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Formation mechanism of aerodynamic drag of high-speed train and some reduction measures

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Abstract: Aerodynamic drag is proportional to the square of speed. With the increase of the speed of train, aerodynamic drag plays an important role for high-speed train. Thus, the reduction of aerodynamic drag and energy consumption of high-speed train is one of the essential issues for the development of the desirable train system. Aerodynamic drag on the traveling train is divided into pressure drag and friction one. Pressure drag of train is the force caused by the pressure distribution on the train along the reverse running direction. Friction drag of train is the sum of shear stress, which is the reverse direction of train running direction. In order to reduce the aerodynamic drag, adopting streamline shape of train is the most effective measure. The velocity of the train is related to its length and shape. The outer wind shields can reduce train's air drag by about 15%. At the same time, the train with bottom cover can reduce the air drag by about 50%, compared with the train without bottom plate or skirt structure.

Key words: aerodynamics of train; high speed train; aerodynamic drag; drag reduction

1 Introduction

Train drag is divided into the aerodynamic drag, the sliding force between the wheel and rails, and the friction force caused by the pantograph system [1−2]. According to the results of several full scale tests, for the bluff shape train running at a speed of 120 km/h, the aerodynamic drag is about 40% of the total drag, which climbs up to 75% when the speed reaches 160 km/h. For the train with the length of streamline shape more than 5 m (train body mount system and a skirt system to smooth the structures underneath the train), the aerodynamic drag is about 75% of the total drag when the speed of train is 200 km/h. For the train with the length of streamline shape up to 10 m, the aerodynamic drag is about 75% of the total drag when the speed is 300 km/h [3]. Therefore, aerodynamic drag plays an important role for the high-speed train. In order to reduce the train drag and the energy consumption, detailed understanding on the aerodynamic drag and its precise evaluation are of great importance [4−6].

Wind tunnel experiment, numerical simulation, and theory analysis were adopted to study the aerodynamic drag of train in this work.

Wind tunnel test was made at the 8 m×6 m wind tunnel of China Aerodynamic Research and Development Center. Model train is marshaled with three cars, i.e. leading car, middle car, and tail car. In order to obtain the car's air resistance under different conditions, a six-component external gauge, which was installed in the car body and fixed on the turntable support pole, was used to measure the aerodynamic forces and moments on the train. The standard error of air resistance coefficient under the small-angle condition of the leading car, middle car and tail car is 0.002. Repeatability precision can meet the test requirements of the train test.

The flow structure around the train was studied by CFD (computational fluid dynamics) simulation method. Three-dimensional Reynolds-averaged Navier-Stokes equations, combined with the RNG (random number generator) k—ε turbulence model, were solved on a multi-block structured grid using finite volume technique. The pressure—velocity fields were coupled by the SIMPLEC (semi-implicit method for pressure-linked equations) algorithm.

2 Formation mechanism of train aerodynamic drag

In the open air condition, the aerodynamic drag of the train is the sum of the tangential forces (skin friction drag) and the normal forces (pressure drag), both of which are parallel to the opposition direction of vehicle's velocity vector. The pressure drag comes from the

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integral of the skin pressure of the train.

The direction of drag is along the positive direction of x axis, as shown in Fig.1. The friction drag can be obtained by the integral of the tangential forces. The drag formula for the train in the open can be expressed as

$$F_x=F_{px}+F_{\tau x} \quad (1)$$

where F_x is the aerodynamic drag, F_{px} is the pressure drag, and $F_{\tau x}$ is the friction drag.

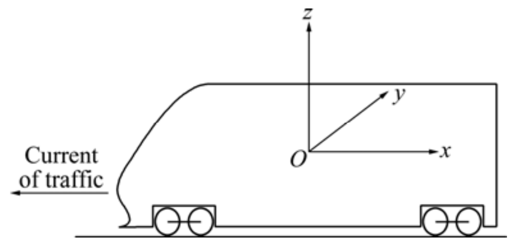

Fig.1 Coordinate definition of train

Therefore, the aerodynamic drag on the traveling train is divided into pressure drag and friction drag. The formation mechanism of the aerodynamic drag will be discussed in the following part.

