Numerical Analysis of the Aerodynamic Characteristics of the Open Line Intersection of Fast Freight Train with the Speed of 160 km/h

Yue Zhang1+, Dongping Wang2
1College of Locomotive and Engineering, Dalian Jiaotong University, Dalian, Liaoning, 116028, China
2School of Mechanical Engineering, Dalian Jiaotong University, Dalian, Liaoning, 116028, China
*Corresponding author’s e-mail: wdp@djtu.edn.cn

Abstract. With the increase of the speed of fast freight train, the aerodynamic effect of freight train in open-line intersection is more obvious. However, at present, there are many domestic researches on the aerodynamic characteristics of high-speed train open-line intersection, and almost no researches on fast freight train. Therefore, it is of great significance to study the aerodynamic characteristics of open line intersection of fast freight train in order to improve the safe operation of freight train in China. Based on the theory of computational fluid dynamics and finite volume method, uses FLUENT software to numerically calculate the three-dimensional, unsteady, compressible and turbulent flow fields in open line intersection of fast freight train at different speeds. The calculations results indicate that: when two freight trains meet, the amplitude of the pressure wave at the intersection side is the largest and the closer to the train bottom, the greater the amplitude of the pressure wave. The pressure amplitude of the bottom measuring point is 34.09% higher than that of the top measuring point. When two cars intersect at the same speed, the higher the speed, the greater the pressure amplitude and the pressure amplitude is proportional to the square of the speed. The fitting formula is: $\Delta P = cV^2$; When two trains intersect at different speeds, the impact on freight train with lower speed is greater than higher one.

1. Introduction
Railway is the lifeblood of China's national economy, and railway transportation is an important way of cargo transportation [1] [2]. China's railway ranks the first annual delivery of goods in the world. It shows that to better develop railway freight logistics must be intensified to develop fast freight transport [3]. The reason is that fast freight train is a modern advanced mode of transportation, with transportation safety, simple procedures, less cargo loss and other advantages of [4]. Due to the angular shape of fast freight train, the gap at the compartment is large, the aerodynamic characteristics are complex, and the speed has been greatly improved than the traditional freight train, the aerodynamic effect is more obvious when freight trains meet on open lines, so the study of the aerodynamic characteristics of the intersection of fast freight train is of great significance to improve the safe operation of freight trains in China.
The study of train aerodynamics started late relatively recently compared with some developed countries. In the early 1990s, China began to study train aerodynamics through the line real vehicle test and model simulation test. In 2008, Li et al. [5] aerodynamic characteristics of 160km/h fast container flat truck and EMU in open line and tunnel rendezvous are numerically calculated. It is concluded that the pressure amplitude in the middle of the vehicle container when the two vehicles intersect in the tunnel is 3.46 times that when the open line intersects. In 2010, Qi [6] adopted CFD finite volume method and mobile grid technology on the surface pressure and pneumatic force of high-speed train during open line crossing to obtain the distribution law of pressure wave peak along the train and the same between the pneumatic force of each carriage. Zhou et al. [7] applied the hydrodynamic software Fluent to simulate the aerodynamic characteristics of 140km/h per speed trains and open speed trains of 250km/h per hour in 2017. By analyzing the calculation results, the general speed trains were more affected than the pneumatic pressure of the EMU during the intersection of the open line. In a word, the aerodynamic characteristics of the train through experiment and simulation has already had the mature research results, but the aerodynamic characteristics of the fast freight train has not further studies. Therefore, this paper carries out research on fast freight trains.

This paper takes the fast freight train with 160km/h as the research object, carries on the numerical simulation of the fast freight train during the open line intersection, analyzes the aerodynamic characteristics of the fast freight train during the open-line intersection, and provides technical reference for the newly developed fast freight train.

2. Overview of the calculation model

2.1 Algorithm principle
This paper analyses the aerodynamic characteristics of the open line intersection of 160 km/h per hour by using the computational fluid dynamics software Fluent, based on the three-dimensional, unsteady, compressible N-S equation. The numerical method adopts the finite volume method, the convection term adopts the second-order upwind style, and the viscosity term adopts the second-order central difference scheme.

