Characteristics of the Pressure Wave Caused by Two Trains with the Same Speed Tracking in the Urban Regional Railway Tunnel

Youcai Wan, Yongxing Jia and Yuanggui Mei

ABSTRACT

The aerodynamic problems occurring need to be taken seriously with the increase of the design speed of subway trains, one of is the pressure wave in the tunnel. Therefore, it is important to study the pressure fluctuations when two trains passing through Urban Regional Railway Tunnel in the same direction. In this study, one-dimensional compressible unsteady non-homotropic flow model is used to establish the airflow equations, and the method of characteristics of generalized Riemann variables is adopted to solve the set of equations effectively. The exterior and interior pressure fluctuations of two trains are investigated and compared with that of a single train. The maximum negative pressure values, the maximum peak pressures and the maximum pressures change per 3 seconds of the two-trains situation are both larger than those of a single train. The results of this paper show that it is necessary to study the pressure fluctuations when there are multiple trains running in the tunnel.

Youcai Wan, Gansu Province Engineering Laboratory of Rail Transit Mechanics Application, Lanzhou Jiaotong University, 88 West Anning Rd., Lanzhou 730070, Gansu, China
Yongxing Jia, Gansu Province Engineering Laboratory of Rail Transit Mechanics Application, Lanzhou Jiaotong University, 88 West Anning Rd., Lanzhou 730070, Gansu, China
Yuangui Mei (Corresponding Author), Gansu Province Engineering Laboratory of Rail Transit Mechanics Application, Lanzhou Jiaotong University, 88 West Anning Rd., Lanzhou 730070, Gansu, China, E-mail: meiyuangui@163.com, Phone NO:13008781029.
1. INTRODUCTION

In recent years, with the rapid development of urban rail transit, some project case and construction requirements have appeared between the fast subway and rapid urban railway in the speed of 100~160km/h in China. For example, the highest design speed of the 18th Metro Line in Chengdu is 140km/h, and the highest design speed of the New Airport Line in Beijing is 160km/h. However, a series of aerodynamics problems, especially in tunnels, cannot be ignored as the speed of the train increases [1]. For example, Guangzhou Metro Line 3, when the train running in the tunnel with the speed of 120km/h, the pressure fluctuations entered into the coaches caused the passenger’s aural discomfort.

At present, there are a lot of researches on the pressure wave of high-speed railway tunnels [2,3,4,5,6], in view of the aerodynamics of subway tunnels, scholars have studied more about ventilation [7], heat transfer [8] and aerodynamic drag of train [9] in subway tunnels. However, there are a few of researchers have studied pressure wave of subway tunnels, Lan Zhu [10] et al. studied the pressure wave and pressure rate of change when a single train operating in the different scenarios based on passenger pressure comfort, Haitian Zhang [11] studied the pressure wave and pressure comfort when a train passing through different design tunnel sections of Shenzhen Metro Line 11 based on ThermoTun software [12].

However, with considering of the tunnel structure and the train operation mode, the study of subway trains running in the underground tunnels is more complex than that of the high-speed trains. On one side, there are stations in the tunnel, and ventilation shafts are located on both sides of the station or between stations in the tunnel. On the other side, there are multiple trains running in the tunnel, and the trains will accelerate, decelerate, run at full speed and even park at the station. In this paper, the exterior and interior pressure fluctuations while two trains with the same speed tracking in the tunnel were simulated based on the one-dimensional compressible unsteady non-homentropic flow model and the method of characteristics of generalized Riemann variables to simulate

2. NUMERICAL SIMULATION METHOD

Although the three-dimensional numerical simulation will describe the local characteristics of the fluid flow better, however, it is not feasible to use the 3D simulation in situations like trains passing through long tunnels considering of the computer performance, the calculation cost and the calculation period. Therefore, the one-dimensional numerical simulation method is used in this paper.

2.1 Basic Equations

The airflow caused by trains running in a tunnel is three-dimensional, compressible, unsteady, and turbulent flow. The tunnel length is much larger than the
tunnel section and train length is also much larger than the annular space cross-section formed by the train and the tunnel, equivalent hydraulic diameter of these two characteristics, thus, the fundamental basis to simplify the three-dimensional flow as one-dimensional flow. Assuming that the air in the tunnel is the perfect gas, there is no slop in the tunnel, there is no mass transfer between the exterior and the interior of the coaches, considering the friction and heat transfer between the tunnel (train) and the air.

