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DYNAMIC PERFORMANCE OF LOW VIBRATION SLAB TRACK ON SHARED HIGH-SPEED PASSENGER AND FREIGHT RAILWAY

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Abstract. This work investigates dynamic performance of a low vibration slab track on a shared high-speed passenger and freight railway, and an optimal modulus of the isolation layer (rubber pad) is proposed to meet the adaptability of the track system under the dynamic actions of high speed passenger and heavy axle-load freight trains. First, detailed finite element models of the slab track with and without the rubber pad between concrete slab and supporting layer are established by using software ANSYS. Further, coupled dynamic models of passenger/freight vehicle–low vibration/tradition slab track system are developed to calculate the wheel–rail forces, which are utilized as the inputs to the finite element model. Finally, the dynamic characteristics of the low vibration slab track, the specific function of the rubber pad, and the optimal modulus of the rubber pad are studied in detail. Results show that the interaction force between the freight vehicle and low vibration slab track is more significant because of the heavy axle-load, which leads to larger vertical stress amplitudes of each track layer. Whereas the accelerations of track components induced by the passenger vehicle are much larger than those induced by the freight vehicle, due to the much faster speed that can generate high wheel–rail interaction frequency. The rubber pad of the slab track does not play a role in attenuating slab vibration; instead it causes an increase of slab acceleration and its surface tension stress. However, the rubber pad can decrease the supporting layer acceleration and the slab compression stress, which plays a significant role in vibration isolation and buffers the direct impact force on the slab caused by vehicle dynamic load. To ensure a reasonable vibration level and dynamic stress of the slab track, the optimal modulus of the rubber pad is suggested to be 3÷7.5 MPa.

Keywords: shared passenger and freight railways, low vibration slab track, dynamic performance, coupled vehicle–track dynamics, vibration isolation, optimal modulus.

Introduction

High-speed railways have the characteristics of large transport capacity, fast speed, high security, small environmental pollution, round-the-clock operation and so on, which have great advantages and play an increasingly prominent role in transport systems. The high-speed railways have become the world trend of railway development (Esveld 2001; Zhai *et al.* 2015). A number of studies have been published on the dynamic performance of high-speed railway tracks. Cheng *et al.* (2014) investigated the dynamic performance of a ballastless track subject to cyclic load and train moving load using a full-scale physical model test. Blanco-Lorenzo *et al.* (2011) analysed and compared the dynamic performance of three types of slab track based on a vertical dynamic model of the train–track system. Kouroussis *et al.* (2015a, 2015b) studied the influence of different vehicle types on ground and track borne vibrations from railways using a fully coupled vehicle/track/foundation model, and the effect of railway track singular defects on ground vibration generation and propagation is also discussed in detail.

As is known that it is quite appropriate to construct the shared high-speed passenger and freight railway at plain or hilly areas where possess developed economy, large passenger volume and a certain quantity of goods cannot be separated. A few countries already have started the attempt of constructing the ballastless track on shared

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*Corresponding author. E-mail: *syzhu@swjtu.edu.cn* passenger and freight railway and achieve good results. However, the technology of ballastless tracks on shared high-speed passenger and freight remains to be further improved due to the limited operating mileage. Lei and Rose (2008) performed vibration analysis of a ballasted track for shared passenger and freight railways, emphasizing the influences of different train speeds and line grades of on track vibrations. Yang (2009) studied the selection of main technical parameters of a new-shared passenger and freight railway line, and corresponding suggested values were given in his work. At present, a high-speed railway project is proposed to use the shared passenger and freight operation mode. Meanwhile, in order to meet the adaptability of the track system under the dynamic actions of high-speed passenger and heavy axle-load freight trains, a low vibration slab track with an isolation layer (rubber pad) between the concrete slab and supporting layer is going to be adopted for this line. Therefore, a stricter requirement of mechanical behaviours of the isolation layer in the slab track is desired under this project background. However, there are few literature reports on the dynamic characteristics of low vibration slab tracks, and on the influence of the isolation layer in slab tracks. Xin and Gao (2011) established a coupled dynamic model of vehicle–track–bridge system involving a slab mat layer between slab track and bridge, and evaluated the effectiveness of the slab mat layer in vibration attenuation. Hui and Ng (2009) analysed the vibration isolation effect of several floating slab systems based on the measured data, and further assessed the effect of bending resonances of slabs on vibration isolation performance. Zhu *et al.* (2015b) applied dynamic vibration absorbers to effectively reduce the low-frequency vibrations of a floating slab exposed to vehicle dynamic load. Cai and Xu (2011) carried out the dynamic optimization design of the structural parameters of a low vibration track and obtained the reasonable ranges of the stiffness under the rail and the block.

Under the research background of the abovementioned high-speed railway project, this work studies the dynamic characteristics of the low vibration slab track subjected to the dynamic actions of a high speed passenger vehicle (400 km/h) and a freight vehicle (160 km/h), respectively, based on the theory of vehicle–track coupled dynamics and finite element method. Further, dynamic properties of the slab track with and without the rubber pad are analysed and compared in detail when the freight vehicle passing through and the specific function of the rubber pad are revealed. Finally, the dynamic characteristics of the low vibration slab track with different elastic modulus for the rubber pad are studied, and the optimal modulus of the rubber pad is determined to ensure a reasonable vibration level and dynamic stress of the slab track. The conclusions obtained in this work can provide a certain reference for the design of low vibration slab tracks on shared high-speed passenger and heavy axle-load freight railways.

