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Dynamic Analysis on Suspended Monorail Vehicles Passing through Turnouts

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Abstract. Turnouts is a key line equipment for suspended monorail transit. In order to analyze the dynamic performance of vehicles passing turnouts, a dynamic model of the multi-degree-of-freedom (MDOF) suspended monorail transit system is established according to the multi-body dynamics theory by taking turnout #5 as an example. The effect of track irregularity on the dynamic performance of Shanghai sky train transformation (SSTT) bogie vehicle passing the turnout is analyzed; a contrast analysis on the dynamic performances of SSTT vehicle and Prose associated bogie vehicles passing the turnout is made. The research findings show that: the deformation of bridges and subsidence of piers can affect the dynamic performance of the vehicles passing the turnout greatly. When an SSTT bogie vehicle is passing the turnout in side move, the maximum guidance force difference of the guide wheels will reach up to 171%; when a Prose associated bogie vehicle is passing the suspended sky train turnout in side / trailing move, the dynamic performance of which can be better than that of the SSTT bogie vehicle and the operation can be more stable.

1. Introduction

For the suspended monorail transit, compared to the traditional steel-wheel-rail track transit, the ground transit can be moved to a high place in order to solve the urban transit problem without expanding the existing highway facilities, the advantages of which will be more and more popular due to low carbon and noise and therefore suspended monorail transit lines will be developed in more cities. Turnouts is an important part of the suspended monorail transit system, which is crucial to the safety and comfort of sky train operation. At present some researches on the suspended monorail transit have been presented both at home and abroad. Reference [1] summarized characteristics of the suspended monorail transit in Dortmund and Duesseldorf, Germany. Reference [2] introduced the development of suspended monorail vehicles, presented the status quo of different kinds of suspended monorail vehicles considering the running gears, described the technical characteristics of suspended monorail vehicles, and made a contrast analysis on the advantages / disadvantages between a straddled-type monorail and a suspended monorail. The research on the wheel-rail dynamics of sky train transit always concerns common sectional lines, Reference [3] analyzed the vehicle-bridge coupling vibration of the rail transit system through the combined simulation of the finite element analysis software ANSYS and multibody dynamics software SIMPACK based on the vehicle-bridge coupling vibration theory; Reference [4] established two kinds of monorail bogie 3D models through SOLIDWORKS, analyzed the characteristics and running mechanism of the asymmetric steel-wheel type and SAFEGE type suspended monorails, established the dynamic models of the asymmetric steel-wheel type and SAFEGE type suspended monorails through the multibody dynamics software SIMPACK and evaluated the dynamic performances of the two kinds of monorail vehicles under normal conditions and cross wind through a contrast analysis; Reference [5] analyzed the curve negotiation performance of suspended monorail vehicles through SIMPACK; Reference [6] established a 41-DOF suspended monorail train model based on the SIMPACK platform, made a simulation analysis on the vehicle-bridge coupling dynamics of the suspended monorail transit system and evaluated the effect of factors such as running speed, track irregularity and train formation on the dynamic response of vehicles and bridges; Reference [7] analyzed the effect of guide wheel pre-pressure on the critical speed and curve negotiation ability of vehicles through SIMPACK. Reference [8] analyzed the main forms of track beam, pier and support constrains of bridge structures for the suspended monorail transit system and presented a kind of suspended monorail bridge structure with double-line simply supported beams. Reference [9] presented dynamic modeling and simulation calculation through SIMPACK and made a simulation analysis on the key parameters (damper between vehicles, guide wheel pre-pressure, steady wheel) for design of suspended monorail trains and key conditions of vehicles (cross wind, air spring) during running. Reference [10] established a vehicle simulation model through the analysis software ADAMS and analyzed the dynamic change of radial force of guide wheels and the effect of which on the curve negotiation performance of vehicles. However for the key equipment - turnouts for sky train vehicle transfer, considering the effect of track irregularity on the dynamic performance of vehicles passing turnouts, no any research on the dynamic performance of vehicles passing turnouts with regard to different kinds of SSTT bogie and Prose associated bogie vehicles has been presented in the world.