2.2 Model establishment
The three-dimensional geometric model of the fast freight train is very complicated, and some structures have little influence on the calculation results of the flow field such as: car lights, pantograph, and bogies. In the process of open line intersection, the changes in aerodynamic characteristics generated by the intersection pressure wave are mainly affected by the head and tail cars. In addition, the outer geometry of the middle carriage of the fast freight train is the same, and the aerodynamic force is almost the same. Therefore, the three-dimensional geometric model of the fast freight train is simplified and unnecessary structures are deleted. Therefore, the fast freight train is simplified to a model of a locomotive plus three cars as shown in Figure 1. The size of the car body are 104.64m * 3.11m * 3.94m.

![Figure 1. Simplified fast freight train calculation model](image)

2.3 Arrangement of monitoring points
As shown in Figure 2, 11 monitoring points are arranged at the front, rear, intersection side, and
non-intersection side of the freight train to monitor the pressure change law of the train during the open line intersection.

2.4 Computing area and grid division
Theoretically, the calculation model of the flow field outside the open line intersection should be infinite. In fact, when the calculation area is large enough, increasing the calculation area will not have much effect on the accuracy of the calculation results. Therefore, in order to ensure that the selection of the calculation area does not affect the accuracy of the calculation results, the nose tips of the two vehicles are set to be 90m apart at the initial time to ensure that they do not interfere with each other before the rendezvous. The final size of the flow field outside the open line will be 490m in length, 160m in width and 60m in height. In this paper, the moving grid method is used to realize the train intersection process. Due to the irregular surface of the train, the surface of the train and a small part of its surrounding area are divided into unstructured grids. Smaller hexahedral grids are used in front of and behind the train to realize the moving grid. The grid is updated, the outer flow field uses a larger size hexahedral grid, and the initial grid unit is about 13.05 million.

3. Calculation result verification and analysis

3.1 Pneumatic characteristics analysis of 160 km/h express

3.1.1 Calculation result validation
The calculation formula of the theoretical value of the nose tip pressure of the train is:
\[ P = \frac{1}{2} \rho v^2 \]  

(1)

P is the pressure at the front end of the fast freight train; \( \rho \) is air density; \( v \) is fast freight train operating speed.

According to this formula, when 160km/h fast freight train is running on the open line, theoretically the pressure \( P \) at the front of the train should be 1207.46Pa. Table 1 shows the compares on between the experimental data and theoretical values.

| Table 1. Comparison of train Pressure and theoretical Pressure |
|---------------------------------------------------------------|
| Pressure (Pa) | 0.2s  | 0.3s  | 0.4s  | 0.5s  | 0.6s  | average value |
|----------------|-------|-------|-------|-------|-------|---------------|
| Difference from theoretical Value (Pa) | 29.33 | 39.61 | 35.43 | 36.45 | 38.73 | 35.91         |
| Error: (%)     | 2.4   | 3.28  | 2.93  | 3.02  | 3.21  | 2.97          |

By comparing the data in the table, it can be seen that the difference between the nasal tip pressure and the theoretical nasal tip pressure at each time is about 3\%, and the error is very small, so the calculation method in this paper is reliable.

3.1.2 Pressure wave characteristics of 160km/h fast freight train open line intersection

To analyze the variation law of pressure wave of freight train rendezvous, the pressure distribution of freight train body should be understood first.

Figure 4 shows the pressure distribution on the surface of the train at 0.5s. It can be seen that when the train is running on the open line without rendezvous, the pressure at the head is the highest, about 1091.6Pa. The body is in a negative pressure state, about -115.79Pa, which is close to one atmospheric pressure, while the shoulder adjacent to the head is in a negative pressure area, with a negative pressure value of -1485.72Pa.

Figure 5 shows the pressure curve at monitoring point 2, which is the intersection pressure wave.
Figure 5. Intersection pressure wave at monitoring point 2 in the rendezvous side of 160km/h fast freight train

When the freight train is running on the open line, the pressure fluctuation trend is relatively stable. At 1.15s, when one train head and shoulder skips another body, the pressure rises and falls instantaneously, with the positive peak reaching 140.34Pa, the negative peak reaching -271.35Pa and the pressure wave reaching about 400Pa. At 2.3s, when the rear of the freight train passes, the pressure produces sudden falls and rises, but the amplitude is relatively small. The positive peak value reaches 36.89Pa and the pressure wave amplitude is about 100Pa. The pressure trend tends to stabilize after the rendezvous.

