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Dynamic performance of a pantograph-catenary system with the consideration of the appearance characteristics of contact surfaces*

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Abstract: In this paper, a modeling method for a pantograph-catenary system is put forward to investigate the dynamic contact behavior in space, taking into consideration of the appearance characteristics of the contact surfaces of the pantograph and catenary. The dynamic performance of the pantograph-catenary system, including contact forces, accelerations, and the corresponding spectra, is analyzed. Furthermore, with the modeling method, the influences of contact wire irregularity and the vibration caused by the front pantograph on the rear pantograph for a pantograph-catenary system with double pantographs are investigated. The results show that the appearance characteristics of the contact surfaces play an important role in the dynamic contact behavior. The appearance characteristics should be considered to reasonably evaluate the dynamic performance of the pantograph-catenary system.

Key words: Catenary, Pantograph, Dynamic performance, Appearance characteristics
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1 Introduction

In the high-speed electric railway, the dynamic performance of a pantograph-catenary system plays an important role in maintaining good contact between the pantograph and catenary and improving the quality of current collection. Standard mathematical models and solution methods have been proposed for the dynamic performance of the pantograph-catenary system (Vinayagalingam, 1983; Cai and Zhai, 1997; Arnold and Simeon, 2000; Collina and Bruni, 2002; Mei and Zhang, 2002; Liu *et al.*, 2003; Park *et al.*, 2003; Metrikine and Bosch, 2006; Lee, 2007; Lopez-Garcia *et al.*, 2007). Furthermore, in recent years, more attention has been paid to the influence of contact wire unevenness, the wear between contact line and collector, the flexible deformation at higher frequencies, and the influence of aerodynamics on the dynamic performance, etc. Zhang *et al.* (2000) investigated the influence of the irregularity of the contact wire on the contact state and discussed how to reduce the influence by modifying the design parameters of the pantograph. Nagasaka and Aboshi (2004) analyzed the influence of the contact wire unevenness on the contact forces between the catenary and pantograph, and devised an instrument to measure the unevenness of contact wires, both accurately and continuously. They proposed a method to evaluate the conditions of contact wires. He *et al.* (1998) investigated the wear and electrical properties of contact wires and collectors used in lightweight systems, based on laboratory tests with a wear equipment. Bucca and Collina (2009) established a wear model for the contact between collectors and contact wires, and

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designed a procedure to simulate the dynamic interaction between the pantograph and catenary. They predicted the wear of collectors and contact wires. The values of contact forces and current were the inputs of the wear model, and the amount of the wear of the collectors and contact wires was determined, generating an irregular profile of the contact wires. Collina *et al*. (2009) identified the modal parameters of the collectors by experiment, and then investigated the dynamic contact behavior of the pantograph-catenary system, considering the deformation modes of the collectors. It is proved that there is an obvious influence of the deformable modes of the collectors on the dynamic behavior of the pantograph-catenary system. Based on the quasi-steady theory formulation of the drag and lift forces on the collectors, Bocciolone *et al*. (2006) analyzed the turbulence of the incoming flow and the dynamic variation of the contact force between the pantograph and catenary, and investigated the influence of the aerodynamic action on the current collection.

However, these studies mainly focus on the dynamic contact behavior in the vertical direction. There have been few published papers on how to comprehensively evaluate the dynamic performance in space, considering the appearance characteristics of contact surfaces of the pantograph and catenary. Therefore, the objective of this research is to put forward a pantograph-catenary system model to investigate the dynamic contact behavior in space and more importantly, to find a reasonable method to analyze the influence of the contact wire irregularity on the contact behavior and the vibration caused by the front pantograph on the dynamic performance of the rear pantograph for a pantograph-catenary system with double pantographs.

2 Model of the pantograph-catenary system

2.1 Catenary model

As shown in Fig. 1, the finite element model of the stitched catenary is composed of a support wire, assistant wire, contact wire, and dropper. A beam element is defined to simulate the support wire and contact wire, and a spring element is used to build the model of the dropper. The length of the 3D finite element model of the catenary is 500 m (ten spans), and the stagger is 300 mm. The material parameters of the catenary are shown in Table 1.

