Effects of Running Speed on Coupling between Pantograph of High-Speed Train and Tunnel Based on Aerodynamics and Multi-Body Dynamics Coupling

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Featured Application: A coupling method between aerodynamics and multi-body dynamics is proposed. The interaction between the pantograph and its surrounding air is achieved by using the method. Its applicability is wide, which is suitable for pantograph-catenary, car body, wind-shield of a high-speed train, as well as coupling analysis between aerodynamics and multi-body dynamics, aerodynamics and structural finite element in other fields.

Abstract: (1) Background: The ratio of railway tunnel to line is larger, which produces tunnel entrance and exit effect, aerodynamic resistance, and sudden pressure changes. When the train passes through the tunnels at high-speed, the interaction between the pantograph on it and its surrounding air intensifies and the coupling effects between the pantograph and tunnel become more significant; (2) Methods: A coupling method between aerodynamics and multi-body dynamics is proposed based on hybrid meshing and grid motion. The layered grid motion method is combined with the viscous mesh deformation method with swift, effective data exchange. The significant coupling effects between the pantograph and tunnel are revealed; (3) Results: The influence laws and evolution mechanism of running speed as it affects important service characteristics and behaviors of the pantograph are accurately quantified. Noteworthy factors include the temporal characteristics of panhead aerodynamic lift, the contact force between the pantograph and catenary, vertical displacement and acceleration of the contact strip, the phase diagram of the contact strip, and various frequency-domain characteristics. The action mechanism of running speed on the coupling effect between the pantograph and tunnel is comprehensively and accurately revealed by the proposed method; (4) Conclusions: The larger service characteristics amplitudes of the high-speed pantograph appear at low frequencies and are not multiple frequencies of the basic frequency. By comparisons, the coupling calculation results are closer to the test results than the non-coupling results regardless of the maximum, minimum, or mean.

Keywords: coupling effect between pantograph and tunnel; high-speed pantograph; high-speed train; running speed; coupled aerodynamics and multi-body dynamics; passing through a tunnel

1. Introduction

Rapid and extensive socio-economic development, climate change, and energy resource shortages have accelerated the speed and intensified the load characteristics of electrified railway transportation systems across the globe. Requirements for the relationship between the pantograph and catenary are growing increasingly strict. As train speed increases, the traveling wind forms a stronger air current. The rods of the pantograph are regarded as blunt bodies in the flow field. A complex flow field is formed by air flowing around the blunt bodies. Chinese train tunnels account for relatively large line proportions and thus particularly complex wave systems which subject the pantograph to a high-speed turbulence vortex.
As an articulated mechanical component, the pantograph relies on its own structure to maintain contact with the contact wire. During operation, its dynamic behavior is easily affected by excitation. There is intense interaction between the pantograph and its surrounding air. Aerodynamic lift is an important factor that determines the contact force between pantograph and catenary. If the contact force is too large or too small, there may be wear on the contact interface or the current collection stability may degrade, the pantograph and catenary can separate, and an accident may occur. Therefore, in the researches of high-speed pantographs, the interaction between the pantograph and its surrounding air should be considered.

Many researchers have investigated pantograph and catenary characteristics based on aerodynamics or structural dynamics. For example, Li et al. [1–3] studied the effect of strip spacing on the aerodynamics and noise characteristics of high-speed train pantographs. Sun et al. [4] investigated the influence of different pantograph parameters and high-speed train lengths on aerodynamic drag via delayed detached eddy simulation (DDES). Simarro et al. [5] explored interactions between eleven pantograph models and two models of overhead conductor rails. Song et al. [6] investigated the high-frequency behavior of pantograph-catenary interaction with cut-off frequencies up to 200 Hz. Yao et al. [7] analyzed the effects of icing on current collection quality between a pantograph and catenary via increased density, uniform load, and combinatorial material methods. Song et al. [8] investigated the effects of contact wire irregularity on pantograph-catenary interactions using the power spectral density function. Yao et al. [9] analyzed the effects of vehicle body vibration on a pantograph-catenary system or a complete track-vehicle-pantograph-catenary dynamics model. Kulkarni et al. [10] studied the differences in contact force between a pantograph and catenary with versus without the consideration of cross wind as a known load. Vesali et al. [11] indicated the broken dropper caused a significant sag in the sub-span and increased the static forces of the adjacent droppers. Song et al. [8] investigated the effect of geometrical distortion of the catenary with contact wire irregularity on the pantograph-catenary interaction. However, in all these studies a single subject was studied.