Take one of the fast freight trains and set four central monitoring points on its roof, intersection side, bottom and non-intersection side, and they are in the same cross section. By comparing the amplitude changes of pressure waves at these four centers, it is analyzed which surface of the freight train is most affected by the intersection pressure waves during the open line intersection.

Figure 6. Amplitude comparison of pressure waves on various surfaces of the body

It can be seen from Figure 6 that the pressure wave amplitude on the intersection side is the largest, about 350Pa. Therefore, the following analysis takes the intersection side of freight trains as example.

3.1.3 Comparison of the amplitude of intersection pressure wave at each measuring point in the longitudinal direction of freight train

Monitoring points 6, 3 and 7 from top to bottom are set at the same plumb-vertical line and different height in the middle of the vehicle. By comparing pressure wave curves at different monitoring points, the similarities and differences of intersection pressure waves at each measuring point in body longitudinal direction are analyzed.
Table 2. Car body longitudinal pressure wave amplitude comparison

| Monitoring point 6 | Monitoring point 3 | Monitoring point 7 |
|-------------------|--------------------|--------------------|
| Positive peak (Pa) | 115.96             | 155.14             | 180.62             |
| negative peak (Pa) | -191.50            | -215.25            | -227.63            |
| Pressure wave amplitude (Pa) | 307.46 | 370.39 | 408.25 |
| Increase rate (%) | 1                  | 20.47              | 34.09              |

From the data in Table 2, it can be seen that the peak value of pressure wave increases gradually from top to bottom at three monitoring points along the longitudinal direction of the train. Compared with the upper monitoring point 6, the pressure wave amplitudes increase by 20.47% and 34.09% at the middle monitoring point 3 and the lower monitoring point 7 respectively. That is, the closer to the vehicle bottom, the greater the pressure wave amplitudes.

3.2 In the case of same velocity rendezvous, comparison and analysis of aerodynamic characteristics of fast freight trains at different speeds

3.2.1 Comparison of amplitude of pressure wave at different running speeds.
Table 3 shows the comparison of amplitude of pressure wave of intersection at the monitoring point 3 at different running speeds. From the data in Table 3, it can be seen that when the freight train operates at 120 km/h, 140 km/h and 160 km/h speeds respectively, the pressure wave amplitudes at 3 monitoring points are 231.92Pa, 307.90Pa, 370.39Pa, 140 km/h and 160 km/h speed, respectively, increased by 33.34% and 59.71% compared with 120 km/h train. That is, the higher the speed of the fast freight train, the greater amplitude of the pressure wave of the fast freight train. The calculation results provide aerodynamic loads for subsequent calculation of train strength fatigue.

Table 3. Comparison of intersection pressure amplitude of different speeds

| speed(km/h) | Middle carriage 1 | Middle intersection side of the monitoring point 3 |
|-------------|-------------------|-----------------------------------------------|
|             | 120               | 140               | 160               |
| Positive-wave amplitude (Pa) | 110.24 | 135.67 | 155.14 |
| Negative wave amplitude (Pa) | -121.68 | -172.23 | -215.25 |
| Pressure wave amplitude (Pa) | 231.92 | 307.90 | 370.39 |
| increasing rate (%) | 1                 | 33.34             | 59.71             |

3.2.2 Relationship between pressure wave amplitude and vehicle speed at same speed meeting condition
The amplitude of intersection pressure wave at monitoring points 4 and monitoring 5 will be fitted with the speed change. The fitting curve of the relationship between pressure wave amplitude and vehicle speed between measuring point 4 and measuring point 5 is listed in Table 4.
Table 4. fits the relationship between fast freight train pressure amplitude and vehicle speed during open line intersection

| Monitoring point | Pressure wave amplitude fitting formula | correlation coefficient: R-square |
|------------------|----------------------------------------|----------------------------------|
| 4                | $\Delta P = 0.008085V^{2.125}$         | 0.9929                           |
| 5                | $\Delta P = 0.01505V^{1.997}$          | 0.9956                           |

The fitting formula in Table 4 shows that the power function is used to fit the relationship between pressure wave amplitude and vehicle speed, and the correlation coefficient (R-square) is greater than 0.99. In addition, in the formula, the power of the speed of the train is about 2, and the fitting coefficient is positive.