1. Dynamic interaction model of coupled vehicle–slab track system

Currently, the vehicle–track coupled dynamics theory (Zhai *et al.* 2009) has already become a basic method that analyses the dynamic interaction between vehicle and track. Its applications have covered the dynamic characteristics of wheel–rail interactions (Blanco-Lorenzo *et al.* 2011; Zhu *et al.* 2015a), fatigue damage of track structures (Zhu *et al.* 2014), railway ground vibrations (Kouroussis *et al.* 2014), and safety and comfort assessments of vehicle operation (Zhai *et al.* 2013). In this work, coupled dynamic models of passenger/freight vehicle–low vibration/tradition slab track systems are developed based on the vehicle–track coupled dynamics method, and the wheel–rail interaction forces induced by high-speed vehicle and freight vehicle are obtained by numerical dynamic simulations. Figure 1 shows the coupled dynamic model of a high-speed vehicle and the low vibration slab track with rubber pad between the concrete slab and supporting layer.

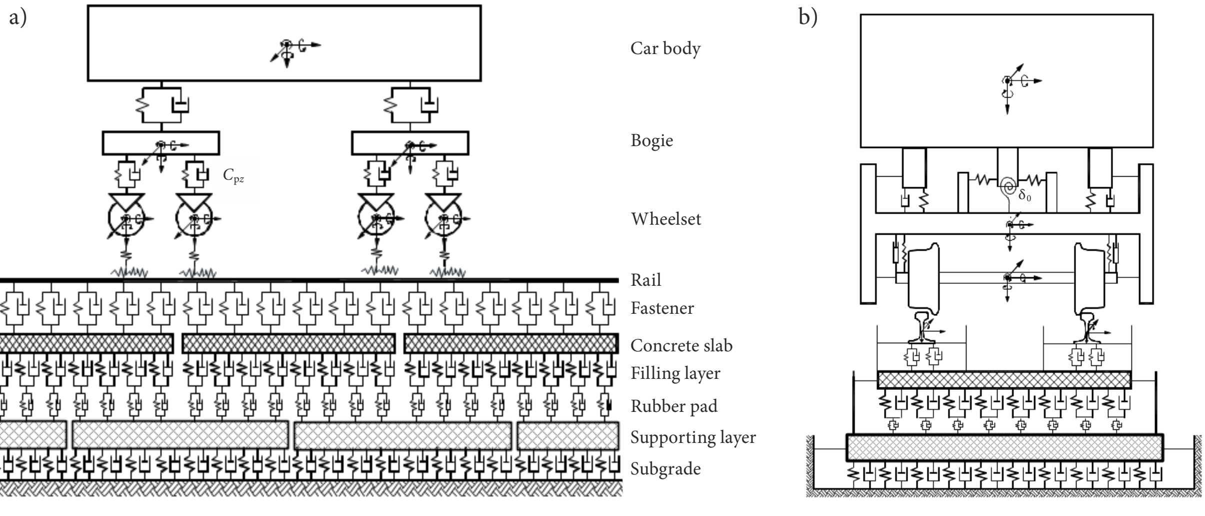

Figure 1. 3D coupled dynamic model of a vehicle and the low vibration slab track: a – elevation view; b – end view

The vehicle is treated as a rigid multi-body model in which the car body is supported on two double-axle bogies with the primary and secondary suspension systems. Totally, 17 degrees of freedom are considered in the vehicle model, including the vertical displacement, the roll angle, and the pitch angle of the car body and bogies, as well as the vertical displacement and the roll angle of the wheelsets. The rails are modelled as Bernoulli-Euler beams taking into account the vertical, lateral, and torsion motions of the rails simultaneously. The concrete slab and concrete base of the slab track are described as elastic rectangle plates based on the elastic thin slab theory (Zhai *et al.* 2009). The vehicle and slab track are coupled through the wheel–rail contact force, which can be written as Eq. (1) based on the nonlinear Hertzian contact theory:

$$P_j = \begin{cases} \left(\dfrac{1}{G}\left(Z_{wj} - Z_r - Z_0\right)\right)^{3/2}, & \text{if } \left(Z_{wj} - Z_r - Z_0\right) > 0; \\ 0, & \text{if } \left(Z_{wj} - Z_r - Z_0\right) \le 0, \end{cases} \quad (1)$$

where: Z_{wj} is the vertical displacement of j-th wheel at time t; Z_r is the track vertical displacement of j-th wheel position at time t; Z_0 is the track irregularity.

The equations of motion of the vehicle can be derived according to D'Alembert's principle based on the system of coordinates moving along the slab track, and the equations of motion of the slab track can be cast by using the elastic thin slab theory and mode superposition method. The general equations of motion of the coupled system can be expressed as:

$$\boldsymbol{M} \cdot \boldsymbol{A} + \boldsymbol{C} \cdot \boldsymbol{V} + \boldsymbol{K} \cdot \boldsymbol{X} = \boldsymbol{F}(\boldsymbol{X_V}, \boldsymbol{V_V}, \boldsymbol{X_T}, \boldsymbol{V_T}), \quad (2)$$

where: $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are the mass, damping and stiffness matrices, respectively; $\boldsymbol{X_V}$ and $\boldsymbol{V_V}$ the vectors of the displacement and velocity of the vehicle system, respectively; $\boldsymbol{X_T}$ and $\boldsymbol{V_T}$ are the vectors of the displacement and velocity of the slab track system; $\boldsymbol{F}(\boldsymbol{X_V}, \boldsymbol{V_V}, \boldsymbol{X_T}, \boldsymbol{V_T})$ is the system load vector representing the nonlinear wheel–rail contact forces which is a function of the motions $\boldsymbol{X_V}$ and $\boldsymbol{V_V}$ of the vehicle and $\boldsymbol{X_T}$ and $\boldsymbol{V_T}$ of the slab track.