There have been many other valuable contributions to the literature. Wang et al. [12] proposed a simplified parametric model to describe the nonlinear displacement-dependent damping characteristics of a pantograph hydraulic damper. Vesali et al. [13] simulated pantograph and catenary dynamic interactions using a fast analytical approach across the entire catenary. Song et al. [14] studied pantograph-catenary dynamic performance considering the spatial vibration of the car body with ambient wind and strong airflow acting on the pantograph as external loads varying with time. Carnevale [15] first calculated aerodynamic lift, then estimated the influence of lift on the contact force between a pantograph and catenary. Considering track excitation, Pombo et al. [16] established a coupling model of a multi-rigid-body pantograph and flexible catenary in interactive mode. By using aerodynamic loads as known loads, Song et al. [17] studied the wind-induced vibration response of a catenary under different wind speeds and angles, and found that the contact force between the pantograph and catenary was affected by random winds. Li [18] applied aerodynamic loads to calculate a pantograph, then studied the coupling characteristics between the pantograph and catenary with or without tunnel effects; compared to that under open air, while passing through tunnel, the mean lift of the pantograph was found to increase by 13.48% as the maximum exit lift increased by 34.3%. Shi et al. [19] investigated the effects of parameters on three-dimensional (3D) pantograph-catenary dynamics under cross wind, which was taken as a known load. However, in all these studies aerodynamic loads were applied to the rods of the pantograph and the finite element grids of the catenary as external loads.

The influence of the aerodynamic forces and the interaction between the air and structure intensify as train speed increases. The interaction is a crucial prerequisite for the effective analysis of dynamic pantograph performance. Nakade [20] studied the lateral vibration of the high-speed train passing through tunnel by using the loose coupling between train and air. Li et al. [21] deployed an improved algorithm in MATLAB/Simulink...
under open air cross winds, where track irregularity was not imposed and the multi-body
dynamic calculation did not begin until the aerodynamic calculation converged. At this
time, the dynamic solution program was embedded in the fluid calculation to prevent
excessive information transmission and minimize wait time. Grid-updating was performed
by spring approximation method and grid remeshing alongside mesh reconstruction.
However, in the pantograph, relatively large rotations exist among the pantograph rods,
and large forward motions coexist with small attitude changes. A grid motion method
with stronger deformability is urgently needed. At present, there are few reports on the
coupled aerodynamics and dynamics of pantographs. Therefore, considering the coupling
between the pantograph and its surrounding air, using the combination of the layered grid
motion method and viscous mesh deformation method, the effects of running speed on
pantograph of high-speed trains passing through tunnels are studied.

2. Model Establishment

2.1. Multi-Body Dynamics Model

The pantograph consists of contact strips, supports and a bracket for the contact strip,
an upper arm, a lower arm, an upper pull rod, a lower pull rod, and a base frame. All
are regarded here as rigid bodies. The contact strips and its supports are fixed together.
The contact strip supports are connected to the bracket by two springs. The base frame is
fixed to ground. A spring lifting the pantograph is fixed on the base frame, and connects
the base frame and lower arm. The other connections are hinged joints. The pantograph
dynamics model established is shown in Figure 1.

![Figure 1. The pantograph dynamics model established.](image)

The multi-body dynamics model of the pantograph is shown in Figure 1. The vertical
dynamics equation for each rod of the pantograph is:

\[ m\ddot{u} + c\dot{u} + ku = F_n + F_A + F_{\text{link}} \]  

(1)

where \( m \) is the rod mass, \( c \) is the rod damper, \( k \) is the rod stiffness, \( u \) is the vertical
displacement of the rod, \( F_n \) is the contact force between the pantograph and catenary for
the contact strip, \( F_n = 0 \) for other rods, \( F_A \) is the aerodynamic force, and \( F_{\text{link}} \) is the action
force from the connecting rods.

