track. However, the indices of wheel-rail dynamic safety and ride comfort on curved track cannot be analyzed by the quasi-static method. The dynamic indices of train at high speed are higher than those at low speed, because they are the key factors of high-speed railway. So, the dynamic indices cannot be simulated by the experience or simple calculation under the condition of high speed.

Since the theory of vehicle-track coupled dynamics was put forward (Zhai 1997), more and more attention had been paid to the wheel-rail dynamic interaction on curved track. This theory can supply the theoretical basis and technical support to solve the complex problem of performance matching. In addition, it is great significant and necessary to carry out the vehicle-track dynamic performance matching of curve negotiation based on this theory. There are two important aspects. Firstly, the design standards of high-speed railway have been established by the developed countries for long time practice (about 50 years). But the blockade on core technology is still posed to Chinese railway. Secondly, the operation condition of Chinese railway is quite different from that of overseas railway. So, the matching technology of vehicle-track interaction should not be copied directly. To solve the problem of vehicle-track dynamic interaction, the operating condition of Chinese railway should be taken into account.

7 Mechanism and application of wheel-rail dynamic performance matching of curved track

7.1 Mechanism of wheel-rail dynamic performance matching of curved track

With the rapid development of high-speed and heavy-haul railway, the wheel-rail dynamic interaction is aggravated, especially on the curved track. On one hand, the dynamic damage to the track structure produced by locomotives and rolling stocks is intensified. On the other hand, the effect of structural vibration of the railway on running quality of vehicle is also increased. For reasonable performance matching of the wheel-rail dynamic interaction on curved track, it is essential to ensure the good condition and efficient operation of railway transportation in the long term. In order to implement the optimal dynamic performance matching of wheel-rail system, the idea of systematic design must be adopted (Zhai 2007). That is, the vehicle system and railway system should be considered as a coupled system, and the design would be optimized by taking the dynamic performance indices of the whole system as the optimization targets. On this basis, a technology of performance matching of wheel-rail dynamic interaction on curved track is proposed (Wang 2013). Fig. 5 shows the framework of this technology.

There are three steps for the technology of dynamic performance matching. First of all, a wheel-rail dynamic model on curved track is established on basis of the theory of vehicle-track coupled dynamics and the corresponding simulation software is compiled. Secondly, the wheel-rail dynamic performance is calculated at different conditions, such as the train passing through the planar curve section, the vertical curve section, and the planar and vertical section. Afterwards, the wheel-rail dynamic performance is synthetically analyzed and assessed. If the indices of wheel-rail dynamic performance are higher than those of the limited specification, the parameters of vehicle and track should be adjusted. The simulation and analysis are repeatedly performed until the results meet the requirements.

It should be noted that, if the theoretical results obtained by simulation and optimization can be verified by the field experiment, it will be significantly practical. Of course, to carry out the experiment in field is a complex and systemic project. It will cost expensive labor power, material and financial resources. Furthermore, the security of the field experiment should be considered in the first place. Therefore, not all theoretical analyses can be verified by the field experiments. The usual method today is to carry out the theoretical analyses by means of the theoretical model and to perform simulation software validated by field experiment.