Detailed descriptions of the equations of the vehicle–track coupled dynamic system can be found in research by Zhai *et al.* (2009). Dynamic responses of the coupled system are solved by using the Zhai (1996) method, which is a simple fast time integration method. Here the main calculation parameters of the high-speed passenger and freight vehicles are shown in Table 1.

2. Finite element model of low vibration slab track

In order to study the dynamic characteristics of the low vibration track on a shared high-speed passenger and freight railway systematically, this paper creates detailed finite element models of the slab tracks with and without the rubber pad by using software ANSYS, respectively, and the wheel–rail interaction forces are then applied as the inputs to the finite element models. As shown in Figure 2, the rail is treated as continuous Bernoulli–Euler beams, which are discretely supported. Linear line elements of *Beam188* are used to model the rail, and hinged boundaries are adopted for it to prevent free body motions. Linear hexahedral elements of *Solid45* are applied for the concrete slab, the filling layer, the rubber pad and the supporting layer, and symmetrical boundaries are applied on the two ends of all track layers to simulate the constraints of construction joints between the slabs. Spring-damper ele-

Table 1. Main parameters of high-speed passenger and heavy axle-load freight vehicles

Item	Unit	Value	
		Passenger vehicle	Freight vehicle
Car body mass	kg	56270	84820
Bogie mass	kg	2528	1300
Wheel set mass	kg	1516	1145
Car body roll moment of inertia	kg·m^2	$1.43 \cdot 10^5$	$1.187 \cdot 10^5$
Car body pitch moment of inertia	kg·m^2	$2.525 \cdot 10^6$	$1.4346 \cdot 10^6$
Bogie roll moment of inertia	kg·m^2	$1.927 \cdot 10^3$	$1.09 \cdot 10^3$
Bogie pitch moment of inertia	kg·m^2	$2.004 \cdot 10^3$	$0.72 \cdot 10^3$
Wheelset roll moment of inertia	kg·m^2	$1.095 \cdot 10^3$	700
Wheelset pitch moment of inertia	kg·m^2	120	100
Vertical damping of primary suspension	N·s/m	$1 \cdot 10^4$	$3 \cdot 10^4$
Vertical stiffness of primary suspension	MN/m	0.89	2.331
Vertical damping of secondary suspension	N·s/m	$1 \cdot 10^4$	0
Vertical stiffness of secondary suspension	MN/m	0.25	13
Distance between wheel sets in bogie	m	2.5	2.3
Longitudinal distance between bogies	m	17.375	8.46
Wheel radius	m	0.46	0.42

ments of *Combin14* are employed to represent rail fasteners and the foundation on the bridge section. The nodes of these spring–damper elements can move in the vertical, lateral and longitudinal directions with the corresponding stiffness and damping coefficients. All the nodes at the bottom of the spring–damper elements of foundation system are subjected to fixed constraints. According to the characteristic of the low vibration track, main track components parameters are listed in Table 2.

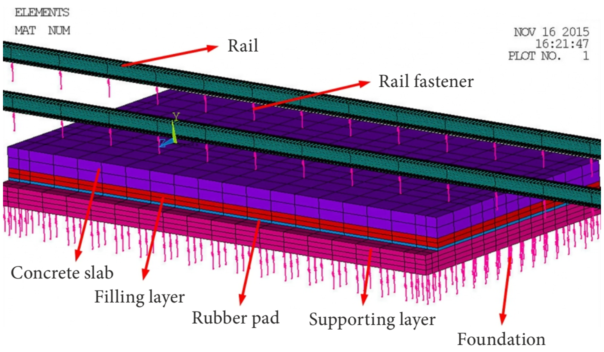

Figure 2. Finite element model of low vibration slab track

Table 2. Parameters of the slab track

Item	Parameter	Unit	Value
Rail	Track gauge	mm	1520
	Elastic modulus	MPa	205900
	Poisson	–	0.3
	Mass	kg/m	65
	Density	kg/m^3	7840
Rail fastener	Vertical stiffness	kN/mm	60
	Fastener space	m	0.60
Concrete slab	Elastic modulus	MPa	36500
	Poisson	–	0.2
	Density	kg/m^3	2500
	Length/width/ thickness	m	5.6/2.6/0.22
Filling layer	Elastic modulus	MPa	28000
	Poisson	–	0.2
	Density	kg/m^3	2500
	Length/width/ thickness	m	5.6/2.6/0.1
Rubber pad	Elastic modulus	MPa	1÷35
	Poisson	–	0.2
	Density	kg/m^3	1000
	Length/width/ thickness	m	5.6/2.6/0.03
Supporting layer	Elastic modulus	MPa	30000
	Poisson	–	0.2
	Density	kg/m^3	2500
	Length/width/ thickness	m	5.6/3/0.21
Foundation	Stiffness	MPa/m	10000

3. Result and discussion

3.1. Characteristics of low vibration slab track on shared passenger and freight railway

When the high-speed passenger vehicle (400 km/h) or the heavy axle-load freight vehicle (160 km/h) runs on the low vibration slab track, the corresponding wheel–rail interaction forces can be calculated using the coupled dynamic models of passenger/freight vehicle and the slab track, respectively. As shown in Figure 3, the sample of track irregularity is generated by means of a time–frequency transformation technique using the Chinese high-speed track spectrum (Zhai *et al.* 2015). The effective wavelengths of the selected track vertical and alignment irregularities are 2÷200 m. Figure 4 shows the time-history curve of wheel–rail interaction forces under the first wheelset. It can be seen that the maximum wheel–rail forces caused by high-speed and freight vehicles are 101 kN and 118 kN, respectively.