The contact force between the pantograph and catenary is:

\[ F_n = \begin{cases} 
  k(x)r^m(x) + c(x)\text{step}(r - d) & r > 0 \\
  0 & r \leq 0
\end{cases} \]  

(2)

where \( x \) is the longitudinal displacement of the contact strip, \( x = vt \), \( v \) is running speed
of the train, and \( t \) is running time. The distance between contact strip and catenary
\( r = u_s - w_0 \), \( u_s \) is the vertical displacement of the contact strip, \( w_0 \) is the un-smoothness
of the catenary, \( w_0(t) = 0.0055|\sin(2\pi vt/9.5)|; \) \( d = 0.0005 \text{ m}; \) \( n(x) = 1; \) stiffness \( k(x) = 7000 - (7000 - 5200)|\sin(\pi vt/9.5)| \text{ N/m} \) and damper \( c(x) = k(x)/100. \)

2.2. Aerodynamic Model

Chinese standard single tunnel model is adopted. Its cross-sectional area is 70 m\(^2\). The geometric model of the tunnel and the aerodynamic model of the outflow field are shown in Figure 2. The aerodynamic models of the pantograph including the vehicle and locally enlarged pantograph are shown in Figure 3.

![Figure 2. The geometric model of the tunnel and the aerodynamic model of the outflow field.](image1)

![Figure 3. The aerodynamic models of the pantograph including the vehicle and locally enlarged pantograph.](image2)

3. Coupling between Aerodynamics and Structural Dynamics

3.1. Coupling Principle

Figure 4 shows “coupling method 1” between aerodynamics and structural dynamics. In the dynamic calculation, the aerodynamic forces and torques of the previous step are used to predict the structure displacements of the current step. Figure 5 shows “coupling method 2” between aerodynamics and structural dynamics. In the dynamic calculation, although the aerodynamic forces and torques of the current step are used, they are calculated regardless of the structure displacements. Figure 6 shows “coupling method 3” between aerodynamics and structural dynamics. Its performance is better than loose coupling, but the data between aerodynamics and structural dynamics are exchanged only once within one time step. To properly account for the interaction between the pantograph and its surrounding air without sacrificing the time accuracy or calculation stability over the entire system, when the train passes through the tunnel at high speed, it is necessary to efficiently couple aerodynamics and structural dynamics. Figure 7 shows the proposed “tight coupling method” between aerodynamics and structural dynamics. Figure 8 shows the flow chart of the proposed method.
In the method proposed, data are exchanged multiple times in a given time step until the predetermined accuracy or the predetermined times is reached. At that point, the data exchanged can be approximately considered as that of the current time step, so there is sufficient interaction between aerodynamics and structural dynamics. When the second-order time accuracy is used for both the fluid and structure, tight coupling brings the overall time accuracy of the fluid-structure coupling to the second order, which is one order higher than that of the traditional loose coupling method and allows the time step to be increased. This approach can be used not only to simulate the relative motion of each rod quickly and conveniently, but also does not require maintaining gaps between the rods, which is consistent with the actual motion of the pantograph.
3.2. Coupling Method

Meshing method and grid motion methods are incorporated into the proposed method. For a pantograph with a high-speed train, the flow field is divided into an inner field and outer field, and the hybrid meshing method is applied as shown in Figure 9. The prismatic boundary layers around the pantograph describe the motion of the boundary and include the surface viscous force. Due to the complex shape of the pantograph, a tetrahedral grid is used outside the boundary layers, which is easy to mesh. A hexahedral grid is used in the front and back of the inner field and the outer field, which is regular and easily controlled. Data are exchanged through interfaces between the tetrahedron and hexahedron and between the inner field and outer field. The grid type is matched with the grid motion method. The layered grid motion method is applied to the front and back of the inner field, which does not reduce the quality of the grid as the grid locations are updated. The viscous mesh deformation method is applied to the flow field around the pantograph and the car body in the middle of the inner field. A two-step interpolation algorithm ensures calculation accuracy when the control points are selected. The control points are selected initially to avoid to traverse the roof during computation for the sake of efficiency. The updating coordinates of the nodes surrounding the flow field are obtained only according to the displacement of the points caused by the change of motion posture. This is suitable for parallel processing during large-scale mesh deformation. The combination of the two methods completes both the overall forward motion of the large size and the small amplitude change of the pantograph posture while guaranteeing the quality of the grid updating.