Thus, the general formula of the relationship between freight train pressure amplitude and vehicle speed is obtained:

$$\Delta P = cV^2$$

(2)

$\Delta P$ is the pressure amplitude of freight train; c is the coefficient of pressure amplitude and vehicle speed; V is the operating speed of freight train. Because the pressure amplitude is different at each monitoring point, the fitting coefficient c is different.

3.3 Analysis of the aerodynamic characteristics of the open line intersection of the unequal fast freight train

The two fast freight trains are travelling at speeds of 100km/h (Vehicle 1) and 140km/h (Vehicle 2) respectively. At the beginning, the two freight trains are 90m apart. After 1.35 seconds, the two freight trains begin to meet, at 2.9s, the head and tail of the two cars meet, and at 4.48s, the two freight trains are separated at the end.

3.3.1 Analysis of aerodynamic characteristics of different speeds rendezvous of fast freight trains

By comparing the pressure wave characteristic curves of of two unequal speed fast freight trains, the similarities and differences of the pressure wave changes at the intersection side are analyzed.

![Figure 7. Pressure wave contrast at monitoring point 3 of 100km/h-140km/h fast freight train (Pa)](image)

It can be seen from Figure 7, when the two cars meet, the pressure wave amplitude generated on the body surface of car 1 is higher than that generated on the body surface of car 2, which is about 300Pa for car 1 and 150Pa for car 2.
Table 5. Comparison of intersection pressure amplitude values of 100km / h-140km / h express freight cars

|                      | Middle carriag 1 central monitoring point 3 |
|----------------------|--------------------------------------------|
|                      | Vehicle 1 (100km/h)                         |
|                      | Vehicle 2 (140km/h)                         |
| Positive-wave amplitude (Pa) | 125.44                                   |
|                       | 65.85                                      |
| Negative-wave amplitude (Pa)    | -180.52                                   |
|                       | -93.47                                     |
| Full-wave amplitude values (Pa)   | 305.96                                     |
|                       | 159.32                                     |
| increasing rate (%)        | 47.9                                       |
|                       | 1                                          |

Taking monitoring point 3 as an example, it can be seen from table 5 that the sudden pressure change of car 1 is obviously larger than that of car 2. And from the full wave amplitude, it can be seen that the full wave amplitude of car 1 is 305.9Pa, and the full wave amplitude of car 2 is 159.32Pa. The intersection pressure amplitude of car 1 is 47.9% higher than that of car 2. This is because the higher speed of car 2 causes higher pressure around the body and acts on the surface of car 1, so the pressure amplitude of car 1 is significantly higher than that of car 2.

By comparing and analyzing the amplitudes of pressure wave at 3 points of monitoring points on the intersection side of two vehicles, it can be seen that when two different speed freight trains meet, the amplitudes of positive and negative pressure wave and full wave at the intersection of low speed freight trains are greater than that of high speed trains. When two trains meet at different speeds, the low speed freight trains will be more affected by the intersection than that of high speed freight trains.

4. Conclusion
This paper takes the newly developed 160km/h fast freight train in China as the research object, simulates the process of fast freight train meeting on open lines at different speeds, researches and analyses the aerodynamic characteristics of fast freight train under different conditions, and the calculation results provide technical reference for the development of new fast freight train.

The main conclusions of the paper are as follows:

- At same speed rendezvous condition, the pressure wave on the side of the intersection is the highest. On the same vertical line, the amplitude of pressure wave increases as the vehicle gets closer to the bottom, the greater the pressure wave amplitude at the bottom measuring point is 34.09% higher than that at the top measuring point.
- At same speed rendezvous condition, the higher the speed, the greater the amplitude of the intersection pressure wave; The amplitude of pressure wave at the monitoring point on middle carriage 1 in 160km/h fast freight train is 59.71% higher than that at 120km/h.
- At same speed rendezvous condition, the amplitude of the rendezvous pressure wave is proportional to the square of the speed. The fitting formula is $\Delta P = cV^2$. The amplitude of pressure wave at each monitoring point is different, and the fitting coefficient $c$ is different.
- At different speed rendezvous condition, the amplitude of pressure wave of the freight train with lower speed is higher than that of the freight train with higher speed. The body pressure amplitude of the fast freight train running at 100km/h is 47.9% higher than that of the train running at 140km/h. That is, lower speed freight trains are more affected by intersection pressure waves than higher speed freight trains.

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