Taking the wheel–rail interaction forces caused by the passenger and freight vehicles as the input excitations to the finite element models of the slab tracks, dynamic responses of the slab tracks are obtained through dynamic simulations, as presented in Figures 5 and 6.

As can be seen in Figure 5, when the freight vehicle runs on the low vibration track, the dynamic displacements of the rail and the supporting layer, and the compression stresses of the concrete slab and support layer are larger than those induced by the passenger vehicle by about 24, 18, 20 and 14%, respectively. The results indicate that compared with the passenger vehicle, the impact force between the freight vehicle and the low vibration track is more significant because of the heavy axle-load, which cause more serious damage to track structures. Therefore, the structural deformation and stress value under the freight vehicle dynamic load should be mainly considered in terms of the strength design of the low vibration slab track on shared passenger and freight railways.

Figure 6 presents time-history curves of accelerations of the rail, the concrete slab and the support layer, when the low vibration slab track is subjected to dynamic loads of the high-speed passenger vehicle and the heavy axle-load freight vehicle, respectively.

As can be seen in Figure 6, when the passenger vehicle runs on the low vibration track, the accelerations of the rail, the concrete slab, and the supporting layer are larger than those of the freight vehicle. This is due to the fact of that wheel–rail interaction frequency of the passenger is higher because of the much faster speed, which leads to larger acceleration amplitudes of each track layer. However, although the freight vehicle possesses heavy axle-load, the acceleration amplitudes of each track layer are smaller attributed to its lower running speed with lower wheel–rail interaction frequency. It is worth pointing out that although the track deformation under the passenger vehicle dynamic load is relatively small, the increase of the structure acceleration might cause running safety issues, and

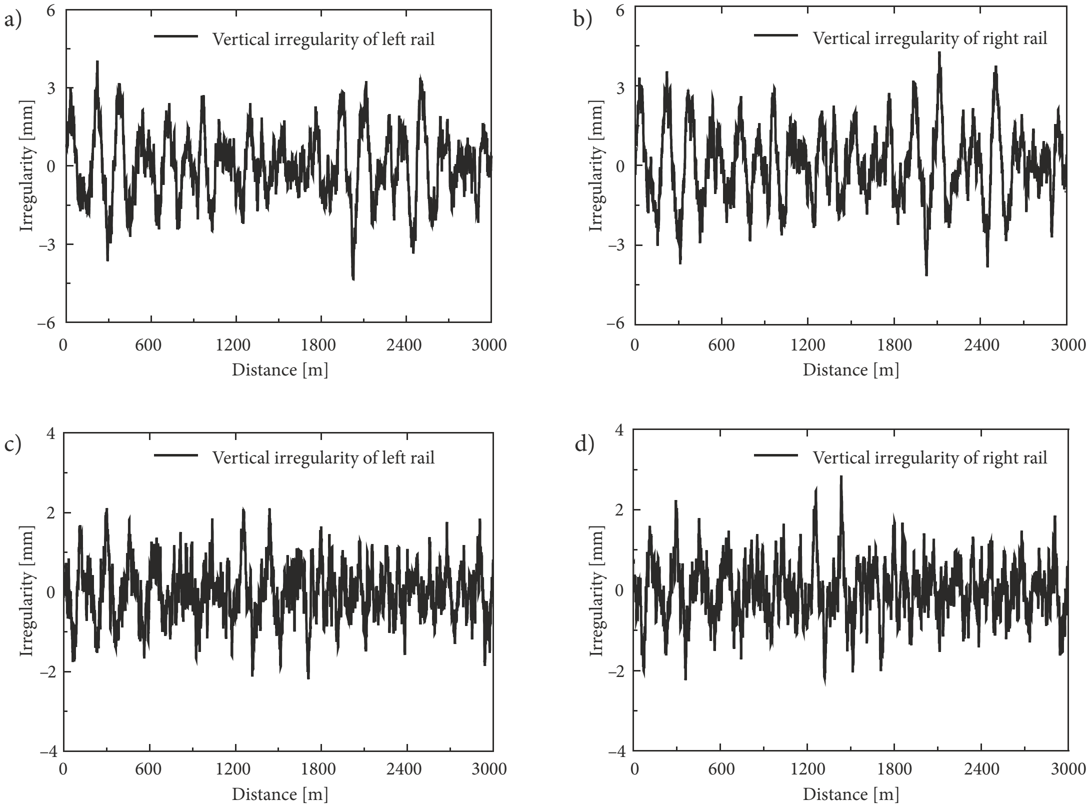

Figure 3. Vertical and alignment irregularities of the selected track: a – alignment irregularities of left rail; b – alignment irregularities of right rail; c – vertical irregularities of left rail; d – vertical irregularities of right rail