2.1 Composition of aerodynamic drag

The train drag is divided into the aerodynamic drag, the sliding force between the wheel and rails, and the friction force caused by the pantograph system. The total drag of train was composed of the sum of each carriage drag.

2.1.1 Relationship between aerodynamic drag and total drag of train

In the open air condition without any cross-wind effect, the total drag on the traveling train can be expressed by Davis experience formula [7]:

$$F_R=a+bv_t+cv_t^2 \quad (2)$$

where F_R is the total drag, a, b and c are the constants determined by the experiment, and v_t is the train velocity relative to the ground.

In general, in Eqn.(2), the total drag can be divided into two contributions: $a+bv_t$ is the mechanical drag which includes the sliding drag between rails and train wheels, and the rotating drag of the wheels; and cv_t^2 is the aerodynamic drag. So the aerodynamic drag can be expressed as

$$F_x=cv_t^2 \quad (3)$$

The coefficient of aerodynamic drag (C_x) can be described as

$$C_x=\frac{F_x}{qS_x} \quad (4)$$

where q is the dynamic pressure, and S_x is the cross-sectional area of train.

Therefore, the aerodynamic drag can be written as

$$F_x=qS_xC_x=\frac{1}{2}\rho S_xC_xv_t^2 \quad (5)$$

Compared with Eqns.(3) and (4), the coefficient (c) can be expressed as

$$c=\frac{1}{2}\rho S_xC_x$$

The aerodynamic drag is proportional to the square of speed of the strain, while the mechanical drag is proportional to the speed of the train. Compared with the mechanical drag, the portion of the aerodynamic drag becomes larger as the train speed increases.

2.1.2 Relationship between aerodynamic drag and each carriage drag of train

The aerodynamic drag of the train is composed of the drag of each carriage. The drag force can be written as

$$F_x=F_{xt}+\sum_{i=1}^{n}F_{xz}(i)+F_{xw} \quad (6)$$

where F_x is the total aerodynamic drag; F_{xt} is the drag of the leading car or locomotive; F_{xw} is the drag of the tail car; $F_{xz}(i)$ is the friction along the train, which includes the bogies, wheels, interference, and bottom structure of the train; and n is the number of middle carriages.

The coefficient (C_x) can be written as

$$C_x=C_{xt}+\sum_{1}^{n}C_{xz}(i)+C_{xw} \quad (7)$$

where C_{xt} is the drag coefficient of the leading car or locomotive; C_{xw} is the drag of the tail car; and $C_{xz}(i)$ is the friction coefficient along the train, respectively.

2.2 Formation mechanism of pressure drag

When the train runs at high speed, there will be a stagnation region with high pressure on the windward face of the train nose, and the flow speed will decrease. At the same time, the flow moves at high velocity along the tail car and the pressure decreases. The pressure drag stems from the pressures due to the abrupt change in the cross-sectional area of the train.

The pressure drag can be obtained by integrating along the whole car

$$F_{px}=\oint_{S_F}p_{bx}\mathrm{d}S_F \quad (8)$$

where p_{bx} is the skin pressure of the train along x axis, and S_F is the area of the train wall surface.

For the high-speed train, the pressure drag comes from the pressure due to the shape of fore-body and after-body of the train, the connecting parts between trains, the train wall surfaces, the pantograph system, the bogie, and underneath structure of the train.

The mechanism of forming pressure drag is given as follows: there is a stagnation region in the leading car nose and air guide sleeve. The flow velocity of air is almost equal to zero, when the pressure reaches the largest in these regions. The flow around the pantograph system and bogie can also cause the increase of the skin pressure and the decrease of speed. And there are large pressure changes in the connecting parts between trains. When the air flow along the train reaches the end car, the flow speed will increase and the pressure will decrease. Air flow separation occurs at the nose of the end car. This results in a great change in the pressure distribution at the end car, leading to the pressure drag.