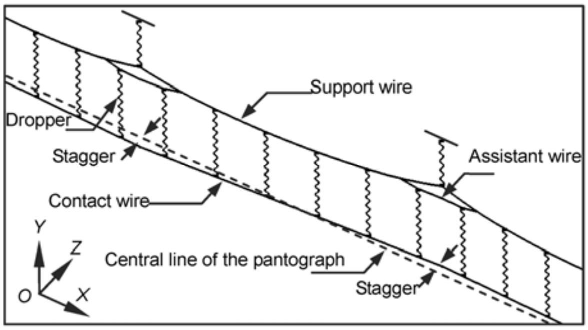


Fig. 1 Catenary model with one span

Table 1 Material parameters of the catenary

Wire	Material	Density (kg/m)	Tension (kN)	Section area (mm^2)
Contact	CTMH-150	1.35	30	150
Support	JTMH-120	1.07	21	120
Assistant	JTMH-35	0.31	3.5	35

2.2 Pantograph model

First, the pantograph is modeled with a rigid-flexible hybrid body, regarding two collectors of the pan-head as a flexible body and the other parts of the pantograph as a rigid body (Fig. 2). With the finite element method, the flexible body model of two collectors is established. A total of 3980 solid elements are used to depict the appearance characteristics of two collectors. Then, for comparison, the pantograph is completely considered as a multiple rigid body system. The two collectors of the pan-head are no longer a flexible body but a rigid body (Fig. 3). Thus, the appearance characteristics of contact surfaces of the pantograph and catenary are not involved.

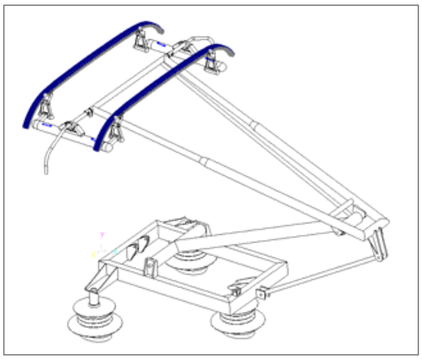


Fig. 2 Rigid-flexible hybrid pantograph model

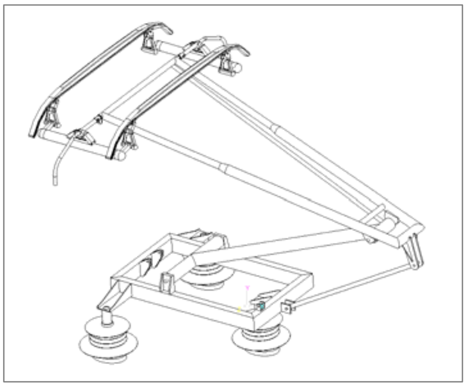


Fig. 3 Rigid pantograph model

2.3 Pantograph-catenary system model

Based on the catenary model and the pantograph model, the coupled model of the pantograph-catenary system is built. If the rigid-flexible hybrid pantograph model is employed, the action contact surfaces are approximated as multi-rectangular patches according to the solid elements of the collectors, and the base contact surfaces are approximated as multi-cylinders in the line of the beam element (Fig. 4). The lines of the base cylinders are examined to determine whether they are in contact with the surfaces of the action patches. And then, the contact force is generated with the compliance characteristics allowing penetration. Thus, the dynamic contact behavior, such as vertical vibration, longitudinal impact, and lateral oscillation of the pantograph and the catenary, may be exactly described by the line-to-surface contact. Compared to the rigid-flexible hybrid model, it can be seen that if the pantograph is simplified as a multiple rigid model, all the appearance characteristics of the collectors will be lost, the contact behavior is only a line-to-line contact, and the contact description will be not more accurate than that defined by the line-to-surface contact.

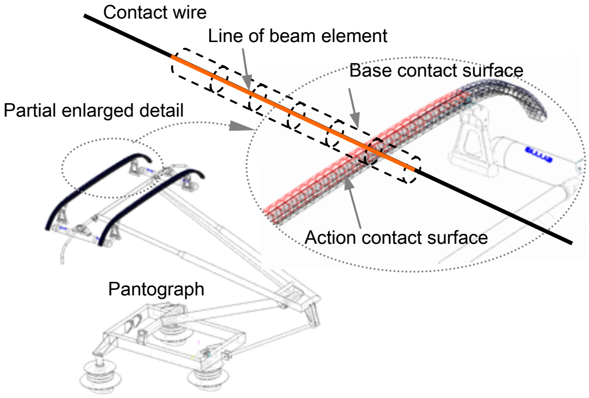


Fig. 4 Contact description of the pantograph-catenary system

3 Results of the dynamic performance

For the pantograph-catenary system, the solution of the dynamic contact behavior has been carried out by means of two kinds of pantograph models. Furthermore, the results of the dynamic performance are obtained, including contact forces and accelerations in space.