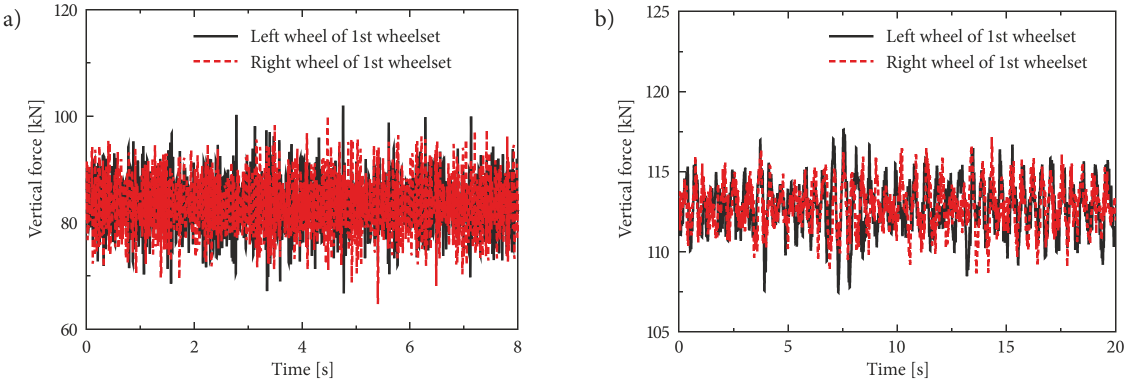

Figure 4. Wheel–rail interaction force: a – high-speed vehicle; b – freight vehicle

even exacerbates fatigue damage of structure components. Therefore, both the structural strength under large freight vehicle loads and the fatigue failure induced by dynamic load of passenger vehicles should be comprehensively addressed in the design of the low vibration track on shared high-speed passenger and freight railways.

3.2. Dynamic characteristic comparison of the slab track with and without rubber pad

The slab track with and without rubber pad here are referred to the low vibration slab track and the tradition slab track, respectively. Taking the freight vehicle (160 km/h) as a research object, the corresponding wheel–rail interaction forces are obtained on the basis of the proposed vehicle–track coupled dynamic model when the freight runs on the slab track with and without rubber pad, respectively. These wheel–rail interaction forces are utilized as the inputs to the finite element models of the slab tracks, and the dynamic responses of track structures are obtained as presented in Figure 7.

As can be seen in Figure 7a, compared with the tradition slab track, the rail displacement of the low vibration slab track increases by about 11%, attributed to the fact of that the stiffness of the low vibration slab track is significantly decreased by inserting the rubber pad.

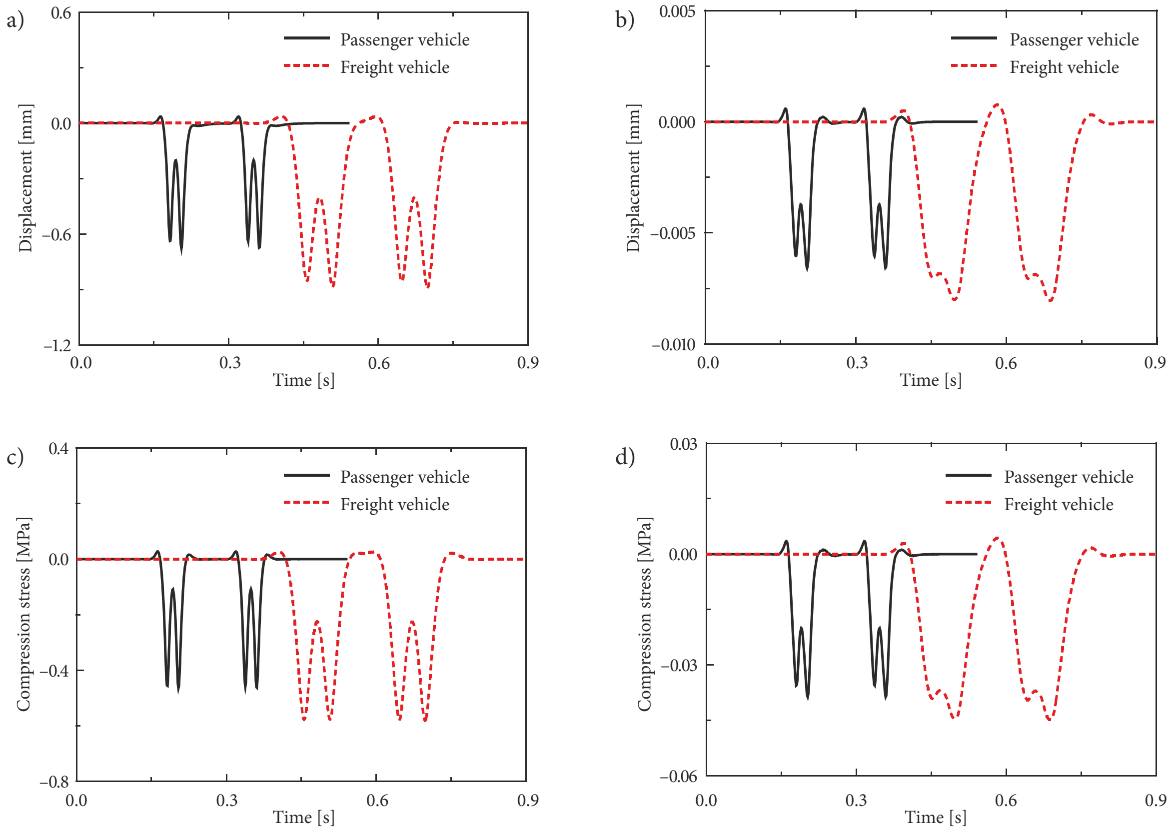

Figure 5. Dynamic characteristics of track structures: a – rail displacement; b – supporting layer displacement; c – compression stress of concrete slab; d – compression stress of supporting layer