The basic equations of one-dimensional compressible unsteady non-hometropic flow model are as follows.

Continuity equation,
\[
\frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial x} + \rho \frac{\partial u}{\partial x} = 0
\]  

Momentum equation,
\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + \frac{1}{\rho} \frac{\partial p}{\partial x} + G = 0
\]

Energy equation,
\[
\left(\frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial x}\right) - a^2 \left(\frac{\partial p}{\partial t} + u \frac{\partial p}{\partial x}\right) = (q - w + uG) \rho (\kappa - 1)
\]

where, \(u\), \(\rho\), \(p\) and \(\kappa\) are the velocity, density, pressure and specific heat ratio of air, respectively. \(a\) is sound speed, \(w\), \(G\) and \(q\) are work expression, friction term and heat transfer term, respectively. \(t\) is time [13].

2.2 Initial Conditions and Boundary Conditions

Before the train does not enter the tunnel, it is assumed that the velocity of air in the tunnel and shaft is 0 m/s, and the pressure is local atmospheric pressure.

When the trains running in a tunnel with shafts, there are some boundary conditions[13]: the condition of the tunnel ports, the transient condition while the nose and tail entering or exiting tunnel ports, the condition on both ends of a train when the whole train running in the tunnel, the condition of shafts when the nose or tail is far from the shafts, the transient condition of shafts while the nose or tail is close to the shafts, the transient condition of shafts after nose or tail passing through the shafts.

2.3 Numerical Method

The equations introduced in 2.1 can be solved with the method of characteristics. the equations (1)~(3) are firstly transferred into characteristic equations in dimensional terms of flow velocity(\(u\)), pressure(\(p\)) and density(\(\rho\)). Then three dimensionless generalized Riemann variables are introduced, there are \(\lambda\), \(\beta\), and non-dimensional \(A_A\) which denotes the entropy of air particle, we transfer the characteristic equations into non-dimensional form by the three dimensionless generalized Riemann variables. Finally, we solve the dimensionless characteristic
line equations, and combine the relationship between the Riemann variables and the physical parameters of the fluid to obtain the required physical quantities[13].

3. CHARACTERISTICS OF PRESSURE WAVE

3.1 Calculation Model

In the study of the pressure fluctuations, we ignore the tunnel mutation section at the stations, the tunnel cross-sectional area along the length of the tunnel is constant, the tunnel slope is ignored, the tunnel and the shaft is connected in the form of vertical. The figure 1 shows the trains running in the tunnel.

![Figure 1. Two trains running in the tunnel.](image)

| TABLE I. PARAMETER OF THE TUNNEL, TRAIN AND SHAFTS. |
|-----------------|-----------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| Tunnel/Train    | Shaft1/Shaft2   | Shaft3/Shaft4 | Shaft5/Shaft6 | Shaft7/Shaft 
| Length/m        | 8280            | 140           | 5             | 27.3          | 5             | 5             | 5             | 5             | 18.4          |
| Section/m²      | 35.4            | 10.75         | 20            | 20            | 20            | 20            | 20            | 20            | 20            |
| Perimeter/m     | 21.51           | 13.85         | 18            | 18            | 18            | 18            | 18            | 18            | 18            |
| Distance from   | /               | /             | 630           | 2410          | 3670          | 3980          | 5390          | 5830          | 7650          |
| the entrance of | the tunnel/m    |               |               |               |               |               |               |               |               |

Table 1 shows the detailed parameters of the tunnel, train and shafts. There are seven measuring points on train body, the measuring points are arranged in the middle of each coach.

3.2 Pressure Variation Characteristics Outside Trains

This article defines: when a single train running in tunnel, which is called the single train. Two trains in the tunnel with the same speed tracking operation, the first entry into the tunnel is called the first train, after a certain departure time interval entry into the tunnel is called the second train.
3.2.1 PRESSURE TIME HISTORY

Two trains with the same speed tracking operation in a long 8280m tunnel, train speed is 140km/h, departure time interval of 120s. In order to compare with the pressure fluctuations of the single train, figure 2 and figure 3 show the pressure time history of noses and tails measuring points respectively, the red dotted lines in the figure indicate the moment of measuring points pass through the shafts, time 0 in the figure indicates the moment when the front end of the trains enter the tunnel.