Data exchange between aerodynamics and multi-body dynamics is also a key problem to be resolved in this process. It is realized by data file reading, which is simple, fast, and easy to implement. In multi-body dynamics, the aerodynamic load data file from aerodynamics is read by substitution of variables (subvars), then the calculated displacement is saved to the file. In aerodynamics, after reading the displacements of each rod, the six-degrees-of-freedom (6DOF) are converted to 3DOF, values are assigned to the control points on the roof, then the displacement of the fluid around the roof is calculated by radial basis function (RBF) before updating the node displacement and saving the calculated force and torque to a file.
3.3. Verification

The contact forces between pantograph and catenary at various train speeds were tested on Beijing-Shenyang line, and fitted. The fitted maximum, minimum and mean values at 100 m/s are shown in Table 1. The train was in a stable state during this test, that is, the processes of starting (acceleration) and braking (deceleration) were not included and the line was considered to be sufficiently long. The pantograph simulation was analyzed to verify the proposed coupling method under 360 km/h speed and open-air conditions while considering the influence of the car body on the flow field.

![Diagram](image)

**Figure 9.** Hybrid meshing and grid motion method.

|                  | Maximum  | Minimum | Mean   | Standard Deviation | Mean Error | Minimum Error |
|------------------|----------|---------|--------|--------------------|------------|---------------|
| Bidirectional coupling | 254.264  | 126.475 | 183.5598 | 25.55415           | -0.05%     | 3.92%         |
| Wind loads as known loads | 255.9772 | 129.5787 | 182.68699 | 25.02823          | -0.58%     | 6.47%         |
| No wind loads    | 216.15146 | 119.43517 | 162.41813 | 21.661             | 11.56%     | -11.56%       |
| Fitted results   | 242.667  | 121.704 | 183.65  | -                  | -          | -             |

The contact forces between the pantograph and catenary with coupled aerodynamics and multi-body dynamics (i.e., “bidirectional coupling”), aerodynamics loads being taken as known loads and aerodynamics loads being not considered are shown in Figure 10. The initial stage at which contact forces between the pantograph and catenary were calculated was removed to maintain accordance with the test results. The results are shown in Table 1; all proportions listed in the table are based on the fitted results.

As shown in Figure 10 and Table 1, in the three cases examined here, the change laws of the contact force between the pantograph and catenary are consistent; thus, only the aerodynamic loads change the values. When aerodynamics loads are not considered, the contact forces between the pantograph and catenary are much smaller compared to the other two cases. Aerodynamics loads on the pantograph appear to significantly affect current collection when the train runs at high speed. In the case of open air, compared with aerodynamic loads as known loads, the standard deviation of the contact force is larger when aerodynamics and multi-body dynamics are coupled. This indicates that contact force fluctuates substantially and the current collection quality is poor. The coupling calculation results are closer to the test results than the non-coupling results regardless of the maximum, minimum, or mean.
According to EN50318, the verification standard of the dynamic coupling simulation between the pantograph and catenary, the mean of contact force \( F_m \leq 0.00097 \times 360^2 + 70 = 195.712 \text{N} \) and the standard deviation of contact force \( \sigma_{\text{max}} < 0.3F_m = 0.3 \times 195.712 = 58.7136 \text{N} \). Accordingly, the fitted simulation results and experimental results satisfy the relevant requirements.

4. Results and Discussion

An aerodynamic model including a head car, middle car, tail car, and pantograph was established using the results given above. A multi-rigid body dynamics model of the pantograph was established accordingly. Considering the coupling of aerodynamics and multi-body dynamics, the dynamic response of the pantograph was calculated as the train passed through the tunnel at speeds of 280 km/h, 320 km/h, 360 km/h, 400 km/h and 420 km/h to evaluate the influence of running speed on the coupling effect of the pantograph and tunnel. In the analysis, multi rigid bodies are adopted in the dynamic calculation, and the sampling frequency is 1000 Hz. The time step is 0.001 s in the aerodynamic calculation. Due to no standard over 350 km/h, the action force of catenary on pantograph is supposed to still be according to Equation (2) at higher speed.

