Study of the Change of the Shaft Shape on the Influence to Aerodynamics Effect of the High-Speed Metro Tunnel

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ABSTRACT
When a metro train passes through the shaft, it will lead to severe pressure fluctuations on surfaces of tunnel and train due to the sudden change of tunnel cross section. Based on the three-dimensional, compressible and unsteady N-S equation method, this paper simulates aerodynamic problems caused by trains when they pass through the airshafts at the speed of 140 km/h by the means of constructing four middle shaft models, one is the real shaft, the other three are the simplifications. Time delays generated on trains’ surfaces after trains pass through shafts in the three simplifications’ model, but on tunnels’ surfaces from entering portals for the different corridor sizes. The tendency of max pressure, min pressure and pressure amplitude at trains’ and tunnels’ surfaces is consistent in four kinds of models. But the different area of shafts’ corridor sizes cause the most used model gets the maximum pressure amplitude, the real model gets the minimum pressure amplitude, and the two simplifications’ are the middle.

Keywords: metro train; shape; shaft; pressure wave; numerical simulation.

1 INTRODUCTION

Compared with the railway tunnel, the metro tunnel has not only increased the
length, enlarges blockage ratio, but also has a large number of relief ducts and complicated structures such as middle shafts. When the metro train passes through the middle shaft and other structures, the pressure on the surfaces of tunnels and the trains will change dramatically due to the change of the cross section of the tunnel [4]. Therefore, many scholars have studied the middle shaft and carried out a large number of numerical simulations.


Li ZhiWei[3] used 3-D, compressible and unsteady N-S equations to simulate the transient pressure of a high-speed train passes through a tunnel with a shaft. Che LunFei[4] uses dynamic grid technology and 3-D numerical simulation method to simulate pressure fluctuation problems when a metro train passes through middle shaft, however, the maximum speed simulated is 100 km/h, and direct simulated train started in the tunnel, which is not conformity with the practical situation of metro operation. The influence of shafts exist or not on the aerodynamic effects of high-speed train is studied by Liu Peisi[10]. ZhaoYu[5] studied the aerodynamic effects of different high-speed railway shafts’ shapes, however, the shafts’ shapes can only be divided into circle and rectangle, don’t simulate the real shape of shaft, and the connection of shaft and tunnel is only one form. Moreover, the high-speed railway tunnel is short and the shafts can relieve the pressure fluctuation in the tunnel, but shafts can increase the pressure fluctuation in the metro tunnel.

This paper uses numerical simulation method of 3-D, compressible and unsteady N-S equations and sliding grid technique to simulate the aerodynamic effect of metro trains passing through the tunnel portals and middle shafts at the speed of 140 km/h, using ICEM to establish 3-D models of four shafts with different shapes and connections by the means of constructing hexahedral grids and using FLUENT for simulation. Compared with the simulation results of their respective tunnel’s and train’s surfaces’ pressure changes, we can conclude if the change of the shapes of the middle shafts can influence the aerodynamic effect of the metro tunnel.
2 COMPUTATIONAL CONDITION

2.1 Computational domain and boundary condition

In this paper, the sliding grid method is used to simulate metro trains passing through the tunnel shafts, and the computational domain shows in Fig. 1. In order to simulate the real situation of trains entrance the tunnel portal, set the sizes of the tunnel entrance field \( 120 \text{ m} \times 60 \text{ m} \times 339.5 \text{ m} \) to ensure the flow around the train full developed, and the distance between train head and tunnel entrance is 50 m, the distance between train trail and air flow domain entrance is 150 m.