2. Suspended sky train turnout

Taking turnout #5 as an example, the designed frog angle is 11°18′36″ and the full length of the turnout beam is 19.960m. A suspended sky train turnout consists of running surface, adjusting rail, movable rail, movable guide surface, compensation rail and switch as shown in Fig. 2 (a) and (b). The movable rail shall be operated together with the compensation rail, movable guide surface and adjusting rail. When the movable rail moves to one side, the movable guide surface will be close to this side with it, realizing the smooth transition of the guide surface; the compensation rail on this side will move away for the incoming movable rail; at this time, the compensation rail on the other side will move to the running position in order to form a running surface; the compensation rail will move to a suitable position to allow smooth running of trains.

The movable rail is a crucial and core part for the suspended sky train turnout; the movable guide surface can be used to improve the regularity of the guide surface and thus no heavy impact can be caused when the guide wheels are passing the turnout. The compensation rail and adjusting rail can form a running surface, eliminating the height difference between both sides and at one side of the track.

The collaborative action of movable parts can help to realize the lowest irregularity of the running and guide surfaces, eliminate the height difference and improve the stability and comfort of trains passing by. In this paper, the running surface is not subject to any height different except the guide surface with a 5mm height difference at the movable guide surface point.

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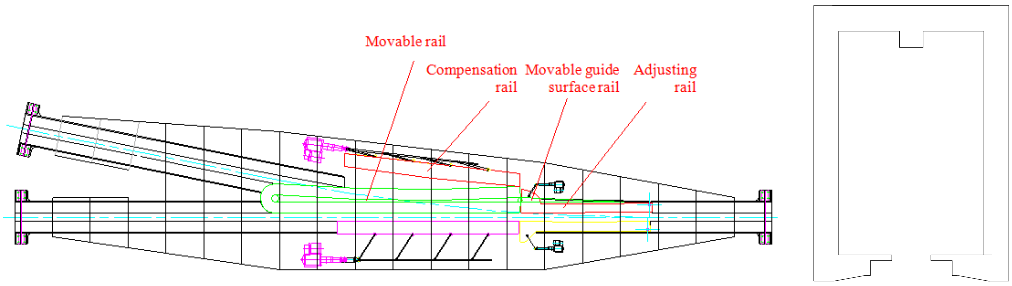
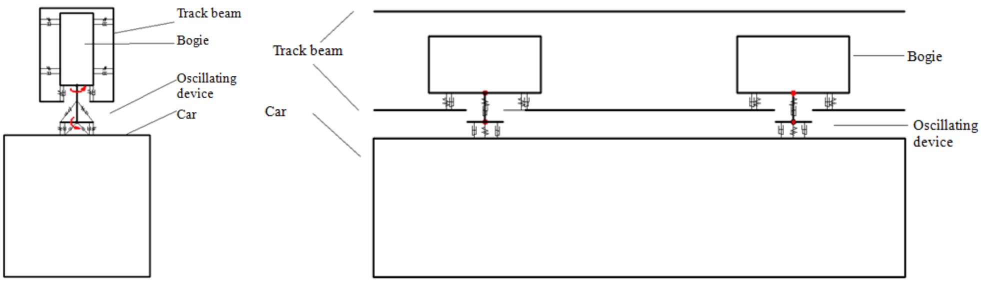


(a) Top view of suspended sky train turnout (b) Sectional view of track beam model
Fig. 1 Track beam model

3. Establishment of dynamic model

The suspended sky train vehicle model consists of three parts mainly: bogie, oscillating device and vehicle body. The bogie is connected with the vehicle body through the oscillating device. In this paper, the SSTT and Prose associated bogies are selected as the examples.