4.1. Time-Domain Characteristics

The proportions described in this section are based on the calculation results for the train passing through the tunnel at 280 km/h.

4.1.1. Aerodynamic Lift

The panhead of the pantograph is composed of contact strips, supports, and a bracket. Aerodynamic lift is an important factor affecting the contact force between the pantograph and catenary. Comparison curves of the aerodynamic lift of the panhead passing through tunnel at different speeds are shown in Figure 11.

As shown in Figure 11, aerodynamic lift values of the contact strip-support and bracket increase as running speed increases. At the same speed, the direction of aerodynamic lift of the contact strip-support is opposite to that of the bracket and the values are smaller than that of the bracket. At a certain distance from the entrance or the exit of the tunnel, fluctuations in panhead aerodynamic lift are relatively flat at different running speeds; the cases are open air, which validates the calculation results given above.

For the contact strip-support aerodynamic lift, the fluctuations and values are smaller at 280 km/h than at other speeds; the differences between at 320 km/h and at 360 km/h are relatively small as the differences between at 400 km/h and at 420 km/h are smaller; the fluctuations and values between 400 km/h and 420 km/h are larger than at other speeds. For the bracket aerodynamic lift, the fluctuations and values are smaller at 280 km/h; the differences at 320 km/h and between 360 km/h and 400 km/h are relatively small; the fluctuations and values are much larger at 420 km/h than that at other speeds.
The aerodynamic lift of the panhead is the sum of that of the contact strip-support and bracket, so it does not strictly increase with increase in running speed. For example, its values at 320 km/h are greater than that at 400 km/h at many positions, and its values at 360 km/h are greater than that at 420 km/h at many positions. This is also a main reason why the contact force does not simply increase with running speed in subsequent tests.

The statistical results of the aerodynamic lift of the panhead passing through tunnel at different speeds are listed in Table 2. The standard deviation and mean value of panhead aerodynamic lift are largest at 420 km/h at 43.33% and 156.72% higher compared to 280 km/h, respectively. No performance index of the aerodynamic lift of the panhead increases strictly with increase in speed. Compared with that at 360 km/h, at 400 km/h, the contact strip-support aerodynamic lift increases more in the positive direction than the negative while that of the bracket increases less in the negative direction. The resultant force of the two, namely, the aerodynamic lift of the panhead, decreases; this is also the main factor that affects the subsequent contact force between pantograph and catenary. Compared with that at other speeds, at 420 km/h, the contact strip-support aerodynamic lift increases more in the positive direction while that of the bracket increases more in the negative direction. So the resultant force of the two, namely, the aerodynamic lift of the panhead, is not always maximal.

Table 2. Statistical results of panhead aerodynamic lift passing through tunnel at different speeds.

|                          | Maximum (N) | Minimum (N) | Mean (N) | Standard Deviation (N) | Standard Deviation Difference | Mean Difference |
|--------------------------|-------------|-------------|----------|------------------------|-------------------------------|-----------------|
| Contact strip + support  | 44.2242     | −6.24535    | 21.39542 | 6.60428                | -                             | -               |
| Bracket 280              | −21.8436    | −21.8436    | −21.8436 | 8.59548                | -                             | -               |
| Panhead-280              | 7.87        | −60.6928    | −21.39542| 12.08294               | -                             | -               |
| Contact strip + support  | 60.4527     | −26.5484    | 33.04816 | 7.99576                | 21.07%                        | 54.46%          |
| Bracket-320              | −23.7578    | −100.617    | −34.97125| 12.85294               | -                             | -               |
| Panhead-320              | −1.0637     | −93.9362    | −34.97125| 14.18627               | 17.41%                        | 75.29%          |
| Contact strip + support  | 67.7074     | −25.5528    | 33.75717 | 9.68588                | 46.66%                        | 57.78%          |
| Bracket-360              | −43.6264    | −111.306    | −68.01941| 13.63352               | 58.61%                        | 64.51%          |
| Panhead-360              | 2.8301      | −110.0323   | −47.25456| 13.16243               | 8.93%                         | 136.85%         |
| Contact strip + support  | 92.6164     | 13.3197     | 52.56508 | 10.52163               | 37.23%                        | 145.68%         |
| Bracket-400              | −49.2168    | −116.733    | −81.84115| 12.75881               | 48.44%                        | 97.79%          |
Table 2. Cont.