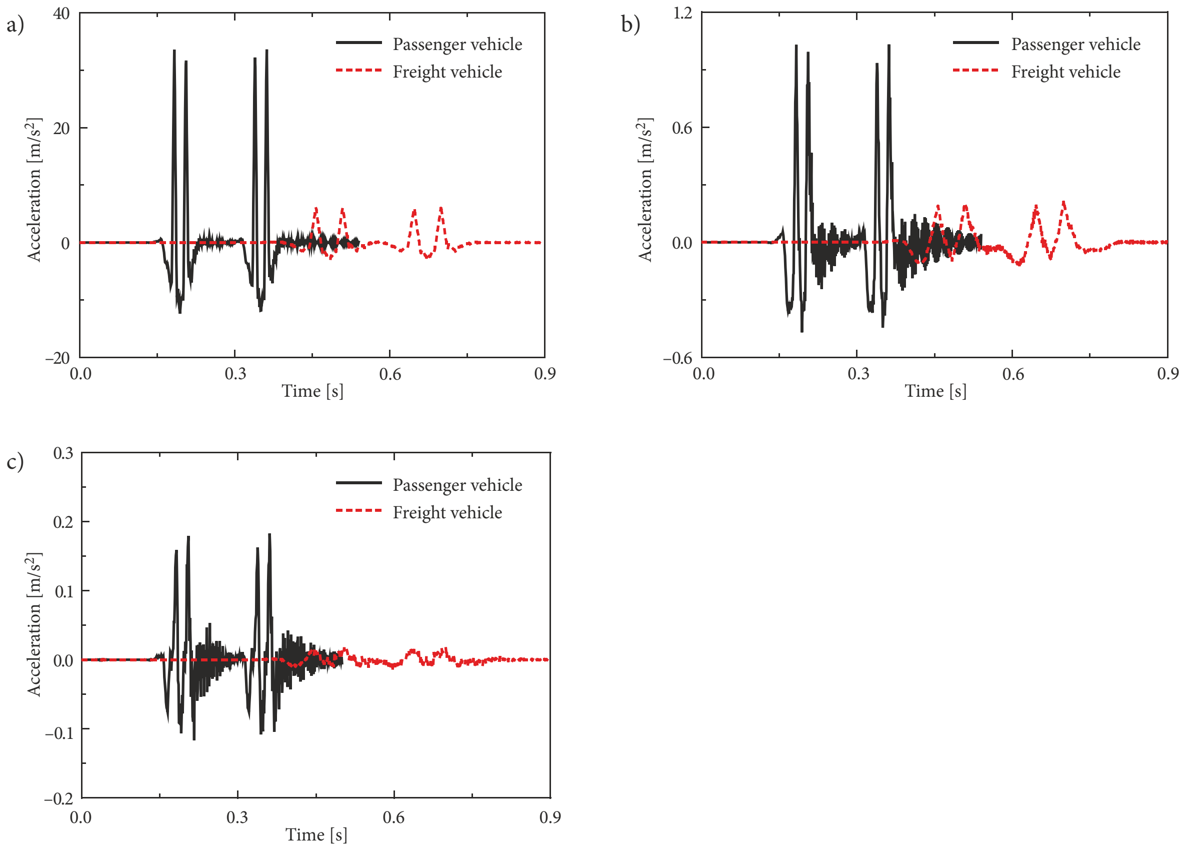

Figure 6. Accelerations of track structures: a – rail acceleration; b – concrete slab acceleration; c – supporting layer acceleration