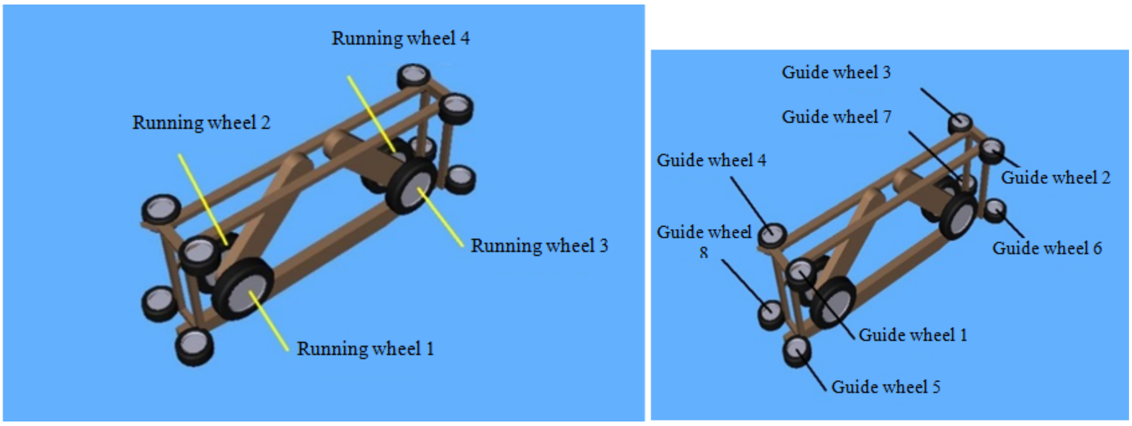
The simplified model is shown in Fig. 1 (a) and (b). It can be seen that there exist DOFs between the oscillating rod and bogie in the yaw direction and between the oscillating rod and vehicle body in the side oscillating direction. Table 1 shows some vehicle parameters. Fig. 3 shows the running wheel and guide wheel numbers of the SSTT bogie; Fig. 4 shows the running wheel and guide wheel numbers of the Prose associated bogie; Fig. 5 shows the acceleration measuring points of the vehicle body.



(a) Front view of model (b) Side view of model
Fig. 2 Plane model of suspended sky train

Table 1. Some key vehicle parameters

Type of bogie	Vehicle L./mm	Vehicle W./mm	Vehicle H. /mm	Vehicle mass /t	Ctr. distance of bogie /mm	Running wheel base/mm	Running wheel gauge/mm	Guide wheel base (upper) /mm	Guide wheel base (lower) /mm	Guide wheel gauge /mm
SSTT bogie	10292	2300	3539	13	6600	1730	340	2410	2754	500
Prose associated bogie	10292	2300	3539	13	6600	1200	360	2020	2020	500