|                | Maximum (N) | Minimum (N) | Mean (N) | Standard Deviation (N) | Standard Deviation Difference | Mean Difference |
|----------------|-------------|-------------|----------|-------------------------|------------------------------|-----------------|
| Panhead-400    | 7.1519      | −76.2796    | −29.27607| 12.59056                | 4.20%                        | 46.74%          |
| Contact strip +support-420 | 102.565 | 10.0293 | 58.27943 | 12.97636                | 96.48%                       | 172.39%         |
| Bracket-420    | −50.0785    | −152.777    | −109.49819| 16.78258                | 95.25%                       | 164.83%         |
| Panhead-420    | 18.2573     | −96.3173    | −51.21876| 17.33287                | 43.33%                       | 156.72%         |

4.1.2. Contact Force between Pantograph and Catenary

Figure 12 and Table 3 show comparison curves of the contact force between the pantograph and catenary and their statistical results, respectively, as the train passes through the tunnel at different speeds. The maximum contact force appears at 360 km/h and minimum contact force at 400 km/h appears. This disparity is obvious especially near the tunnel exit, e.g., where the contact force is 272.87 N near 627.4 m at 360 km/h and is 92.72 N near 636 m at 400 km/h. The differences among different speeds inside the tunnel are larger than those outside the tunnel, which indicates that the tunnel effect is significant and consistent with the objective fact.

Figure 12. Comparison curves of contact force between pantograph and catenary passing through tunnel at different speeds.

Table 3. Statistical results of contact force between pantograph and catenary passing through tunnel at different speeds.

|                | Maximum (N) | Minimum (N) | Mean (N) | Standard Deviation (N) | Standard Deviation Difference | Mean Difference |
|----------------|-------------|-------------|----------|-------------------------|------------------------------|-----------------|
| 280 km/h       | 259.666     | 117.859     | 178.09312| 26.84069                | -                            | -               |
| 320 km/h       | 264.356     | 122.616     | 184.08905| 26.12482                | −2.67%                       | 3.37%           |
| 360 km/h       | 293.885     | 127.550     | 196.55243| 28.08317                | 4.63%                        | 10.36%          |
| 400 km/h       | 290.781     | 92.366      | 173.37707| 29.66925                | 10.54%                       | −2.65%          |
| 420 km/h       | 292.640     | 110.554     | 186.40273| 29.76878                | 10.91%                       | 4.67%           |

Compared with that at 280 km/h, the maximum, minimum, and mean values of the contact force between the pantograph and catenary at 320 km/h increase and the
standard deviation slightly decreases at a ratio of 2.67%. These changes are beneficial in terms of the stable contact between the pantograph and catenary. Compared with that at 360 km/h, the maximum, minimum, and mean values of the contact force between the pantograph and catenary decrease at 400 km/h and 420 km/h, but the standard deviations increase. Taking 280 km/h as the benchmark, the ratios are 5.91% and 6.28%, respectively; the minimum values decrease to greater extent at ratios of 29.85% and 13.32%, respectively. These changes are detrimental to the stable contact between the pantograph and catenary and in practice could easily separate them. This is the fundamental reason for restricting the speed of the train. When the speed increases from 320 km/h to 360 km/h, the standard deviation increases rapidly from 26.12482 N to 28.08317 N at a ratio of 7.5%. According to the corresponding aerodynamic lift and contact force values, the aerodynamic lift critically affects the contact force between the pantograph and catenary, but it is not the only influencing factor.