![Figure 1. Sizes and boundary of the computational domain.](image)

To simulate the metro’s environment of the super-long tunnel, the paper sets the boundary condition of the tunnel outlet as the pressure - far field (it means no reflected pressure waves return), furthermore, to avoid outlet boundary influenced by wake flow, the length of flow field should guarantee the wake flow full developed. To avoid the blocking effect of flow field \(^2\), set tunnel length behind the platform 1000 m. In order to maintain the accuracy of the calculation results, platform model is seated in the middle of the tunnel. The sizes of the shield shaft before and after the platform is \( 13 \text{ m} \times 13 \text{ m} \times 7 \text{ m} \), and sizes of the platform is \( 340 \text{ m} \times 5 \text{ m} \times 8 \text{ m} \). In order to simulate the effect of shaft on the surface of the tunnel and the train, the paper sets up the shaft model \(^3\) of the rectangular cross section. Among them, the sizes of the shaft wall is \( 4 \text{ m} \times 4 \text{ m} \times 50 \text{ m} \), and the outlet domain of the shaft is \( 50 \text{ m} \times 50 \text{ m} \times 30 \text{ m} \).

A moving boundary condition is given to the surface of the train: the velocity component of X direction is equal to the train velocity \( V \), and the velocity component of Y, Z is 0. The boundary conditions of domain’s two sides, top surface, bottom surface and tunnel wall are given without slippage, and an interface is defined between these two domains. At the same time, in order to get the flow field full developed, the inlet boundary condition is set as the relative pressure \( P_{\text{out}} = 0 \).
2.2 Model and grid

2.2.1 MODELS AND ARRANGEMENT OF MEASUREING POINTS

In this paper, a kind of A-type vehicle model of 6-car marshalling is adopted. The paper simplifications the shape of the metro train\textsuperscript{11}, ignoring the influence of the bogie and the pantograph\textsuperscript{11}. Fig.2 shows the model of the A-type train of 6-car marshalling. In this case, the length of the train model is 3.8 m, and the width is 3m. The overall train length ($L_{tr}$) can be calculated as: $L_{tr} = (23.7 \text{ m}) \times 2 + (22.1 \text{ m}) \times N + (0.74 \text{ m}) \times (N + 1) = 139.5 \text{ m}$, and N is the number of middle Cars (four here). And the section area of the train is 9.785m$^2$.

According to the condition of the existing metro tunnel whose rated speed is 120km/h, the tunnel model section is established as shown in Fig.3. The cross area is 26m$^2$, and the blocking ratio is 0.376. In order to make the data analysis simple and effective, measure pressure points of the tunnel and train model is carried out. There are 17 measure pressure points on the surface of the metro train, and the layout shows in Fig. 2. The arrangement of measuring points on the surface of tunnel shows in Fig. 3 where total of 42 points are arranged.

To research whether shapes change of shafts has influence to tunnel aerodynamics effect, the paper establishes four shaft models, whose sizes of the shaft wall (ventilation outlet above) and sizes of shafts export domain are equal, but changes corridor sizes underside ventilation. Fig.4 shows the sizes of 4 models,
one of them is a real shaft model, the other one is the most widely used model, the
rest two are simplified shaft models based on the real shaft model.

Figure 4. Shapes of 4 middle shafts: (a) real model; (b) most used model; (c) simplified model 1;
(d) simplified model 2. (unit: m).

2.2.2 GRID GENERATION SCHEME

ICEM software is used to divide the entire computing region by hexahedral
mesh in this paper. Because the metro tunnel blocking ratio is large, fluctuation of
pressure waves caused by boundary layer is small, so the boundary layer is not carried out in the numerical calculation. Around C-grid and O-grid is used in the tunnel’s flow field. In order to build a wall without
thickness, the surfaces of the train and tunnel are mapped to the faces of Blocks in
the mesh. Some specific grid division is exhibited in Fig.5.
Figure 5. Grids of metro trains and tunnel: (a) Some c-grids, 0-grids around the train; (b) 3-D view of the train and the tunnel (unit: m); (c) grid of real shaft model; (d) grid of most used shaft model; (e) grid of simplified shaft model 1; (f) grid of simplified shaft model 2 (unit: m).

Because the shaft is perpendicular to the tunnel, like a T-shape or a three-branch pipe. So we can generate a three-way grid by the means of generating a three-way o-block. And grids of four middle shafts are exhibited in Fig.5.