(a) Running wheel numbers (b) Guide wheel numbers

Fig. 3 Wheel numbers of SSTT bogie

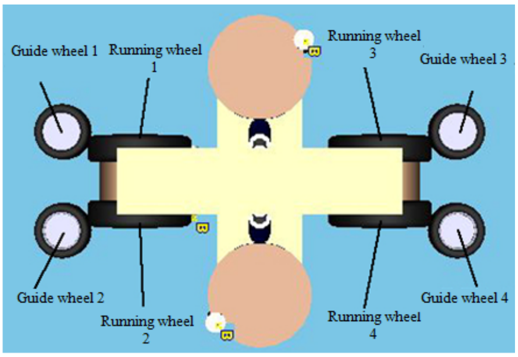


Fig. 4 Wheel numbers of Prose associated bogie

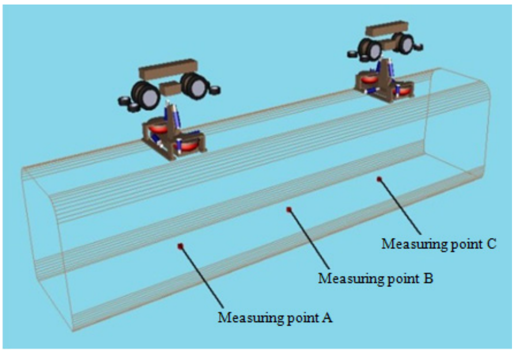
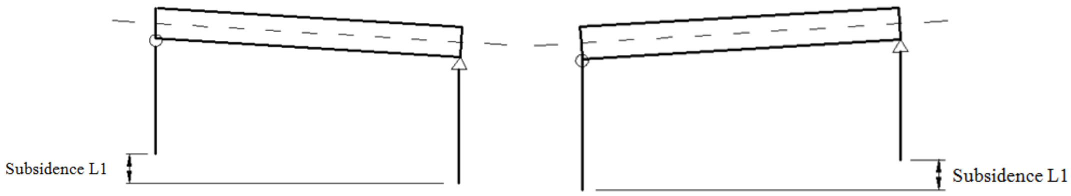


Fig. 5 Acceleration measuring points of vehicle body

3.1. Simulation of track irregularity

The suspended sky train transit is a rubber wheel-rail system, which is different from the steel-wheel-rail system of common railways. The running surface of suspended sky train vehicles consists of steel plates, the surface regularity of which is better than that of highway surfaces, and as a kind of track transit, the track irregularity is more suitable for reflecting the irregularity of running surface and therefore the 6^{th} grade track irregularity power-spectral-density (PSD) of railways in the USA is selected; The height difference between the movable guide surface and guide surface is 5mm, which can be considered as inherent structure irregularity. According to the *Fundamental Code for Design on Railway Bridge and Culvert* of China, the track beam span is 20m, and the allowed vertical deflection, L/800, so the vertical deflection is set as 25mm. The suspended sky train turnout has a complicated structure, the main movable parts of which move laterally. If the lateral deformation of the turnout beam is severe, the movable rail and movable guide surface will cause a big safety problem when moving close to one side and affect the normal operation of the compensation rail and adjusting rail. So generally the set lateral deformation is 5mm. For the pier subsidence, considering the separate subsidence at both front and rear ends of the turnout beam as shown in Fig. 6, the maximum subsidence is set as 10mm. Table 2 shows the simulated track irregularity under different conditions.



(a) Pier subsidence 1 (b) Pier subsidence 2

Fig. 6 Pier subsidence

Table 2. Track irregularity

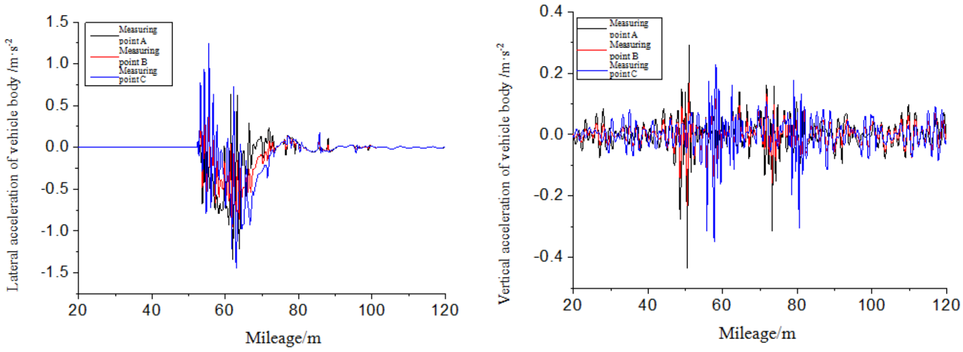
Cond.	The 6th grade track PSD of the USA	Inherent structure irregularity	Vertical bridge deflection	Lateral bridge deformation	Pier subsidence 1	Pier subsidence 2
Cond. 1	√	√				
Cond. 2	√	√	√			
Cond. 3	√	√	√		√	
Cond. 4	√	√	√			√
Cond. 5	√	√	√	√	√	
Cond. 6	√	√	√	√		√