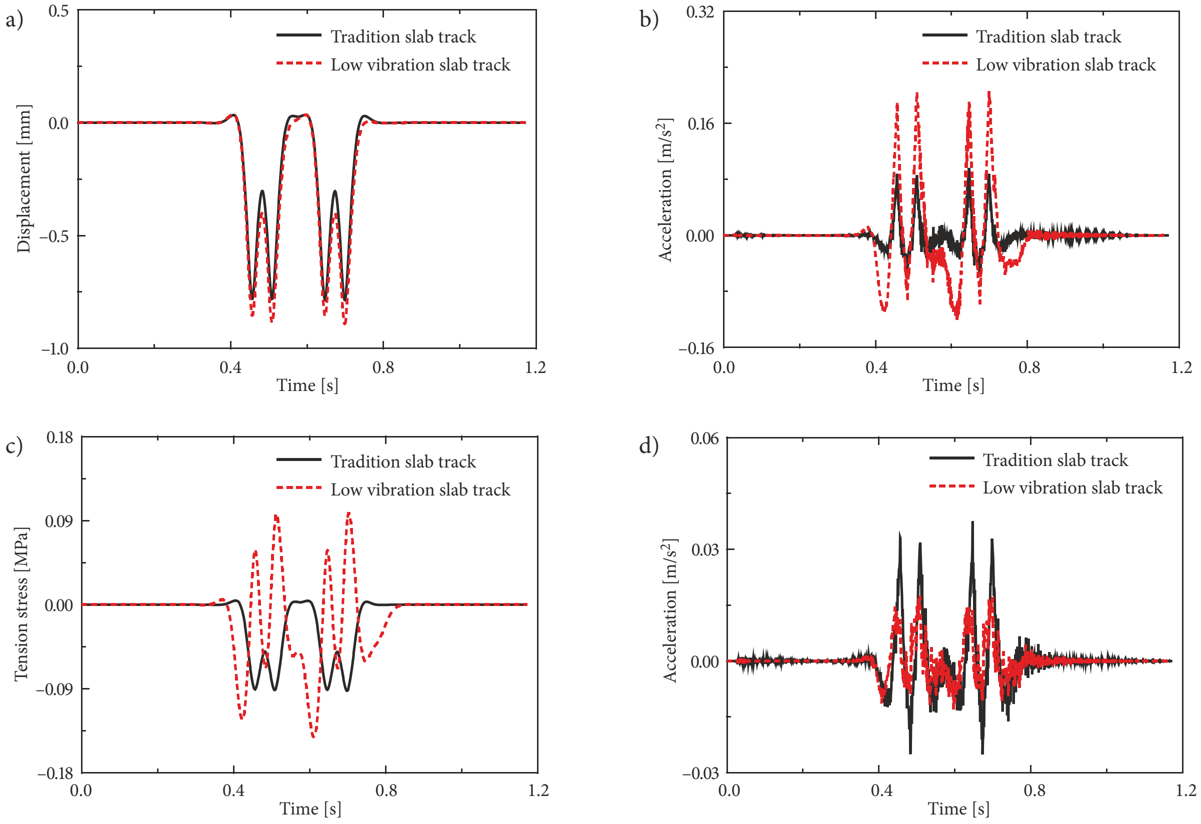

Figure 7. Dynamic characteristics of track structures: a – rail displacement; b – concrete slab acceleration; c – tension stress of concrete slab; d – support layer acceleration

As can be seen in Figure 7b, the concrete slab acceleration of the low vibration slab track increases by around 54% compared with that of the tradition slab track. In addition, it can be known from Figure 7c, the tension stress of the low vibration slab track increases by about 35%. These results illustrate that adding the rubber pad with a relatively small elastic modulus does not play a role in mitigating slab vibration, instead it causes an increase of acceleration and bending vibration deformation of concrete slab, and consequently increasing the tension stress of concrete slab. Therefore, inserting the rubber pad between the concrete slab and the supporting layer might, to a certain extent, accelerate the tension fatigue damage of the concrete slab and reduce its durability in the long-term operation. Nevertheless, as showed in Figure 7d, the acceleration of the supporting layer in the low vibration slab track is smaller and its attenuation rate is accelerated compared with the tradition slab track, which indicates that the rubber pad have an important function in the vibration isolation.

Under the repeated dynamic loads of the freight vehicle, the vertical interaction force on the slab track is relatively drastic, which might induce compression fatigue damage issues of the concrete slab. Figure 8 shows the time history curves of the compression stress of the concrete slab, the filling layer and the supporting layer of the slab tracks with and without rubber pad under the freight vehicle dynamic load.

As can be seen in Figure 8, compared with the tradition slab track, the compression stresses of the concrete slab, the filling layer and the supporting layer of the low vibration slab track are smaller than those of the tradition slab track. These results indicate that the rubber pad can alleviate the direct impact force of vehicle dynamic load on the concrete slab and other components, thus the compression fatigue damage of concrete slab under the long-term train dynamic load is relieved to a certain extent.

3.3. Optimization analysis of the rubber pad elastic modulus of low vibration slab track

In order to ensure a reasonable level of each dynamic response of the low vibration slab track, the optimal modulus of the rubber pad is analysed in the current analysis. In the calculation, various elastic modulus from 1÷30 MPa is selected for the rubber pad, and the dynamic response of the low vibration slab track under the freight vehicle load with a speed of 160 km/h is calculated using the proposed vehicle–track coupled dynamic model. The detailed calculation results are listed in Table 3.

As presented in Table 3, the rail displacement, the concrete slab acceleration and the tension stress of concrete slab all decrease with an increase of the elastic modulus of the rubber pad. Whereas the compression stress of the concrete slab and supporting layer, and the acceleration and tension stress of the supporting layer all increase with

