Study on the Influence of Blocking Ratio on Slipstream in Tunnel

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ABSTRACT

When a train moves through air, it generates a turbulent flow around it called a slipstream. The slipstream is associated with high air velocities and rapidly-changing pressure fields. The air velocity, pressure variation and direction of the flow inside tunnels are different to the slipstream in open air. These differences depend on the size of the tunnel and length of the tunnel and the shape and speed and length of the train.

In the present paper, the effect of tunnel length and blocking ratio on the velocity flow and pressure inside is investigated. The investigation uses computational fluid dynamics techniques (CFD), in which a model of the CRH380A train is used. Two blocking ratios are also investigated; one is 0.16 called case 1 and the other is 0.187 called case 2. The sliding mesh technique is employed to simulate the movement of the train in the tunnel. The simulation uses unsteady RANS and applies the Shear Stress Transport (SST) turbulence model. The effect of blocking ratio on both pressure and velocity fields is discussed.

Keywords: slipstream; tunnel; high-speed train; SST

1. INTRODUCTION

Flow around high speed trains has received considerable attention from researchers in the last three decades.\cite{1,4} Investigations have been performed using different experimental and computational techniques, including full-scale\cite{6}, physical modelling \cite{6,7} and numerical simulations\cite{2,3,5,9}. With the increasing speed of the train, the aerodynamics of train has become a big issue for both train operators and
train manufacturers. When a train is running at high speed, it will generate several regions of highly turbulent flow due to the viscosity of air around the train known as slipstream\textsuperscript{[8][10]}. Slipstream is often accompanied by drastic changes in velocity speed and direction and pressure.

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Velocity, pressure variation and direction of the flow inside tunnels are different than those around a train in open air\textsuperscript{[11][12][13]}. These differences can be related to the cross section and the length of the tunnel. Therefore, the focus of this thesis is to investigate the effect of the blocking ratio on the pressure variation and the velocity around a high-speed train in a single-track tunnel.

2. NUMERICAL MODELING

2.1 Train and tunnel geometries

The main train model used in this study is the CRH380A train. The length and cross sectional dimensions of the idealized CRH380A train model are shown in Figure 1. The tunnel used in the CRH380A train simulations is of rectangular cross section with no portal at the entrance or exit. Simultaneously, table 1 shows the calculating conditions.

2.2 The numerical domain and boundary conditions

The tunnel, the train model and two environments before and after the tunnel form the computational domain of the CRH380A train simulation, shown in Figure 2. The initial conditions of the simulation were zero pressure and zero velocity in the two domains. The entry speed of the train (V\textsubscript{train}) was set to 83.33 m/s for the model CRH380A train. At the beginning of the simulation, the train nose is located at the beginning of the environment; the distance of the train to the tunnel entry is 50m. This gives enough space for the turbulent flow to develop before the train arrives to the tunnel entry. A solid walls boundary condition was used for the tunnel walls and
for the train body. A non-reflective boundary condition, based on a Fourier decomposition of the solution at the boundary face, was used for the external domain and the tunnel extremity. The cross-sectional section of the train was centered inside the tunnel, a symmetry boundary condition was then used to divide the computational domain by two. A common interface was calculated between the sliding domain and the stationary domain.

![Figure 2. Computational domain for CRH380A train.](image)

### 2.3 Mesh and numerical details

The commercial software STAR-CCM+ has created all the meshes in this work. Polyhedral meshes were used in all the domains; moving and stationary. The same mesh strategy has been used for all the meshes, in which the mesh is concentrated around the train and in the wake region. However, the stretching ratio kept less than 1.2 everywhere. Figure 3 shows the mesh distribution around the train and tunnel portal. The time derivative terms are discretized using the backward scheme which is a second order, implicit scheme. The convective and diffusive terms are discretized using the second order schemes. The total simulation time allowed for the tail of the train to be at least 25m from the exit of the tunnel.

The Courant-Friedrichs-Lewy Condition also known as the Courant Number has to be taken into consideration for checking the convergence of the solution.

\[
C = \frac{U\Delta t}{\Delta x}
\]

where, \(U\) is the maximum velocity in m/s, \(\Delta x\) is length of cells in m, \(\Delta t\) is the time-step of the simulation in s. The time-step for the simulation is determined such that the Courant Number stays below 1 for most of the cells. The characteristic time scale \(T_{ref}\) is given by the ratio of the characteristic length scale and the free stream velocity \(\frac{H}{U_x}\) which is 0.044s. The time-step for the simulations \(\Delta t\) is \(0.027T_{ref}\).
Figure 3. Surface mesh distributions on the train model and tunnel portal.

4. RESULTS AND DISCUSSION

Figure 4 and figure 5 shows the position of the monitoring points.

Figure 4. The positions of monitoring points along the tunnel.

Figure 5. The positions of p3,p4,p5,p6,p7 and p8 monitoring points.
Figure 6 shows the time history of the pressure at P6 and P7 during the simulation. The two pressure curves show quite similar magnitudes and trends which suggest a proper exchange of data between the stationary and the moving domains through the interface. And we can see from the figure 6 that the pressure change of P6 is more dramatic than that of P7 because it is closer to the train body.

