Numerical Simulation of an Express Freight Train and a High-Speed Train Meeting in a Tunnel

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ABSTRACT

A numerical simulation of an express freight train and a high-speed train meeting in a tunnel has been conducted by using the CFD technique. The RNG $k-\varepsilon$ double equation turbulence model has been adopted. A real train experiment has been conducted and the results of simulation based on simplified models agree reasonably with the experimental data. Distributions of velocity vectors and pressure, aerodynamic performances and pressure monitoring were analyzed. Results show that aerodynamic performances and pressure distributions of two trains are influenced greatly by the meeting process. Pressure monitoring shows that the minimum value of pressure is influenced more greatly than the maximum value. Moreover, aerodynamic performances of the express freight train change more significantly than that of high-speed train due to their distinct aerodynamic shapes.

Key words: numerical simulation, express freight train, high-speed train, meeting, tunnel

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1. INTRODUCTION

The speed of trains becomes an important symbol to indicate the modernization of railways. However, the residence force and energy consumption will increase remarkably with the rising speed of trains [1]. Moreover, the debasement of safety, comfortability and the increase of environmental destruction occur when trains are meeting at high speeds or running through a tunnel [2]. Issues related to tunnel aerodynamics are expected to become increasingly important with the trend for increasing speeds [3]. Nevertheless, aerodynamic studies of tunnels in the past concentrated on streamlined high-speed trains ordinarily [4]. The known research about the aerodynamic performances of freight trains do not relate to tunnel environment [5]. To enhance competitiveness and meet the needs of economic development, raising the speed of express train is imperative to be adopted. When freight trains run at more than 160km · h$^{-1}$, they cannot run on existing railways and they must meet high-speed trains. In fact, aerodynamic problems of freight trains running in tunnels with high speed also need to be studied. The aerodynamic performances of freight trains are obviously different from that of high-speed trains due to the blunt locomotive [6].

The meeting process of an express freight train and a high-speed train is simulated in this paper. The change process of velocity, pressure and aerodynamic performance were studied. Relevant data for the design and manufacturing of the express freight train were provided.

2. ANALYSIS METHODS

2.1 Models

Models of an express freight train and a high-speed train were used in this study. Two models were simplified and a smooth treatment was used for the surface of trains as shown in Figure 1. The length, width and height of the locomotive of the express freight train is 22.3m, 3.3m and 4.7m while the size of a single express freight train is 22.3m × 2.95m × 4.65m as shown in Figure 1(a). The whole length of the express freight train is 91.2m. However, Figure 1(b) shows that the length, width and height of the head car and tail car of the high-speed train is 25.7m, 3.38m and 3.7m. The middle car has the same width and height as the head car and tail car but it is 25m long. The whole length of the high-speed train is 77.4m.
2.2 Computational conditions and mesh

The computational domain in this study consists of two open-air regions and a tunnel region is shown in Figure 2. Two open-air regions are the same size and the length of the tunnel region is 1000m. The cross-sectional area of the tunnel is 92m². The end surface of open-air 1 is defined as pressure inlet while another end surface of open-air 2 is defined as pressure outlet. Two sides and the top surface of two open-air regions are defined as symmetry to extend flow field virtually. Other surfaces are defined as wall. Besides, the liquid is defined as ideal gas. In this simulation, the speed of the express freight train is 160km·h⁻¹ and the speed of the high-speed train is 250km·h⁻¹, each train moves from an open-air region to another open-air region by crossing the tunnel region and two trains will meet in the tunnel region.

There is a relative motion when two trains passing by each other, the relative displacement also occurs between two moving trains and stationary tunnel. The above motions can be simulated by a sliding mesh technique. There is a train in
each slip region so that the train can move with the slip region.

Figure 3 shows the meshes of models. The surface of the tunnel is discretized by quadrilateral meshes while the surfaces of trains are discretized by triangular meshes, as shown in Figure 3(a), (b) and (c). Moreover, Figure 3(d) shows that the computational domain is divided into several regions and discretized by hybrid meshes, structured and unstructured. Spatial meshes around trains are tetrahedral and the other regions are divided by hexahedral meshes. Considering that the flow field around trains varies greatly, meshes around trains are dense. Furthermore, data between adjacent regions can be exchanged by the interface.

Figure 3. Mesh: (a) tunnel; (b) express freight train; (c) high-speed train; (d) area around trains.

2.3 The simulation method

In this paper, a pressure-based solver in Fluent, based on the finite volume method, was used to obtain the pressure wave. The gradients are computed with a least-squares approach in control volumes surrounding the cells. RANS equations and the RNG $k$-$\varepsilon$ double equation turbulence model were used to simulate an express freight meeting a high-speed train in a tunnel. Governing equations of flow field are shown in reference [7].

2.4 Verification

A real train experiment was adopted by Key Laboratory of Rail Traffic Safety,
Ministry of Education to validate the accuracy of the numerical method. In this experiment, the testing high-speed train is shown in Figure 4(a), whose overall length is about 200m. The length of the testing tunnel is 987 m while the cross-sectional area of the testing tunnel is 60 m$^2$ as shown in Figure 4(b), and the speed of the train was 200km•h$^{-1}$. A point was arranged at 500m from the tunnel entrance and 1.5 m above the top surface of the rail is used to compare the pressure waves between the numerical simulation and the experiment. Certainly, the parameters in the numerical simulation are consistent with those that were used in the real train experiment.