### 3 RESULTS AND ANALYSIS

Before trains pass through shafts, the maximum pressure is at the nose of the train as shown in Fig.6. The increase of air pressure in front of the train is not significant for the shaft’s relief effect. After trains pass through shafts, the pressure in front of trains increases rapidly, and the negative pressure behind the train decrease rapidly. And from the pressure contours, we find the pressure of four models is almost the same except the corridors themselves when pass through shafts.
Figure 6. Pressure distribution in the tunnel around shaft: (a), (b), (c), (d) show pressure distributions before trains pass through shafts; (e), (f), (g), (h) show pressure distributions after trains pass through shafts. (unit: Pa).

The pressure waves of the surfaces on the train and tunnel can be obtained by the Fluent numerical calculation. Fig. 7 shows the pressure waves of the middle measure point of the fifth carriage in four different shafts models. From Fig. 7, we can get the information that the pressure is almost the same before the trains enter the shaft, from then the pressure get small differences. The pressure of the real model is the minimum, the most used model is the maximum, and the most used models and two simplified models have time delays from the train passed through the shaft for the different corridor sizes. And Fig. 8 also shows nearly the same conclusion except the pressure waves get different at the time when train enters the portal.

Figure 7. Curves of pressure distribution for measuring point on surface of middle train: (a) real model; (b) most used model; (c) simplified model 1; (d) simplified model 2. (unit: Pa).

Figure 8. Curves of pressure distribution for measuring point on surface of tunnel near shaft (22th measure point): (a) real model; (b) most used model; (c) simplified model 1; (d) simplified model 2. (unit: Pa)
Figure 9. Relationship between pressure amplitude along the surface of train and surface of tunnel when pass through shafts: (a), (b), (c), (d) show pressure amplitude along the surface of train (line 1); (e), (f), (g), (h) show pressure amplitude along the surface of tunnel (line 2). (unit: Pa).

Figure 10. Relationship between max pressure along the surface of train and surface of tunnel when pass through shafts: (a), (b), (c), (d) show pressure amplitude along the surface of train (line 1); (e), (f), (g), (h) show pressure amplitude along the surface of tunnel (line 2). (unit: Pa).

Figure 11. Relationship between min pressure along the surface of train and surface of tunnel when pass through shafts: (a), (b), (c), (d) show pressure amplitude along the surface of train (line 1); (e), (f), (g), (h) show pressure amplitude along the surface of tunnel (line 2). (unit: Pa).

From Fig. 9~Fig. 11, we can get the conclusion that the tendency of max pressure, min pressure and pressure amplitude at trains’ and tunnels’ surfaces is consistent in four models. And the real model’s pressure amplitude is the minimum, the most used model gets the maximum, two simplifications’ are the
middle. And these results are generated for the different area of the corridor sizes. Pressure amplitude decline from head car to the 5th car, but on tail car rises because of the instable wake waves. Pressure amplitude near the shaft is the smallest, and pressure increases extend from shafts on both sides. The most difference of pressure amplitude in line 1 is 2.28% between the real and the most used model. The most difference of pressure amplitude in line 2 is 14.18% between the real and the most used model.

4 CONCLUSION

This paper mainly studies the change of pressure variation of the tunnel and train’s surfaces by the means of trains passing through the tunnel from portals at the constant velocity with different shapes of shafts, and the following conclusions can be obtained from numerical simulation:

(1) The pressure of four models is almost the same except the corridors themselves when trains pass through shafts.

(2) The pressure of the surface of trains is almost the same before the train enters the shaft, from then the pressure get small differences but small differences generated from the start for surfaces’ pressure on tunnel, and the most used model has a time delays.

(3) The tendency of max pressure, min pressure and pressure amplitude at trains’ and tunnels’ surfaces is consistent in four kinds of models. The most used model gets the maximum, two simplifications’ are the middle. And these results are generated for the different area of the corridor sizes.

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