4.1.3. Vertical Displacement of Contact Strip

Comparison curves of the vertical displacement of the contact strip as the train passes through the tunnel at different speeds, and the corresponding statistical results, are shown in Figure 13 and Table 4, respectively. The vertical displacement of the contact strip increases sequentially from 280 km/h to 320 km/h to 360 km/h. The differences among different speeds inside the tunnel are greater than those outside the tunnel, which indicates that the tunnel effect is significant as is consistent with the objective fact. Compared with that at 280 km/h, at 320 km/h, the maximum and minimum vertical displacements of the contact strip decrease while the mean value and the standard deviation increase at ratios of 14.65% and 12.2%, respectively. Compared with that at 360 km/h, at 400 km/h, the maximum, minimum, and mean values of the vertical displacement of the contact strip decrease while the standard deviation increases. Taking 280 km/h as the benchmark, the mean value decreases by 36.36% and the standard deviation increases by 21.54%. Although the amplitude decreases, the fluctuation is relatively large and in practice would readily cause separation between the pantograph and catenary. Compared with that at 400 km/h, at 420 km/h, the maximum value and standard deviation of the contact strip vertical displacement increase to lesser extent as the minimum and mean values increase to greater extent.

Figure 13. Comparison curves of vertical displacement of the contact strip passing through tunnel at different speeds.
Table 4. Statistical results of vertical displacement of the contact strip passing through tunnel at different speeds.

| Speed (km/h) | Maximum (m) | Minimum (m) | Mean (m) | Standard Deviation (m) | Standard Deviation Difference | Mean Difference |
|--------------|-------------|-------------|----------|------------------------|------------------------------|----------------|
| 280          | 0.01982     | 0.00383     | 0.01092  | 0.00246                | -                            | -              |
| 320          | 0.01947     | 0.00282     | 0.01252  | 0.00276                | 12.20%                       | 14.65%         |
| 360          | 0.0265      | 0.00469     | 0.01468  | 0.00331                | 34.55%                       | 34.43%         |
| 400          | 0.02477     | 0.00208     | 0.01071  | 0.00384                | 56.10%                       | -1.92%         |
| 420          | 0.02498     | 0.00398     | 0.01293  | 0.00387                | 57.32%                       | -18.41%        |

4.1.4. Vertical Acceleration of Contact Strip

Comparison curves of the vertical acceleration of the contact strip as the train passes through the tunnel at different speeds, and the corresponding statistical results, are shown in Figure 14 and Table 5, respectively. The vertical acceleration of the contact strip at 280 km/h and 320 km/h is generally smaller than it is at 360 km/h, 400 km/h, or 420 km/h. The differences among different speeds inside the tunnel are greater than those outside the tunnel, which is again consistent with the objective reality of tunnel effect. Compared with that at 280 km/h, at 320 km/h, the minimum value and the standard deviation of the contact strip vertical acceleration increase at ratios of 58.55% and 7.25%, respectively. Compared with that at 360 km/h, at 400 km/h, the maximum, minimum, and standard deviation of the contact strip vertical acceleration decrease. Taking 280 km/h as the benchmark, the corresponding ratios are 16.50%, 93.04%, and 13.73%, respectively. The maximum, minimum, and standard deviation of the contact strip vertical acceleration are the largest at 360 km/h compared to those at other speeds.

Figure 14. Comparison curves of vertical acceleration of the contact strip passing through tunnel at different speeds.

4.2. Frequency-Domain Characteristics

Power spectral density curves of the contact force between the pantograph and catenary, the vertical displacement of the contact strip, and the vertical acceleration of the contact strip as the train passes through the tunnel at different speeds are shown in Figures 15–17, respectively. Running speed does not appear to change the laws of the vibration characteristics. The basic frequency of the contact force between the pantograph and catenary is 2.11 Hz and the amplitudes are larger at the basic frequency versus multiple frequencies of 3 times, 4 times, 6 times, 10 times, 11 times, 15 times, 20 times, 25 times, 30 times,
or 35 times, where higher frequencies appear. The line test data after 20 Hz filtering is insufficient for the high-speed pantograph. Valleys appear immediately after the peaks at many frequencies (e.g., 5 times, 10 times, 15 times). At running speeds of 360 km/h, 400 km/h and 420 km/h, larger amplitudes appear at low frequencies (e.g., around 1.75 Hz, 8.8 Hz, 12.26 Hz) and are not multiple frequencies of the basic frequency.