Fig. 5 shows the contact forces in the vertical (*Y*) direction at the speed of 350 km/h. It can be found that there is an obvious difference in the contact forces for two kinds of pantograph models, and the fluctuation of contact forces based on the rigid-flexible hybrid model is more volatile than that based on the rigid model. Meanwhile, it can be found that, for the rigid model, although there are contact losses on the rear collector, the total contact forces do not appear to be a zero value. It shows that the contact loss on the front and rear collectors does not occur at the same time. However, for the rigid-flexible hybrid model, the total contact forces already present the zero value, and there is a simultaneous contact loss on the front and rear collectors.

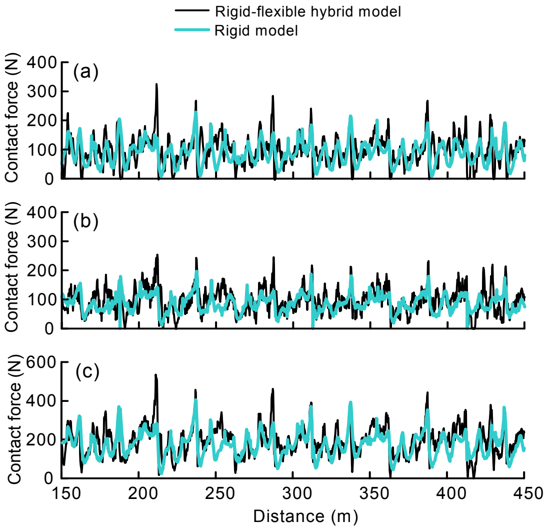


Fig. 5 Contact forces of the front (a) and rear (b) collectors and the total contact force (c) in the *Y* direction

Fig. 6 shows the total contact forces in the longitude (X) and lateral (Z) directions at the speed of 350 km/h. Similarly, it can be found that the obtained contact forces in the X and Z directions, based on two pantograph models, have a basically same rule, and the contact forces by means of the flexible-rigid hybrid model are slightly larger than those by means of the rigid model.

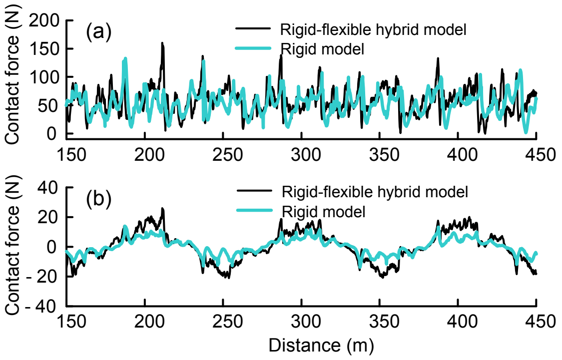


Fig. 6 Total contact forces in the X (a) and Z (b) directions

Fig. 7 shows the contact loss between the pantograph and catenary at different speeds. It can be seen that the contact loss is not detected until the speed is higher than 325 km/h for the rigid-flexible hybrid model. However, for the rigid model, there is no contact loss when the speed is lower than 400 km/h. Thus, it indicates that the calculated maximum operating speed based on the rigid-flexible hybrid model is less than that based on the rigid model.

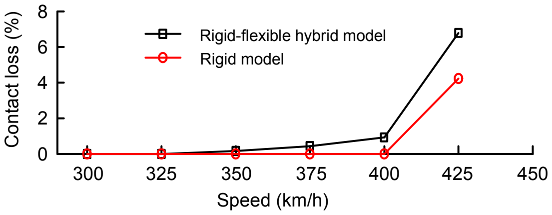


Fig. 7 Contact loss at different speeds

Fig. 8 shows the accelerations and the corresponding spectra at the speed of 350 km/h. It can be found that the obtained maximum accelerations by means of the flexible-rigid hybrid model in the X, Y, and Z directions are much larger than those by means of the rigid model. Especially, in the Y direction, the former is about six times larger than the latter. For the spectrum of the former, the contribution from the lower and higher frequency bands can be observed. Furthermore, at a higher frequency, there is an obvious contribution from the frequency component of about 110–120 Hz.