2.3 Formation mechanism of friction drag

Due to the viscosity of the air, boundary layer occurs on the wall of train when the air flows along the train surface [8−9]. The height of boundary layer is equal to zero at the nose of the train, and becomes larger at the leeward. The speed of flow increases from zero to running velocity of the train along the boundary layer normal direction. The tangential forces are caused by the difference of the velocity in the boundary layer normal direction, which is shear stress on the train surface.

Friction drag of the train is the sum of shear stress, which is in the reverse direction of the train running direction. Friction drag can be obtained by integrating along the whole train:

$$F_{\tau x} = \oint_{S_F} \tau_{ix} \mathrm{d}S_F \tag{9}$$

where τ_{ix} is the shear stress on the train along x axis.

The shear stress is proportional to the viscosity of the air (μ) and the velocity gradient. The velocity is related to the height of boundary layer. However, the boundary is closely related to the shape of the train, the smooth of the train wall, the running velocity and the ambient surround. Therefore, the friction drag is relevant to the shape of the train, the smooth of train surface, the running velocity and the ambient surround.

3 Measures of reduction of aerodynamic drag

When the train runs at high speed, the flow around the train will be formed due to the viscosity of air. It is the synthesized influence of the separation and interaction around the flow of the train. The drag of train is decided by the flow structure around the train. As far as the flow discipline of train concerned, different shapes of the train have different flow structures, while the similar train shape has the same flow structure. Therefore, it is important to study the flow structure discipline deeply to find the best streamline shape of the train and the measures of reduction of train drag [10−11].

Train-induced flows include the flow around fore-body and after-body of the train, the flow underneath the train, and the flow around bottom and side of train and the connecting parts.

3.1 Desirable flow structure around end car

The shape of the fore-body and after-body of the train can significantly influence the aerodynamic characteristics [12−14]. Fig.2 shows the pressure distribution of for-body and after-body of the train. When air flows around the fore-body of bluff train, the flow velocity becomes slower, and the pressure becomes larger. From Fig.2, the whole fore-body of train is almost in positive pressure region except the top of the fore-body. This is because the bluff body generates the biggest stagnation region on the fore-body of the train. However, for the flow around the streamline shape of the train, the velocity of flow becomes faster and skin pressure becomes smaller. The negative pressure acts on the large part region of the fore-body of the train except

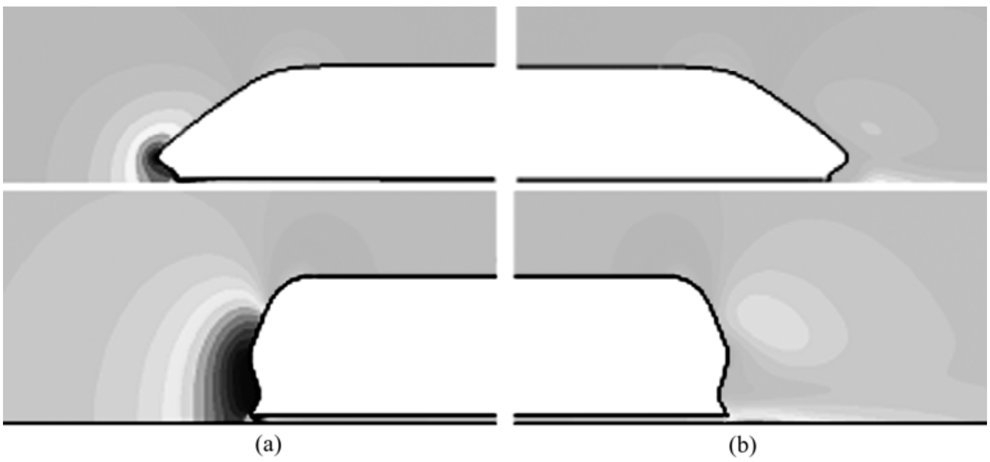

Fig.2 Pressure contours of fore-body and after-body of train: (a) Fore-body of train; (b) After-body of train

that the pressure is almost equal to zero in the region of fore-window. The positive pressure acts on the nose of train and air guide sleeve. The same conclusions could be drawn from Ref.[15].