![Figure 4. Real train experiment: (a) the testing train; (b) the testing tunnel.](image)

Figure 4 presents the variations of pressure with time monitored by both numerical simulation and experiment. It shows that the fluctuation tendency has a good correlation between the two methods. The evidence that the error of maximum difference between peaks and troughs is merely 4.5% indicates that the numerical method in this paper is suitable for simulate a train running across a tunnel.

![Figure 5. Variations of pressure with time.](image)
3 ANALYSIS

3.1 Velocity vectors

As the pressure distribution is caused by the airflow, the flow vectors around the train need to be researched. Velocity vectors are shown in Figure 6 at a horizontal where the height is 2m from the railway. It is obvious that the closer the flow gets to trains, the higher flow speed. Moreover, in Figure 6(a), when two trains are going to meet each other and the distance between them remains 75.08m, airflows between two trains are pushed to be compressive. It shows that more airflows are driven by the express freight train due to the blunt locomotive. Figure 6(b~d) display the trend of velocity vectors during the meeting process. It shows that airflows around each train are driven along with trains. However, airflows in front of each train are driven forward to far field of the tunnel. It illustrates that airflows in front of each train experienced the process of meeting, compressing, and running backward during two trains are meeting.

![Figure 6. Velocity vectors: (a) t=9.0s; (b) t=9.6s; t=10.2s; t=11.4s.](image)

3.2 Pressure distribution

Pressure distribution on trains and the tunnel at 6 different moments are shown in figure 7 to analyze the changing process of surface pressure when two trains are meeting. As shown in Figure 7(a), it is palpable that the inner tunnel wall between two trains emerges as a barotropic region. It can be seen from Figure 6(a) that the barotropic region is caused by the airflow which is propelled by two trains running in opposite directions. The airflow in front of each train is driven forward by running trains as shown in Figure 6(b~e). Hence the airflow around two trains is becoming tenuous and the pressure is tending to be negative when they are meeting. Figure 7(b~e) show that the surface pressure on both two trains and the tunnel are reduced evidently during the meeting process. In Figure 7(f), the
meeting process is complete but the surface pressure of trains and the tunnel is still negative. It illustrates that surface pressure of trains and the tunnel will be reduced remarkably during the meeting process.

3.3 Pressure monitoring

To analyze the instantaneous pressure characteristics on the surface of trains and the tunnel, several monitoring points are set up, as shown in Figure 8. Total number of points for monitoring is 20, including 11 points on the side close to another train while 9 points on another side. Points on two sides are symmetrically arranged along the central axis. In addition, two points (point 8 and point 10) on the intermediate section of the second freight train at different heights are arranged on the side close to another train.
Table I shows the pressures of several points on the surface express freight train. $P_{\text{max}}$ and $P_{\text{min}}$ are the maximum and minimum value while $\Delta P$ is the difference between them. Overall, though the $P_{\text{max}}$ of 20 points are not very different, the $\Delta P$ on the side close to another train is bigger than that on another side due to the difference of $P_{\text{min}}$. The result shows that the $P_{\text{max}}$ is not influenced by the meeting process greatly but the $P_{\text{min}}$ changes substantially when two trains are meeting.

### Table I. PRESSURES OF MONITORING POINTS.

| Num. | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $P_{\text{max}}$ | 622 | 728 | 650 | 582 | 722 | 650 | 588 | 652 | 657 | 661 |
| $P_{\text{min}}$ | -1498 | -1486 | -1648 | -1353 | -1232 | -1332 | -1715 | -1717 | -1718 | -1704 |
| $\Delta P$ | 2120 | 2214 | 2297 | 1935 | 1954 | 1982 | 2302 | 2369 | 2375 | 2365 |

| Num. | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20  |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $P_{\text{max}}$ | 572 | 572 | 663 | 573 | 512 | 514 | 550 | 509 | 598 | 514 |
| $P_{\text{min}}$ | -1890 | -1469 | -1488 | -1577 | -1996 | -1894 | -1959 | -1712 | -1723 | -1776 |
| $\Delta P$ | 2461 | 2042 | 2152 | 2150 | 2508 | 5490 | 2510 | 2222 | 2321 | 2291 |

#### 3.4 Aerodynamic forces

Figure 9 shows that drag forces fluctuate greatly during the meeting process to analyze the aerodynamic performances of two meeting trains quantitatively. For the express freight train, drag forces of locomotive and 3\textsuperscript{rd} freight train are bigger than that of 1\textsuperscript{st} and 2\textsuperscript{nd} freight train. For the high-speed train, compared to the less mutative wave form of middle car, fluctuation ranges of the head and tail car are relatively higher.
Moreover, aerodynamic performances of the express freight train change more significantly than that of high-speed train due to their distinct aerodynamic shapes.

4 CONCLUSIONS

A numerical simulation of an express freight train and a high-speed train meeting in a tunnel has been conducted. The results of simulation based on simplified models agree reasonably with the real train experimental data.

Results of the simulation show that airflows between two trains are pushed to be compressive before they are meeting and it lead the inner tunnel wall between two trains to a barotropic region. Airflows in front of each train experienced the process of meeting, compressing, and running backward during two trains are meeting and surface pressure of trains and the tunnel will be reduced remarkably during the meeting process. In addition, more airflows are driven by the express freight train.

Monitoring data show quantitatively that the $P_{\text{max}}$ is not influenced by the meeting process greatly but the $\Delta P$ varies a lot because $P_{\text{min}}$ changes substantially when two trains are meeting.

Variations of aerodynamic forces show that aerodynamic performances of two trains are influenced greatly by the meeting process. Moreover, aerodynamic performances of express freight train changes more significantly than that of high-speed train due to their distinct aerodynamic shapes.

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