![Figure 2. The pressure time history of train nose.](image)

It can be seen from figure 2: whether it is the single train or the two trains, the measurement points of noses through the shafts will cause a sudden surge in pressure; however, there are significant pressure fluctuations differences between the single train and the two trains. When the departure time interval of 120 seconds, at the beginning of 120 seconds, due to the first train has not yet been affected by the second train, and the pressure fluctuations of the first train is the same as the single train. But starting from the moment of 120 seconds, the pressure fluctuations of the first train becomes more intense than the single train. Due to the pressure fluctuations generated by the first train in tunnel before the second train enters the tunnel, the pressure fluctuations are always different from the single train.

![Figure 3. The pressure time history of train tail.](image)

It can be seen from figure 3: the measurement points of tails through the shafts will cause a sudden drop in pressure, the pressure at the tail measuring points of the single train and the first train are always negative pressure, but there are some positive pressures are measured at the tail measuring points of the second train.
3.2.2 PEAK PRESSURE VALUES

Figure 4 shows the maximum positive and negative pressure values and the maximum pressure peak-to-peak values obtained from the external measuring points of different coaches.

From figure 4 (a) and (b), it can be seen that there is the same pressure change rule (from the head to the tail, the maximum positive pressure decreases, and the maximum negative pressure increases gradually) between the single train and the first train. Furthermore, the maximum positive pressures of the first train are as same as the single train, but the maximum negative pressure values are bigger than the single train. From nose to tail, there is no obvious pressure change rule that the maximum positive and negative pressures of the second train. But the maximum positive pressure values are bigger than the single train, and the maximum negative pressure value are larger than the single train but less than the first train. The negative pressure environment of the first train is worse than the second train, but the positive pressure environment is better than the second train.

From figure 4 (c), it can be seen that the maximum peak-to-peak pressures of the first and the second trains are both bigger than that of the single train.

3.3 Pressure Variation Characteristics Inside Trains

In the study of interior pressure fluctuations, we assume that the train airtight index $\tau = 4$ s. Figure 5 and figure 6 show the maximum pressures change per 3 seconds time history of train nose and tail respectively.

From figure 5 (a) and figure 6, it can be seen that at the beginning of 120 seconds, the maximum pressures change per 3 seconds of the first train is the same as the single train. But starting from the moment of 120 seconds, the maximum pressures change becomes more intense than the single train. The maximum pressures change of the second train pressure are always different from the single train.
Figure 7 shows the maximum values of the maximum pressure change per 3 seconds for the internal measuring points of different coaches.

![Figure 5](image1.png) Figure 5. The maximum pressures change per 3 seconds time history of nose.

![Figure 6](image2.png) Figure 6. The maximum pressures change per 3 seconds time history of tail.

![Figure 7](image3.png) Figure 7. The maximum values of the maximum pressures change per 3 seconds.

From figure 7, it can be seen that the maximum values of maximum pressure change per 3 seconds of each coaches of the first and second train are both bigger than that of the single train, and the maximum values of the first train are bigger than the second train.
4. CONCLUSION

In this paper, the characteristics of internal and external pressure waves generated by two trains running at the same speed in the tunnel with length of 8280m and seven shafts are studied. The conclusions are as follows:

1) The measuring points of train nose through the shaft will cause a sudden surge in pressure, measuring points of the tail through the shaft will cause a sudden drop in pressure;

2) When the second train has not yet entered the tunnel, the outside pressure fluctuations of the first train is the same as that of the single train passing through the tunnel. But after the second train enters the tunnel, the pressure fluctuation of the first train becomes intense;

3) The maximum negative pressures and the maximum peak-to-peak pressures of the first and second trains are both bigger than those of the single train, and the maximum positive pressures of the second train is bigger than the single train;

4) We assume that the train airtight index $\tau = 4s$. the maximum values of maximum pressure change per 3 seconds of each coaches of the first and second train are both bigger than that of the single train, and the maximum values of the first train are bigger than the second train;

Therefore, it is necessary to study the pressure fluctuations when there are multiple trains running in the tunnel.

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