The wake structure of train is schematically shown in Fig.3. From Fig.3, for the blunt body of the train, there are two asymmetry vortices in the wake of train, which makes the flow velocity become faster. However, there is not vortex in the wake of streamlined after-body of the train. Therefore, the flow velocity is slower and the skin pressure is larger compared with those of the bluff body train. From Fig.2, there is large positive pressure in the wake of bluff body.

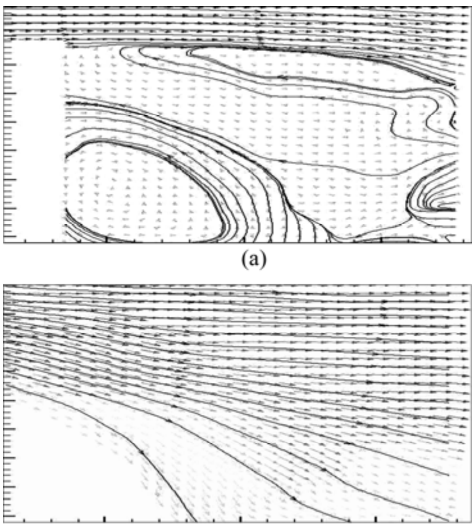

Fig.3 Flow structures in wake of after-body of different shape train: (a) Wake of bluff body train; (b) Wake of streamline shape head train

According to the above analysis, some conclusions can be obtained. For the bluff body train, there is larger pressure drag due to the greater pressure in the fore-body and less pressure in the after-body of the train. However, for the streamline shape of the train, pressure drag is small due to lower pressure in the fore-body and higher pressure in the after-body of the train. Therefore, adopting streamline shape for fore-body and after-body of the train can reduce the pressure drag significantly.

As far as the effect on the aerodynamic drag of the streamline shape concerned, it has been studied in detail in Ref.[15]. The conductor parameters and control parameters of streamline shape of the train have a great influence on the aerodynamic drag of the train. The control parameters include the length, the height and the width of the streamline shape. The conductor parameters include the maximum control conductor along the longitudinal direction, the horizontal direction, and the cross-section of the train body section.

The research results show that the longer the streamline shape of train, the lower the pressure drag of leading car and tail car. With the increase of the length of the streamline shape, the aerodynamic drag coefficient decreases linearly. The relationship between the length of the streamline shape and the drag coefficient can be expressed as

$$C_{xt}=|a_{RTL}|-|b_{RTL}|L_d \tag{10}$$

The drag coefficient of the tail car is proportional to the exponential of the streamline shape reciprocal.

$$C_{xw}=|a_{RWL}|\exp(\frac{|b_{RWL}|}{L_d})+c_{RWL} \tag{11}$$

where L_d is the length of the streamline shape, a_{RTL} and b_{RTL} are the coefficients related to the drag of the leading car and the length of streamline shape, and a_{RWL}, b_{RWL} and c_{RWL} are the coefficients which are related to the drag of the tail car and the length of the streamline shape.

According to the research results, in order to design the shape of the train, the desirable length values of streamline shape head can be obtained at different running velocities. Table 1 lists the suggested length values of streamline shape head.

Table 1 Suggested length of streamline shape head at different velocities

Velocity/(km·h^{-1})	200	250	300	＞350
Length of streamline shape/m	4	＞5	＞6	＞9

The research results suggest the following conclusions. (1) Under the condition without cross wind, air drag of the leading car is the smallest with ellipsoid shaped head and is the largest with flat-wide shaped head, while the air drag of tail car is the smallest with flat-shuttle shaped head and is the largest with convex-wide shaped head. Because of the interaction between the train speed and the cross wind speed that affect the air drag clearly, the air drag of ellipsoid shaped head will exceed that of the flat-wide shaped head under crosswind condition. That is to say, the air resistance of flat-wide shaped head with crosswind is smaller, while the ellipsoid shaped head is larger. (2) Air resistance of the front car will increase appreciably, and air resistance of end car will decrease slightly, if the control curve in longitude symmetric plane changes from plump sidewall to flat. (3) When the maximum horizontal control curve is in rectangular shape, the drag of the leading car and the tail car will reach the largest. If the slope angle is enlarged by 4°, the drag of leading car decreases by 3% and the drag of the tail car decreases by 4%.