4. Dynamic characteristics of vehicles passing turnouts

In this section the dynamic model is used. For the calculation, taking the suspended sky train turnout #5 as an example, the circular curve radius is 50m, the designed speeds in side / trailing move are 15km/h and 50km/h respectively, therefore the vehicle speeds passing the turnout in trailing / side move are set as 55km/h and 20km/h respectively. Under the set interstice of 6mm the negotiation performance can be analyzed according to the lateral / vertical vibration acceleration of the vehicle body, the vertical force of the running wheels and the guidance force of the guide wheels. A 50m straight line section shall be set in front of and behind the turnout respectively before calculation. The parts concerned are the turnout beam and the zones near it, so the zone of 50-70m will be analyzed mainly.

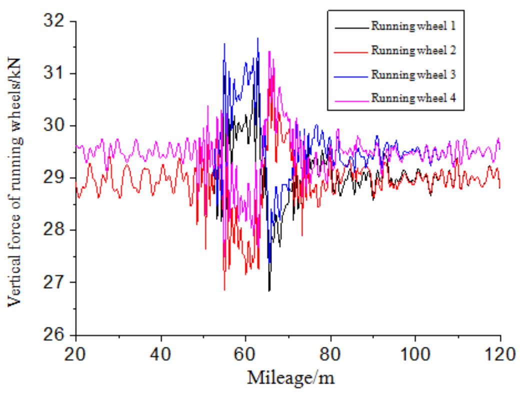
4.1. Analysis on effect of track irregularity on dynamic performance of vehicles passing turnouts

In order to analyze the effect of track irregularity on the dynamic performance of vehicles passing turnouts, a dynamic simulation of the SSTT bogie is made based on the 6 kinds of track irregularity shown in Table 2. Fig. 7 and 8 show the dynamic wheel-rail response under Condition 5 when passing the turnout in side move. Table 3 shows the maximum dynamic indices when a vehicle is passing the turnout in trailing / side move under different track irregularity.

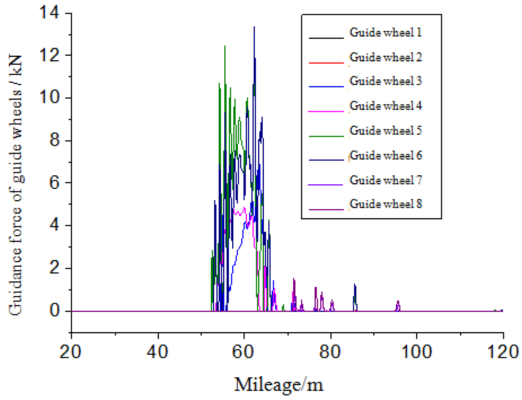


(a) Lateral acceleration of vehicle body (b) Vertical acceleration of vehicle body

Fig. 7 Acceleration of vehicle body with SSTT bogie



(a) Vertical force of running wheels



(b) Guidance force of guide wheels

Fig. 8 Dynamic wheel-rail interaction of SSTT bogie

Table 3 .Dynamic indices of vehicles passing turnouts

Evaluated dynamic index	Cond. 1		Cond. 2		Cond. 3		Cond. 4		Cond. 5		Cond. 6	
	Trailin g move	Side move	Trailin g move	Side move	Trailin g move	Side move	Trailin g move	Side move	Trailin g move	Side move	Trailin g move	Side move
Lateral acceleration of vehicle body ($m·s^{-2}$)	0.13	0.87	0.14	1.11	0.14	1.13	0.13	1.17	0.34	1.44	0.33	1.42
Vertical acceleration of vehicle body ($m·s^{-2}$)	1.04	0.19	1.14	0.36	1.27	0.41	1.06	0.41	1.29	0.43	1.10	0.40
Vertical force of running wheel (kN)	32.21	31.91	32.22	32.34	32.22	32.35	32.26	32.39	32.16	31.67	32.20	31.66
Guidance force of guide wheel (kN)	17.82	4.97	17.80	7.86	17.41	7.98	17.45	8.21	21.00	13.34	21.10	13.46