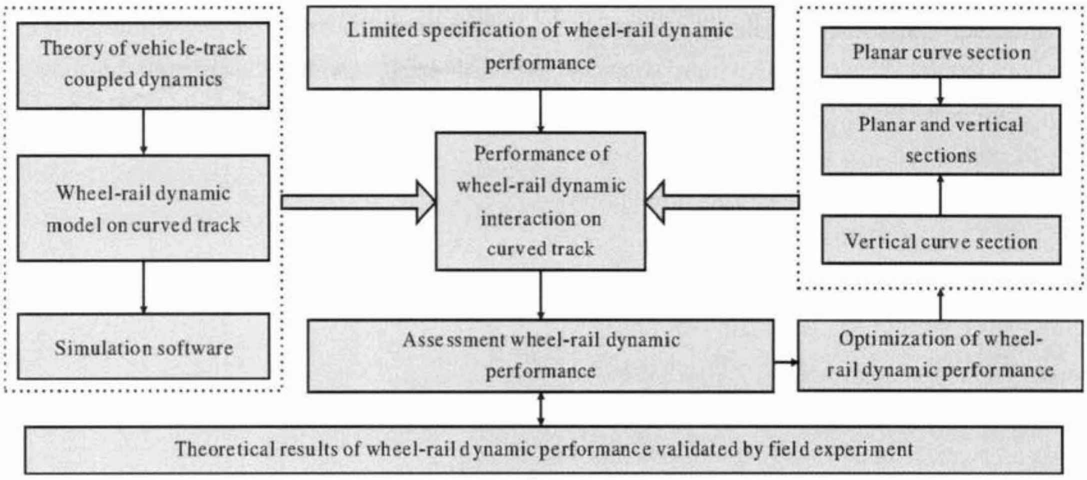


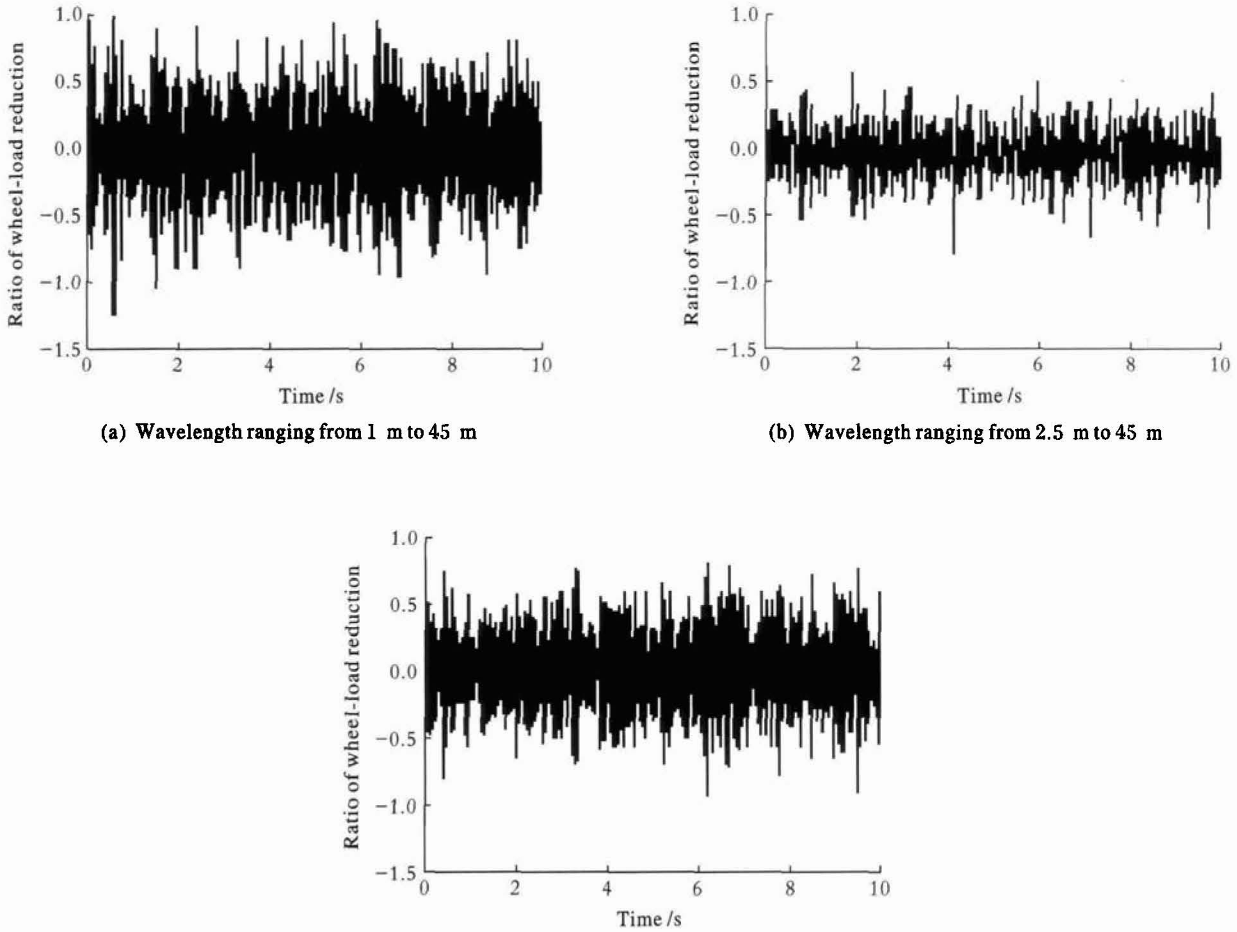
Fig. 5 Framework of performance matching of wheel-rail dynamic interaction on curved track