For the rigid-flexible hybrid pantograph model, the modal analysis of the flexible body is performed

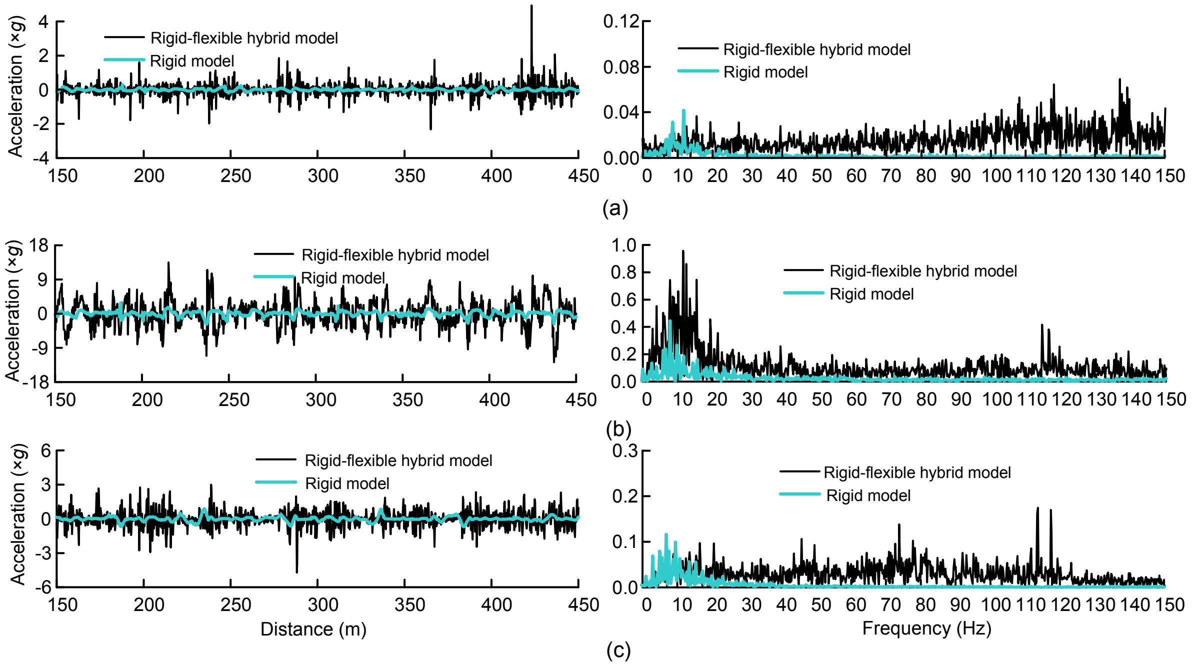


Fig. 8 Accelerations and the corresponding spectra at the speed of 350 km/h in the X (a), Y (b), and Z (c) directions

to obtain natural frequencies and mode shapes. Table 2 shows the natural frequencies and corresponding mode shapes of the flexible collector.

Combining the results of the modal analysis for the flexible body, it is obvious that the frequency component of about 110–120 Hz mainly comes from the contribution of the second mode of the collector. The flexible deformation of the collector in the *X* and *Y* directions has an important influence on the dynamic performance. Furthermore, for the rigid-flexible hybrid model, there are multiple degrees of freedom for the pan-head, and it can exactly describe the motion and the contact behavior of the pan-head, and excite the flexible deformation at higher frequencies. However, if the pantograph model is considered as a rigid body system, all shape features of the pan-head are lost and its flexible deformation cannot be considered. Thus, it can be seen that it is the consideration of the appearance characteristics that may inevitably lead to the difference of the calculation results.

4 Validation by a field test

A field test of dynamic performances, aimed at identifying contact forces and accelerations of the pantograph, has been performed on a 350 km/h railway line. The contact forces between pantograph and catenary are measured by means of force sensors. Four force sensors are divided into two groups to respectively determine the contact forces of the front and rear collectors. The No. 3 force sensor between the collector and the triangular frame of the pantograph is shown in Fig. 9.