Table 5. Statistical results of vertical acceleration of the contact strip passing through tunnel at different speeds.

| Speed  | Maximum (m/s²) | Minimum (m/s²) | Mean (m/s²) | Standard Deviation (m/s²) | Standard Deviation Difference | Minimum Difference |
|--------|----------------|----------------|-------------|---------------------------|-------------------------------|-------------------|
| 280 km/h | 10.6145        | −7.42214       | −0.2054     | 2.51441                   | -                             | -                 |
| 320 km/h | 10.243         | −11.7679       | 0.01795     | 2.6966                    | 7.25%                         | 58.55%            |
| 360 km/h | 12.1125        | −15.0945       | 0.0103      | 3.10342                   | 23.43%                        | 103.37%           |
| 400 km/h | 10.3612        | −8.02659       | 0.04289     | 2.75807                   | 9.69%                         | 8.14%             |
| 420 km/h | 10.0105        | −8.3469        | 0.02085     | 2.9433                    | 17.06%                        | 12.46%            |

Figure 15. Power spectral density curves of contact force between pantograph and catenary passing through tunnel at different speeds.

The basic frequency of contact strip vertical displacement is 2.11 Hz and the amplitudes are larger at the basic frequency and multiple frequencies of two times, three times, and five times. The main frequencies are mainly concentrated at frequencies below 25 Hz. At running speeds of 360 km/h, 400 km/h, and 420 km/h, larger amplitudes appear at lower frequencies (e.g., around 1.75 Hz) and are not multiple frequencies of the basic frequency. Above 250 Hz, the vertical displacement amplitude of the contact strip at 420 km/h drops rapidly and there is a large oscillation approaching 500 Hz.

The basic frequency of contact strip vertical acceleration is 2.11 Hz, and the amplitudes are larger at the basic frequency and multiple frequencies of two times, three times, five times, six times, 10 times, and 15 times. At running speeds of 360 km/h, 400 km/h, and 420 km/h, larger amplitudes appear at low frequencies (e.g., around 1.75 Hz, 4.98 Hz, 5.6 Hz, 7.1 Hz, and 8.8 Hz) and are not multiple frequencies of the basic frequency. The main frequencies are not obvious over 50 Hz. Until reaching 500 Hz, the amplitudes do not approach very small values.
4.3. Phase Diagram of Contact Strip

Figure 18 shows a phase diagram of the contact strip passing through tunnel at different speeds. Attractors are basically formed at the left and right ends with signs of entering into a chaotic state. Compared with speeds of 280 km/h or 320 km/h, the phase diagram shifts to the right at 360 km/h. Compared with that at speeds of 360 km/h or 420 km/h, the phase diagram shifts leftward at 400 km/h; at 400 km/h and 420 km/h, open loops are formed at the left end. There are more unsmooth positions at 420 km/h than at other speeds and more chaos in the middle of the phase diagram.
5. Conclusions

A new coupling method between aerodynamics and multi-body dynamics was established in this study to evaluate the significant interaction between a pantograph and its surrounding air as a high-speed train passes a tunnel. The coupling effect between the pantograph and tunnel was investigated accordingly. The main conclusions can be summarized as follows.

- The aerodynamic lift of the panhead does not strictly increase with the increase in running speed. However, the standard deviation and the mean value are largest at 420 km/h than at other speeds—43.33% and 156.72% higher than those at 280 km/h, respectively.
- Compared with that at 360 km/h, at 400 km/h or 420 km/h, with 280 km/h as the benchmark, the contact strip standard deviations increase by 5.91% and 6.28%, respectively, while the contact strip minimum values decrease by 29.85% and 13.32%, respectively. These changes are detrimental to the stable contact between the pantograph and catenary.
- Compared with that at 360 km/h, at 400 km/h, taking 280 km/h as the benchmark, the mean value of contact strip vertical displacement decreases by 36.36% whereas the standard deviation increases by 21.54%.
- At 360 km/h, the maximum, minimum, and standard deviation of contact strip vertical acceleration are larger than those at other speeds.
- At running speeds of 360 km/h, 400 km/h and 420 km/h, there are larger amplitudes of the contact force between the pantograph and catenary. The larger amplitudes of vertical displacement and vertical acceleration of the contact strip appear at low frequencies (e.g., around 1.75 Hz) and are not multiple frequencies of the basic frequency.

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