3.2 Flow structure's change in connection place of adjacent cars

For the train with inner wind shield but without outer wind shield at the connecting parts between adjacent cars, there are a series of grooves at the connecting positions. On the windward side of the connecting positions, air flow directly scours the end wall's surface of grooves, which results in the free stagnation flow. The air flow moves slowly, which induces much higher positive pressure. On the leeward side of the connecting positions, air flow separates at the grooves, which makes the flow field more complicated. At the same time, irregular vortex is formed, which makes most of the end wall surface negative pressure zones and locally positive zones. Without outer wind shield, the superposition of the positive pressure of the windward and the negative pressure of the leeward side will cause much higher air pressure difference.

When the outer wind shield is set between adjacent cars, it will extend the outer surface of the car body's connection by flexible wind shield, which makes the distance between two cars body's outer surfaces shorter. It is the best to narrow to less than 200 mm. During the train's running, the space formed by the inner wind shield, outer wind shield and car body works as a static pressure chamber. The flow speed inside static pressure chamber is quite low, on which the pressure distribution is much even and stable. Full scale test and wind tunnel test results show that: under the same train speed, no mater windward side or leeward side, the pressure on the end wall's surface is positive. And the measured pressure differences between different measure points are very small, which means that the pressure distribution on the end wall is stable. Therefore, when the outer wind shield is designed, the positive pressure of the windward offsets the positive pressure of the leeward side, which makes the pressure difference much smaller.

Adopting the outer wind shield will change the flow structure of the connecting position, which reduces air resistance with dramatic effects. According to wind tunnel test results, the outer wind shields can lower train's air resistance by 15% or so.

3.3 Improvement of flow structure of car bottom and other position

Generally, there are not bottom covers and skirt plates at the bottom of medium and the low speed rolling stocks. That is, all the equipment at the bottom of the train is exposed. It is normal for high-speed train setting bottom cover at the bottom of the vehicle. That is, all the equipment at the bottom of car between the two bogies and both sides of the two bogies will be covered, so that the bottom of the car except bogies has smooth surface. For simplicity, apron plates are usually set at the bottom of the high speed train. The exterior siding that seems as skirt piece is installed under the side beam of the frame. The bottom equipment has been blocked between the two skirt pieces.

There is a variety of hanging equipment at the bottom of the train. Due to an effect of the rough surface of the uneven equipment on air flow, flow field at the bottom of train is so complicated and flow around is so disturbed. There are a series of local small-scale positive and negative pressure zones along the longitudinal direction of the train, which can induce the friction resistance and increase the air resistance. When the bottom cover is set at the bottom of the train, the outer surface at the bottom is smooth. It is very difficult to form a vortex, thus the disturbance to air flow from the bottom equipment is reduced. The aerodynamic frictional drag and pressure drag of the train are greatly reduced. When the apron plate of the train is set at the bottom of the train, the side outer surface is smooth and the vortex formed between the two bottom apron plates will change the air flow without bottom cover and apron plate at the train bottom, which is an effective way to reduce air resistance of train.

The results of wind tunnel test show that the train with bottom cover can reduce the air resistance by about 50% compared with the train without bottom plate or apron plate. The air resistance is reduced by about 30% on the head car, about 50% on the middle car and about 25% on the end car. The car body with skirt plate at the bottom can reduce the air resistance by about 25%. The air resistance is reduced by about 28% on the head car, about 25% on the middle car, and about 18% on the end car.