For passing the turnout in side move, as shown in Table 3, under Condition 2 the vertical bridge deflection is added based on Condition 1, the lateral / vertical vehicle acceleration has increased by about 28% and 90% respectively, and the guidance of guide wheels, by about 58%; Under Condition 3 and 4 different pier subsidence are added based on Condition 2, the maximum values of all dynamic indices have not changed much, the vertical acceleration of the vehicle body has only increased by 14%, indicating that the pier subsidence has little effect on the dynamic performance of the vehicle passing the turnout in side move; Under Condition 5 and 6 the lateral bridge deformation is added based on Condition 3 and 4, the maximum lateral acceleration of the vehicle body has increased by about 27%, while the vertical acceleration of the vehicle body has not changed much, the maximum guidance force of the guide wheels has increased by about 67%. According to the overall evaluation with regard to different conditions, the effect of the bridge deformation on the dynamic performance of the vehicle passing the turnout is more obvious than that of pier subsidence. When the vehicle is passing the turnout in side move, the maximum lateral acceleration of the vehicle body has increased by 66%, and the maximum guidance force of the guide wheels and maximum vertical acceleration of the vehicle body, by 171% and 126% respectively; under all conditions, almost no change of the vertical force of running wheels has been caused.

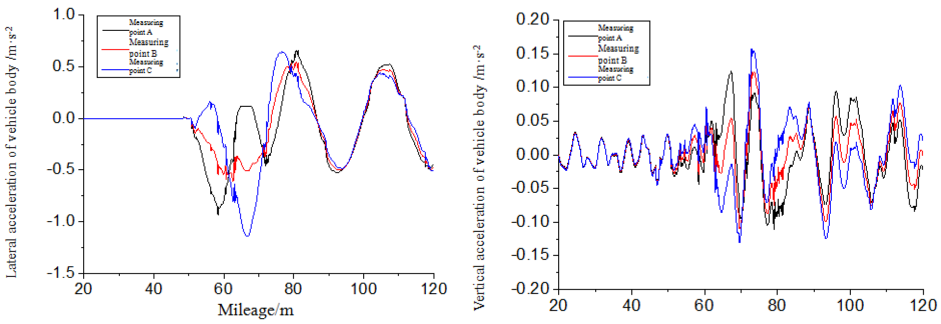
For passing the turnout in trailing move, the SSTT vehicle can pass the turnout in trailing move smoothly at the designed speed under all conditions. Under Condition 2 the vertical bridge deflection is added based on Condition 1, almost no change of the maximum values of all dynamic indices has been caused, indicating that the vertical bridge deflection has little effect on the dynamic performance of the vehicle passing the turnout in trailing move; Under Condition 3 and 4 different pier subsidence are added based on Condition 2, the lateral / vertical vibration acceleration of the vehicle body have not changed much, while the maximum guidance force of the guide wheels has increased by about

40%; Condition 5 and 6 the lateral bridge deformation is added based on Condition 3 and 4, the maximum lateral acceleration of the vehicle body has increased by about 154%, while almost no change of the vertical vehicle acceleration has been caused, the maximum guidance force of the guide wheels has increased by about 21%. According to the overall evaluation with regard to different conditions, the effect of the lateral bridge deformation and pier subsidence on the dynamic performance of the vehicle passing the turnout in trailing move is more obvious than that of the vertical bridge deflection. The maximum lateral acceleration of the vehicle body has increased by 154%; the maximum guidance force of the guide wheels has increased by 42%; the maximum vertical acceleration of the vehicle body has increased by 24%. Almost no change of the vertical force of the running wheels has been caused.

The vertical force of the running wheels has not changed much under different conditions, because though the bridge deformation and pier subsidence affect the regularity of the running surface, the change is smooth i.e. the irregularity is subject to medium-long wave mainly and the running wheels are rubber tyres with good anti-shock and damping effects.