Two accelerometers are fixed to measure the acceleration of the front and rear collectors (Fig. 10). As mentioned above, the obtained force by the force sensors is actually the interaction force ($\boldsymbol{F}_t$) between the collector and the triangular frame, and is not the contact force ($\boldsymbol{F}_c$) between the collector and the contact wire. For the collectors, the applied force may be written as

$$\boldsymbol{F}_c=\boldsymbol{F}_t+M_t\boldsymbol{a},$$

where M_t is the mass of the collector, $\boldsymbol{a}$ is the vertical acceleration, and $M_t\boldsymbol{a}$ is the inertial force. Thus, the actual contact force is equal to the test interaction force plus the inertial force. Moreover, the inertial force is determined by the test acceleration of collectors. Fig. 10 shows the contact force for the pantograph at the speeds of 300 and 350 km/h.

The results in Fig. 11 show that there is no contact loss at the speed of 300 km/h, and the

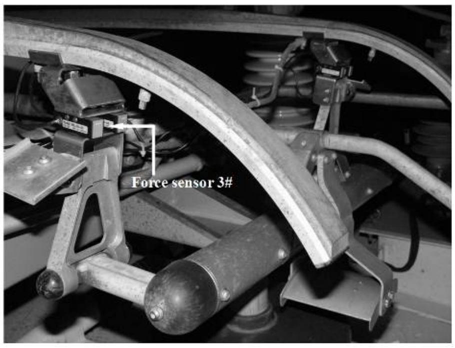


Fig. 9 Force sensor of the pantograph

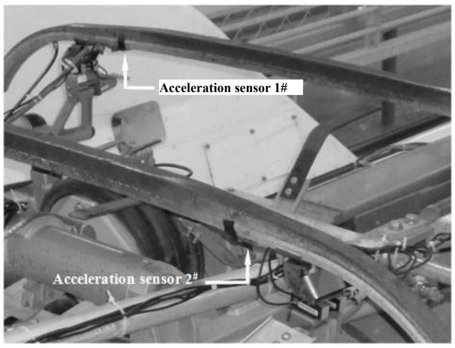
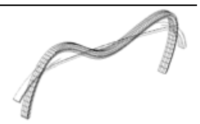


Fig. 10 Accelerometers of the collector

Table 2 Natural frequencies and mode shapes of the flexible body

Mode number	1	2	3	4	5
Mode shape					
Frequency (Hz)	60.57	111.68	141.90	150.07	240.59

pantograph may keep a steady contact with the catenary. However, when the operating speed is increased to 350 km/h, the contact forces between the pantograph and catenary vary more strongly than those at 300 km/h. The steady contact is lost, and the quality of current collection is worsened. Furthermore, the comparison with the calculated contact forces by means of the two pantograph models at the speed of 350 km/h is shown in Table 3. It can be seen that the contact forces obtained by means of the rigid-flexible hybrid model is basically consistent with the test results; however, for the rigid model, there is an obvious difference in the statistical results of the contact forces between tests and simulation. Thus, through the field test, it is proved that the rigid-flexible hybrid model, with consideration of the appearance characteristics, is more reasonable.

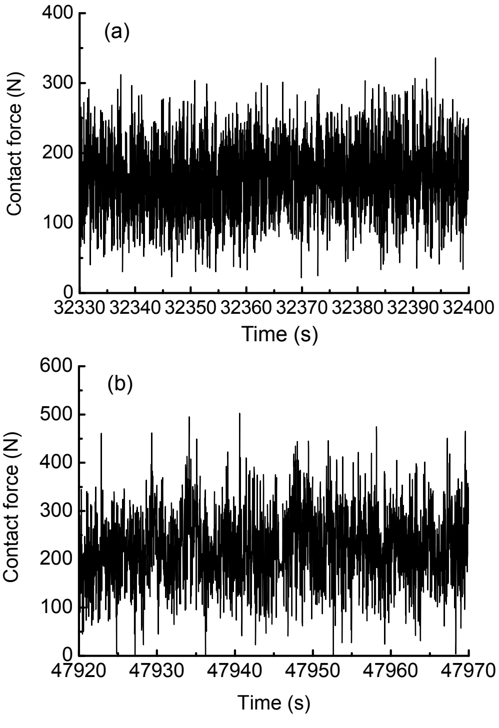


Fig. 11 Contact forces in the *Y* direction at the speeds of 300 km/h (a) and 350 km/h (b)