At the same time, the whole train set should adopt the same cross-section shape to reduce the air pressure drag. Train's surface should be smooth to reduce train's air frictional drag. The top of the train except pantograph position, should be smooth as much as possible. Dome can be designed for the pantograph base to make the air flow transit more smoothly. Drum-shaped wall should be designed on the side wall to reduce the additional air drag.

4 Conclusions

(1) Aerodynamic drag is proportional to the square of speed. With the train speeds up, the aerodynamic drag is the main part of the total drag.

(2) Aerodynamic drag is composed of the pressure drag and friction drag. The pressure drag of the train is the force caused by the pressure distributed on the train along the reverse running direction. Friction drag of the train is the sum of shear stress, which is the reverse direction of train running direction.

(3) It is necessary to design the flow structure of the fore-body and after-body of the train. It is an effective measure to decrease the aerodynamic drag by adopting

streamline shape head. The velocity of the train is related to the length and shape of the train.

(4) It is a good measure to reduce the aerodynamic drag by changing the connecting part of the train. The outer wind shields can lower train's air drag by about 15%.

(5) Smoothing the underneath structures of the train by using the body mount system or the skirt system can largely reduce the aerodynamic drag. The train with bottom cover can reduce the air resistance by about 50%, compared with the train without bottom plate or apron plate.

References

[1] RAGHUNATHAN R S, KIM H D, SETOGUCHI T. Aerodynamics of high-speed railway train [J]. Progress in Aerospace Sciences, 2002, 38(6/7): 469−514.

[2] SCHETZ J A. Aerodynamics of high-speed trains [J]. Annual Review of Fluid Mechanics, 2001, 33: 371−414.

[3] WATKINS S, SAUNDERS J W, KUMAR H, Aerodynamic drag reduction of goods trains [J]. Journal of Wind Engineering and Industrial Aerodynamics, 1992, 40(2): 147−178.

[4] BARCALA M A, MESEGUER J. An experimental study of the influence of parapets on the aerodynamic loads under cross wind on a two-dimensional model of a railway vehicle on a bridge [J]. Journal of Rail and Rapid Transit, 2007, 221(4): 487−494.

[5] SUZUKI M, TANEMOTO K, MAEDA T. Aerodynamic characteristics of train/vehicles under cross winds[J]. Journal of Wind Engineering and Industrial Aerodynamics, 2003, 91(1/2): 209−218.

[6] TIAN Hong-qi. Study evolvement of train aerodynamics in China[J]. Journal of Traffic and Transportation Engineering, 2006, 6(1): 1−9. (in Chinese)

[7] OZAWA S. Aerodynamic forces on train [M]. Tokyo: The Japan Society of Mechanical Engineers, 1990.

[8] SCHLICHTING H, GERSTEN K. Boundary layer theory[M]. Berlin: Springer-Verlag, 2000.

[9] STEPHEN B P. Turbulent flows [M]. Cambridge: Cambridge University Press, 2000.

[10] TIAN Hong-qi, ZHOU Dan, XU Ping. Aerodynamic performance and streamlined head shape of train [J]. China Railway Science, 2006, 27(3): 47−55. (in Chinese)

[11] LAI Y C, BARKAN C P L, ONAL H. Optimizing the aerodynamic efficiency of intermodal freight trains[J]. Transportation Research Part E: Logistics and Transportation Review, 2008, 44: 820−834.

[12] GUILMINEAU E. Computational study of flow around a simplified car body [J]. Journal of Wind Engineering and Industrial Aerodynamics, 2008, 96(6/7): 1207−1217.

[13] GROSCHE F R, MEIER G E A. Research at DLR Göttingen on bluff body aerodynamics, drag reduction by wake ventilation and active flow control [J]. Journal of Wind Engineering and Industrial Aerodynamics, 2001, 89(14/15): 1201−1218.

[14] COGOTTI A. Evolution of performance of an automotive wind tunnel [J]. Journal of Wind Engineering and Industrial Aerodynamics, 2008, 96(6/7): 667−700.

[15] TIAN Hong-qi. Train aerodynamics [M]. Beijing: China Railway Publishing House, 2007. (in Chinese)

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