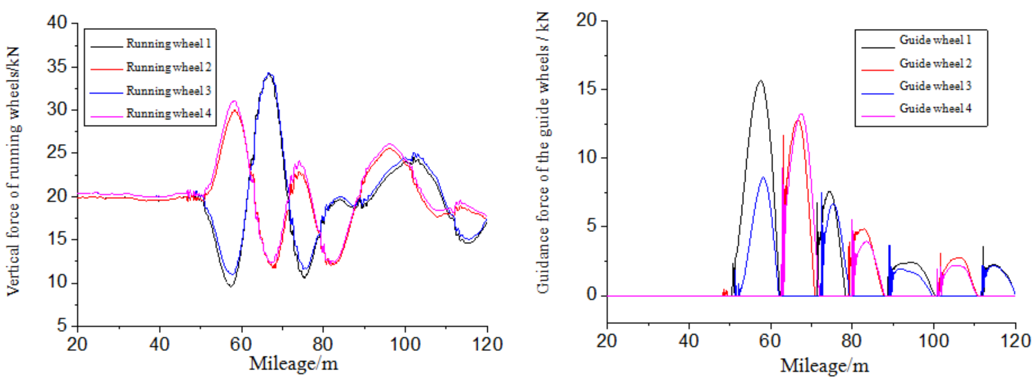
4.2. Contrast analysis on dynamic performances of Prose associated bogie and SSTT bogie vehicles passing turnouts

In order to make a contrast analysis on the dynamic performances of Prose associated bogie and SSTT bogie vehicles passing turnouts, a dynamic simulation of a Prose associated bogie vehicle passing a turnout is made based on Condition 5 and 6 shown in Table 2. Fig. 9 and 10 show the dynamic wheel-rail response when the vehicle is passing the turnout in side move under Condition 5. Table 4 shows the maximum dynamic indices when the Prose associated bogie and SSTT bogie vehicles are passing the turnout in trailing / side move under Condition 5 and 6.



(a) Lateral acceleration of vehicle body (b) Vertical acceleration of vehicle body

Fig. 9 Acceleration of vehicle body with Prose associated bogie vehicle



(a) Vertical force of running wheels (b) Guidance force of guide wheels

Fig. 10 Dynamic wheel-rail interaction of Prose associated bogie

As shown in Fig. 9 and 10, under Condition 5, when the train is passing the suspended sky train turnout in side move at 20km/h, both the lateral / vertical acceleration of the vehicle body are low, however the attenuation of the lateral acceleration will slow down after passing the turnout. The fluctuation amplitude of the vertical force on the running wheels is high and the running wheels at both sides change alternately; the guidance force of the guide wheels is high when passing the turnout, reaching about 15.66kN. According to Table 4, when the train is passing the suspended sky train turnout in trailing move at 55km/h, the lateral acceleration of the vehicle body is low; the vertical acceleration of the vehicle body has increased compared to that when the vehicle is passing the turnout in side move, however the overall amplitude is still low. The guidance force of the guide wheels is low - less than 20kN and the vertical force on the running wheels at both sides is low.

Table 4. Dynamic indices of the vehicle passing the turnout

Evaluated dynamic index	Prose associated bogie				SSTT bogie			
	Cond. 5		Cond. 6		Cond. 5		Cond. 6	
	Trailing move	Side move	Trailing move	Side move	Trailing move	Side move	Trailing move	Side move
Lateral acceleration of vehicle body ($m \cdot s^{-2}$)	0.05	1.14	0.05	1.19	0.34	1.44	0.33	1.42
Vertical acceleration of vehicle body ($m \cdot s^{-2}$)	0.24	0.18	0.23	0.17	1.29	0.43	1.10	0.40
Vertical force of running wheel (kN)	25.10	34.34	25.51	33.76	32.16	31.67	32.20	31.66
Guidance force of guide wheel (kN)	19.06	15.66	17.10	15.66	21.00	13.34	21.10	13.46