4.1 Slipstreams in the tunnel

Figure 7 shows the histories of the velocity magnitude and three velocity components at points P6, P7 and P8, shown in Figure 5. When the train approaches the points velocity magnitude and velocity component are measured. The velocity magnitude is about 17% of the train velocity when the head of the train arrives at the section of the monitoring points. The maximum velocity magnitude always occurs near the wake, from the single case, It can be seen also from Figure 7 that in the wake flow, point P8 has the maximum velocity followed by point P6 and then P7. This is because P8 is close to the ground and in this region the flow is affected by the underbody complexities. Also P6 is close to the train surface and is influenced by the train. We can get that the location of the maximum velocity magnitude is different at different monitoring points, the maximum velocity magnitude of P7 and P8 occurs 6.5H behind the train tail, while P6 occurs 4.2H behind the train tail. It is also concluded that the velocity magnitude of the same point in case 1 is larger than that in case 2, because the smaller blocking ratio can compress air and result in larger slipstreams. Figure 7(b) shows that the longitudinal velocity component is negative at the three points and the point P6 is the closest to the train surface, the velocity is influenced by the boundary layer region of the train slipstream and thus has less reversed flow than the other two furthest points. In the near wake region, the maximum velocity magnitude and the longitudinal velocity component have the same trend and value. Figure 7(c) and Figure 7(d) show the history of the span-wise and vertical velocity components at the three points. It can be seen that these two components have zero velocity before the train head approaches the section of the monitoring points. There are some changes in these two components when the train head and tail passes but the magnitude of these components is very small in comparison to the longitudinal velocity component.
4.2 Pressure in the tunnel

The static pressure inside the tunnel was monitored during the simulation at different points. The location of the specific monitoring points as shown Figure 4 and Figure 5. Figure 8 shows the history of the static pressures at the five points as a function of the distance between the train nose and the tunnel entrance. From the Figure 7 we can see that a sharp increase in the pressure occurs at points P1, P6, P10 and P11, while the pressure at P12 is nearly zero. This is because P12 is at the exit of the tunnel and is influenced by the static pressure of the exit environment. Once the train enters the tunnel, there is a slight increase in the pressure at point P1. This increase in pressure is quickly disappears after the train nose and the pressure at point P1 is nearly the same as the environment. When the tail of the train enters the tunnel, there is a drop of the pressure at the entrance. The largest pressure is calculated at point P6 as it reaches a maximum pressure once the train nose enters the tunnel. The passes of the train nose causes a drop of the pressure at point P6. This is followed by another drop in the pressure at the moment the tail of the train enters the tunnel. Along the length the train is passing the point there is a gradual decrease in the static pressure at point P6 until the tail passes the point after which there is a build-up of the pressure. There is also another increase of the pressure at point P6 when the train nose leaves the tunnel. The situation of P10 and P11 is the same as P6, only the pressure value is different with the same trend of change. There is no significant effect of the train enters the tunnel at point P12 (tunnel exit). The only effect is when the train nose passes the point, at which there is a slight drop in the pressure which
quickly build-up to zero when the train is completely exits the tunnel. Figure 8 shows that the pressure change trend is the same in case 1 and case 2, the only difference is the specific pressure value and the pressure gradient. In case 1 the maximum positive pressure is 2000Pa, the maximum negative pressure is 2100Pa, while in case 2 the maximum positive pressure is 1500Pa, the maximum negative pressure is 1600Pa.

![Figure 8. Static pressure histories at the monitoring points.](image)

### 4.3 Wake flow in the tunnel

Inside the tunnel, the air is dragged behind the train while in the region around the train the air moves backward towards the wake flow. This is due to the high pressure ahead of the train and the low pressure in the wake. As is known to us that the largest slipstream happens near the wake, so Figure 9 shows that the vortex flow using the second invariant of velocity gradient tensor (Q-criterion). We can get that the flow structure near the wake in case 1 and case 2 is similar, but the difference is that the distance in case 1 is longer than that of case 2, in case 1 the distance is 12.16H, in case 2 the distance is 11.38H. Furthermore, the velocity near the wake in case 1 is larger than that of case 2.

![Figure 9. Static pressure histories at the monitoring points.](image)
4. CONCLUSION

Influence of blocking ratio on slipstream in tunnel is studied, the sliding technique method is enough to simulate the relative motion between the train and the tunnel. The maximum slipstream occurs near the wake of the train, which can reach 0.4 of the train velocity, and the smaller blocking ratio can result in larger slipstream. The magnitude of the span-wise and vertical velocity components is very small in comparison to the longitudinal velocity component, only have some changes when the train head and tail passes. The location of the maximum velocity magnitude is different at different monitoring points, the maximum velocity magnitude of P7 and P8 occurs 6.5H behind the train tail, while P6 occurs 4.2H behind the train tail. Higher pressures are observed in the smaller tunnel. In general, there is a sudden increase in the pressure in the tunnel when the train enters and when the train nose leaves the tunnel, a sudden decrease in the tunnel pressure occurs when the tail of the train enters the tunnel and when the train nose passes. We can get that the flow structure near the wake in case 1 and case 2 is similar, but the difference is that the distance in case 1 is longer than that of case 2, in case 1 the distance is 12.16H, in case 2 the distance is 11.38H, furthermore the velocity near the wake in case 1 is larger than that of case 2.

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REFERENCES