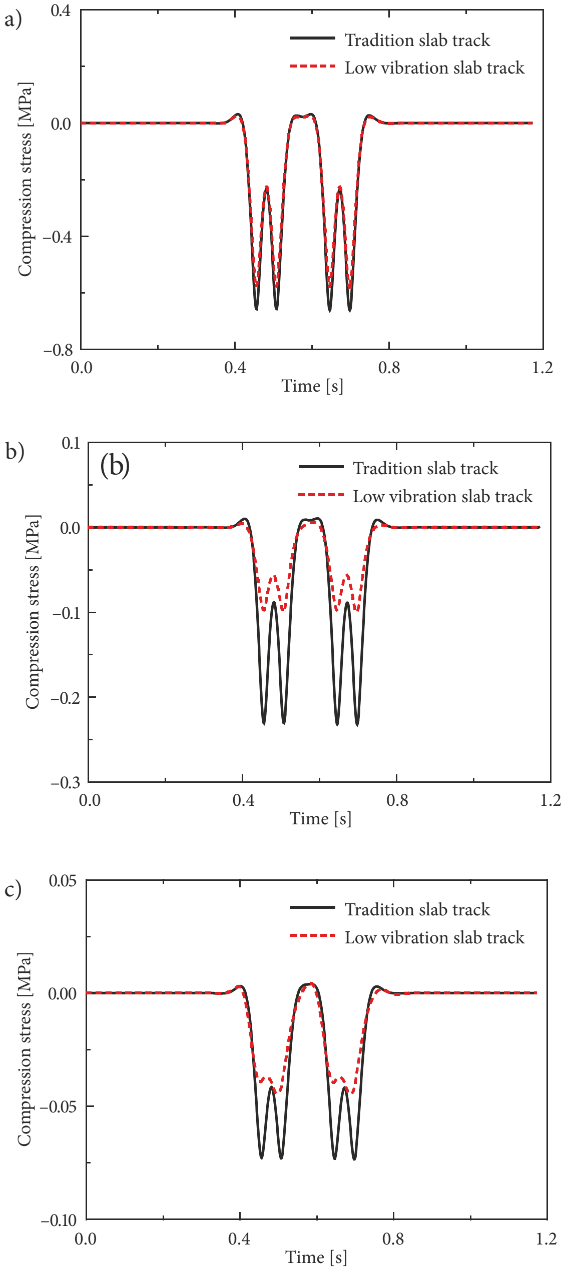

Figure 8. Dynamic compression stresses of track structures: a – concrete slab; b – filling layer; c – supporting layer

an increase of the elastic modulus of the rubber pad. Under the prerequisite of meeting the requirement of rail displacements, the optimal modulus of rubber pad can be determined by changing the elastic modulus with the aim of ensuring a reasonable level of each dynamic index of the slab track. In order to systematically analyse the influence of elastic modulus of the rubber pad on dynamic characteristics of the slab track, the normalized dynamic responses are obtained by treating each maximum dynamic index (shown in Table 3) as the reference value, as showed in Figure 9. As it can be seen, the influence rules of the dynamic indexes of the low vibration track are different with each other. Based on the aforementioned concept, by comprehensively considering all the dynamic responses of the track structures, the optimal modulus of the rubber pad can be determined to be 3÷7.5 MPa according to the intersection points in Figure 9.

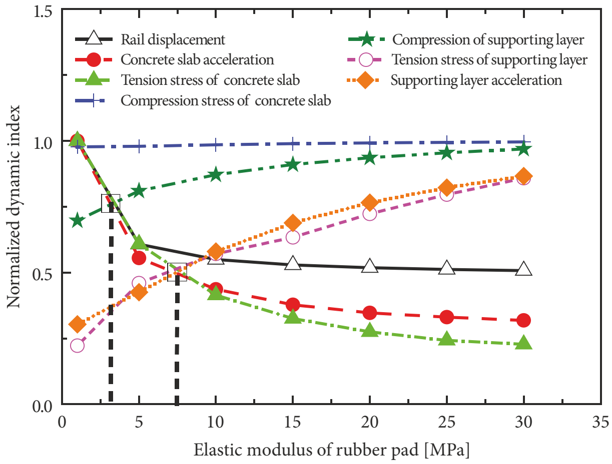

Figure 9. Influence of elastic modulus of rubber pad on dynamic response of the slab track

Conclusions

In this work finite element models of the slab tracks with and without the rubber pad have been firstly created by using software ANSYS. Further, coupled dynamic models of passenger/freight vehicle–low vibration/tradition slab

Table 3. Effect of elastic modulus of rubber pad on dynamic characteristics of track structure

Elastic modulus of rubber pad [MPa]	Rail displacement [mm]	Slab acceleration [m/s^2]	Slab tension stress [MPa]	Slab compression stress [MPa]	Supporting layer acceleration [m/s^2]	Tension stress of supporting layer [MPa]	Compression stress of supporting layer [MPa]
1	1.623	0.483	0.3413	0.5770	0.0091	0.0053	0.0358
5	0.986	0.268	0.2076	0.5781	0.0127	0.0109	0.0416
10	0.892	0.211	0.1415	0.5815	0.0173	0.0136	0.0448
15	0.858	0.182	0.1115	0.5840	0.0205	0.0151	0.0468
20	0.841	0.167	0.0938	0.5858	0.0228	0.0172	0.0481
25	0.831	0.159	0.0827	0.5870	0.0245	0.0189	0.0491
30	0.824	0.153	0.0776	0.5881	0.0258	0.0204	0.0498

track systems have been developed to calculate wheel–rail interaction forces, which are utilized as the inputs to the finite element models. The dynamic performance of the low vibration slab track, as well as the specific function of the rubber pad and its optimal modulus has been investigated in detail. The findings can be summarized as follow:

1) The interaction force between the freight vehicle and the slab track is more intensive because of the heavy axle-load, which causes larger displacements of the rail and the supporting layer, as well as larger compression stress of the concrete slab and the supporting layer. Whereas the wheel–rail interaction frequency of the passenger vehicle is higher due to the fast speed, which results in larger accelerations of the rail, the concrete slab and the support layer. Therefore, both the structural strength under heavy freight vehicle loads and the fatigue failure induced by high frequency dynamic load of passenger vehicles should be comprehensively addressed in the design of the low vibration track on shared high-speed passenger and freight railways;
2) By inserting the rubber pad between the concrete slab and the supporting layer, the slab acceleration and slab tension stress of the low vibration track are larger, while the compression stress of each track layer is smaller compared to the tradition slab track. This indicates that the rubber pad plays an important role in buffering the direct impact force on the concrete slab, and consequently alleviating the compression fatigue damage of the concrete slab under long-term vehicle dynamic load. Meanwhile, the rubber pad also has functions in vibration isolation because it reduces acceleration of the support layer and accelerates its attenuation rate;
3) The influence of elastic modulus of the rubber pad on dynamic characteristics of the low vibration slab track is systematically analysed, and the optimal modulus of rubber pad is suggested to be 3÷7.5 MPa, which can ensure a reasonable level of each dynamic index of the slab track.

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