Table 3 Statistical results of the contact forces at the speed of 350 km/h

Method	Contact force (N)		
	Mean	Min	Max
Field test	223.87	0	502.11
Rigid-flexible hybrid model	192.40	0	534.95
Rigid model	174.80	23.81	405.32

5 Analysis of the influence of contact wire irregularity

Based on the modeling and simulation method mentioned above for the pantograph-catenary system, the influence of contact wire irregularity on the dynamic performance has been analyzed. The catenary model composed of ten spans and the rigid-flexible hybrid pantograph model are established. The contact wire irregularity is artificially considered as the height error at the location of the third dropper of the eighth span (about 370 m from the initial location), as shown in Fig. 12.

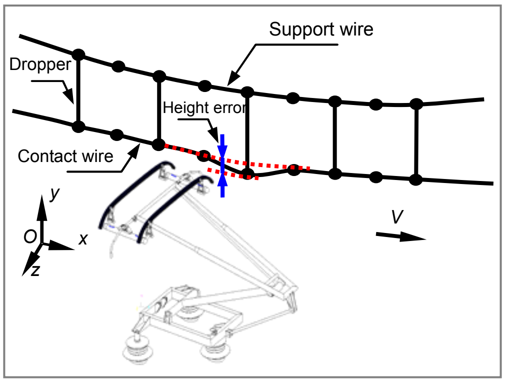


Fig. 12 Model considering the contact wire irregularity

Fig. 13 shows the acceleration of the front and rear collectors at the speed of 350 km/h, considering the height error of 20 mm. Compared to the results in Fig. 8 without consideration of height error, it can be found that when the pantograph passes through the eighth span of the catenary, there is an obvious difference in the acceleration. Especially, at the location of about 370 m, the acceleration in the *Y* direction is much larger than 40*g*, the acceleration in the *X* direction is up to 20*g*, and the acceleration in the *Z* direction is greatly increased.

By means of the rigid pantograph model, the influence of contact wire irregularity on the dynamic performance is similarly analyzed. Fig. 14 shows the acceleration of the front and rear collectors based on the rigid model at the speed of 350 km/h. However, it can be seen that, when the pantograph runs through the location of about 370 m, a significantly evident difference in the acceleration is not observed. The influence of contact wire irregularity on the dynamic performance cannot be truely represented, due to the

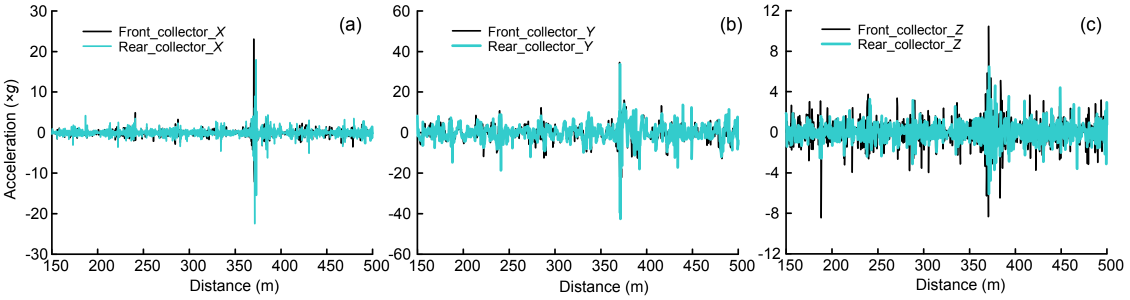


Fig. 13 Acceleration of the front and rear collectors based on the rigid-flexible hybrid model in (a) *X*, (b) *Y*, and (c) *Z* directions