7.2 Application in practical engineering

Taking the experiment result of CRH train on speed-raised lines for example, the maximum value of the wheel-load reduction ratio was more than 0. 8 (Fig. 1), which was a serious problem affecting the safety of the train. Based on the mechanism of performance matching, the wheel-rail dynamic problem was investigated (Wang et al. 2008). Investigation efforts focused on the effect of track irregularity on the wheel-load reduction ratio at the speed of 250 km/h. The values of wheel-load reduction at the speed of 160, 180, 200, 210, 220, 230, 240, and 250 km/h were calculated with the irregularity wavelength ranging from 1 m to 45 m. The predominant frequencies of wheel-load reduction at the speeds ranging from 160 km/h to 250 km/h were about 30-40Hz. The sensitive wavelengths of wheel-load reduction were in the range from 1 m to 2.5 m. The wavelength of 2.5 m was the threshold value. So, three different ranges of wavelength were proposed, including 1-2.5 m, 2.5-45 m and 1-45 m. The influences of different ranges of wavelength on wheel-load reduction were analyzed at the running speed of 250 km/h. The calculated results are shown in Fig. 6.

The results show that, due to the excitation of the irregularity with wavelength ranging from 1 m to 45 m, the value of the wheel-load reduction ratio is generally more than 0.8. However, under the irregularity with wavelength ranging from 2.5 m to 4.5 m, the value of the ratio is less than 0.65. So, there is large influence of the irregularity with wavelength ranging from 1 m to 2.5 m on the wheel-load reduction.

Then, under the irregularity with wavelength ranging from 1 m to 2.5 m, the effect of the amplitude on wheel-load reduction was analyzed. For the irregularity with wavelength ranging from 1 m to 45 m, the amplitude of irregularity with wavelength ranging from 1 m to 2.5 m decreased by 30%-80%. The maximum value of the wheel-load reduction ratio at the speed of 250 km/h is listed in Tab. 1. It can be seen the rate of wheel-load reduction is reduced efficiently by reducing the amplitude of irregularity with wavelength ranging from 1 m to 2.5 m. As the limited value of the reduction ratio is 0.8, the wheel-load reduction can meet the requirement of operation safety when the amplitude is reduced by 40% or more. It provides the theoretical support not only to the operation safety of the high-speed train, but also to the maintenance of the track irregularity.



(a) Wavelength ranging from 1 m to 45 m

(b) Wavelength ranging from 2.5 m to 45 m

(c) Wavelength ranging from 1 m to 2.5 m

Fig. 6 Calculated results of wheel-load reduction ratio with different ranges of wavelength

Tab. 1 Calculated results of wheel-load reduction ratio

Decreased amplitude	original	30%	40%	50%	60%	80%
Wheel-load reduction ratio	1.00	0.81	0.74	0.68	0.63	0.55

8 Conclusions

Until now, the researches on wheel-rail dynamic performance on curved track can be summarized in three types of methods. First, the mechanism of curve negotiation and the influence of vehicle parameters on the steady-state performance are investigated from the perspective of steady-state theory, and the parameters of railway line are designed from the view of quasi-static theory. Second, from the dynamic point of view, the dynamic models of vehicles are established without considering the influence of the track vibration. By means of these models, the mechanism and assessment of curve negotiation can be analyzed. Also, the parameters of vehicle structure and suspension can be optimized, and the parameters of planar and vertical sections can be designed. Third, on basis of the theory of vehicle-track coupled dynamics, the mechanism and assessment of curve negotiation are analyzed, and the parameters of vehicles and the planar and vertical sections are optimized. However, it is difficult to solve the wheel-rail interaction problem caused by high speed and raising speed by the first and second methods, but the third method might provide a possibility of analyzing the dynamic interaction on curved track for solvement.

Therefore, on basis of the theory of vehicle-track coupled dynamics, a framework of performance matching of wheel-rail dynamic interaction on curved track is proposed for the modern railways. For the dynamic engineering, in which the wheel-load is reduced obviously when the speed of train is raised to the range from 200 km/h to 250 km/h, the application of the technique of performance matching is introduced. The results show that, the irregularities with wavelength ranging from 1 m to 2.5 m have large influence on the wheel-load reduction. By decreasing the amplitude of irregularity with wavelength ranging from 1 m to 2.5 m, the wheel-load reduction ratio can be reduced effectively. When the amplitude is reduced by 40% or more, the wheel-load reduction can meet the requirements of running safety.

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