As shown in Table 4, under the most unfavorable two conditions 5 and 6, for the Prose associated bogie vehicle passing the turnout, the lateral acceleration of the vehicle body can reach up to 1.19 m/s^2, which is less than that (1.44 m/s^2) for the SSTT bogie vehicle; When the Prose associated bogie is passing the turnout in side move, the maximum lateral acceleration of the vehicle body is 0.18 m/s^2, which is 0.4 times that for the SSTT bogie vehicle under the same condition; The maximum vertical force of the running wheels and guidance force of the guide wheels for the Prose associated bogie vehicle passing the suspended sky train turnout in side move are a little bit higher than those for the SSTT bogie vehicle.

For the Prose associated bogie vehicle passing the turnout in trailing move, the maximum vertical acceleration of the vehicle body is 0.24 m/s^2, which is far less than that (1.27 m/s^2) for the SSTT bogie vehicle; The maximum vertical force of the running wheels is 25.51kN, which is far less than that (32.20kN) for the SSTT bogie vehicle.

According to the Technical Specification for High Speed Turnouts TBT/T-3301-2013, when the vehicle is passing turnout, the lateral / vertical vibration acceleration of the vehicle body shall not be higher than 1.5m/s2 and 2.0m/s2 respectively. Both the two kinds of bogie vehicles can pass the suspended sky train turnout smoothly at the designed speed under different conditions, and the vertical force of the running wheels and guidance force of the guide wheels are kept within a reasonable range. The dynamic response of the Prose associated bogie vehicle, whether passing the suspended sky train turnout in side move or trailing move, is always better than that of the SSTT bogie vehicle, and the operation is stabler, especially when the vehicle is passing the turnout in trailing move, the advantage of the Prose associated bogie is more obvious, the lateral / vertical vibration of the vehicle body is very low and the force on the running wheels is low and stable; However compared to the SSTT bogie vehicle, the attenuation of the lateral vibration acceleration for the Prose associated bogie vehicle is slow.

5. Conclusions

In this paper, a dynamic model is established through the software UM, the effect of track irregularity on the dynamic response of vehicles passing turnouts is analyzed; under an unfavorable track irregularity, a contrast analysis on the dynamic responses of Prose associated bogie and SSTT bogie vehicles passing turnouts is made. The detailed conclusion is shown below:

(1) For the SSTT bogie, when the vehicle is passing the turnout in side move, the vertical

vibration acceleration of the vehicle body will be most sensible to the vertical bridge deflection. The lateral response of the vehicle is sensible to the vertical deflection and lateral deformation of the bridge; when the vehicle is passing the turnout in trailing move, the lateral vibration of the vehicle body will be the most sensible to the lateral bridge deformation. The guidance force of the guide wheels and vertical acceleration of the vehicle body are sensible to the pier subsidence and lateral bridge deformation.

(2) For the SSTT bogie, when the vehicle is passing the turnout in side move, the dynamic performance of the vehicle will be more sensible to the vertical deflection and lateral deformation of the bridge; When the vehicle is passing the turnout in trailing move, the dynamic performance of the vehicle passing the turnout will be more sensible to the lateral bridge deformation and pier subsidence.

(3) According to the calculated results with regard to the SSTT bogie and Prose associated bogie vehicles, the vehicles can pass the suspended sky train turnout smoothly at 20 km/h in side move and 55km/h in trailing move. The designed side / trailing move speeds of 15km/h and 50 km/h respectively for passing the suspended sky train turnout are reasonable.

(4) For the Prose associated bogie, when the vehicle is passing the suspended sky train turnout in side / trailing move, the dynamic response will be better than that corresponding the SSTT bogie vehicle. For example, under Condition 5, when passing the turnout in side move, the lateral accelerations of the vehicle body are 1.14 and 1.44 m/s^2 respectively.

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