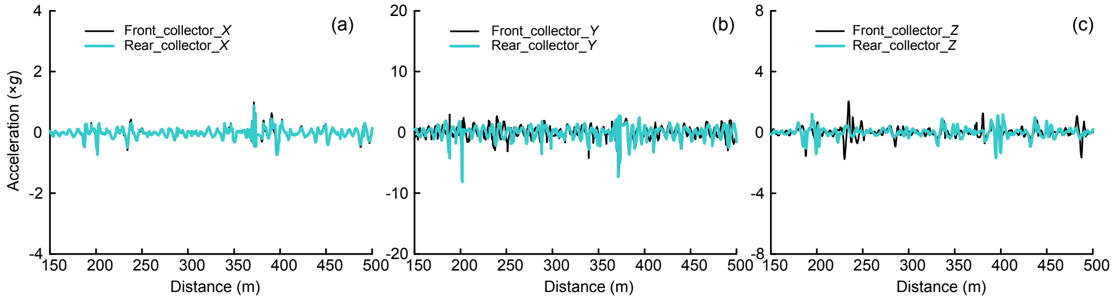


Fig. 14 Acceleration of the front and rear collectors based on the rigid model in (a) *X*, (b) *Y*, and (c) *Z* directions

lack of appearance characteristics. Thus, the appearance characteristics should be taken into consideration to reasonably evaluate the influence of contact wire irregularity on the dynamic performance, using the rigid-flexible hybrid pantograph model.

6 Analysis of the influence of double pantographs

By means of the similar modeling and simulation methods mentioned above, the influence of the vibration caused by the front pantograph on the rear pantograph has been analyzed. A pantograph-catenary system model with double pantographs was built, and the space between two pantographs is 200 m, as shown in Fig. 15.

Fig. 16 shows the contact forces in the *Y* direction at the speed of 350 km/h by means of two pantograph models. It can be observed that, when the rigid pantograph model is employed, the contact forces of the rear pantograph fluctuate slightly and are basically consistent with those of the front pantograph. However, for the rigid-flexible hybrid pantograph model, there is an obvious difference in

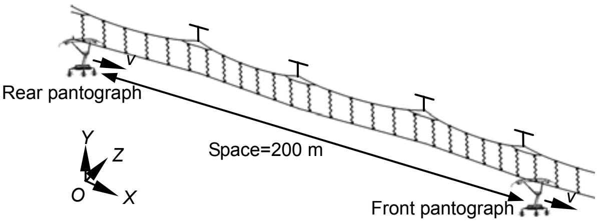


Fig. 15 Pantograph-catenary system model with double pantographs

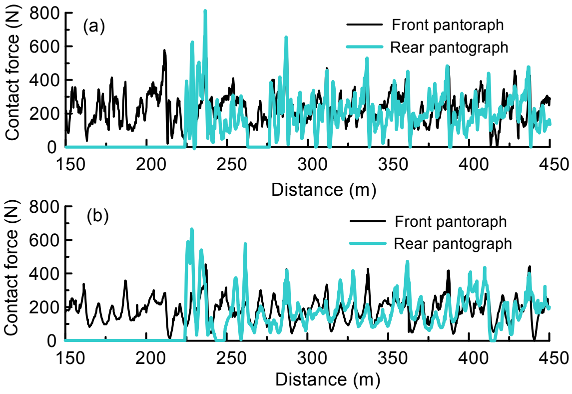


Fig. 16 Contact forces in the *Y* direction at the speed of 350 km/h based on the rigid-flexible hybrid model (a) and rigid model (b)

the contact forces between the rear pantograph and the front pantograph. The contact forces between the rear pantograph and the catenary vary more greatly, and the quality of current collection deteriorates. Thus, taking into consideration of the appearance characteristics plays an important role in the analysis of the influence of the vibration caused by the front pantograph on the rear pantograph for a pantograph-catenary system with double pantographs.

7 Conclusions

Based on the conventional pantograph-catenary system model, a rigid-flexible hybrid pantograph model has been put forward to include a consideration of the appearance characteristics of contact surfaces of the pantograph and the catenary. The dynamic behavior of the pantograph-catenary system in space has been investigated by means of two levels of modeling, with and without consideration of the appearance characteristics. Furthermore, the influence of the contact wire irregularity and the vibration caused by the front pantograph on the rear pantograph for a pantograph-catenary system with double pantographs has been analyzed. The results show that the appearance characteristics of contact surfaces play an important role in the analysis of dynamic performance. The obvious difference of the contact force, the maximum operating speed, the acceleration and the corresponding spectrum is observed. A consideration of the appearance characteristics is thus essential to reasonably evaluate the dynamic performance, using the rigid-flexible hybrid pantograph model.

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