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Numerical study on the aerodynamic pressure of a metro train running between two adjacent platforms

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ABSTRACT

As a fast and efficient short distance transportation means, the subway line has been built and expanded in an increasing number of cities. The pressure in the tunnel fluctuates significantly while metro trains pass. This kind of pressure may damage the equipment and workers in the tunnel. Considering that, the metro train does not have airtightness, and that pressure can spread inside the vehicle, passengers in the vehicle would be directly affected by the alternating aerodynamic pressure, which causes discomfort to passengers. This phenomenon is exacerbated at high speeds. Therefore, it is important to estimate the aerodynamic alternating pressure generated by the metro train in the tunnel before construction. In this study, the aerodynamic performance of a metro train running between two adjacent platforms in a tunnel was simulated by using FLUENT. In this work, the effects of acceleration and speed of the metro train, and of platform spacing, on the alternating pressure on the train and in the tunnel are studied. In the analysis of the impact of train acceleration, the pressure change inside a passenger train in a 1 s timespan was used to evaluate the comfort of passengers. Maximum and average ΔP (pressure changes in amplitude) shows an exponential relationship with a (acceleration), V_c (constant speed) and $L_{platform}$ (platform spacing), especially the ΔP measured on tunnel surface. The fluctuation of the train surface pressure is more intense than that of the tunnel. The P_{min} (minimum pressure) on the train surface and in the tunnel is not affected by the acceleration of the train, but it is mainly related to the highest train speed in the tunnel. When the platform spacing is higher than 1500 m, P_{max}, P_{min}, and ΔP in the tunnel and on the train surface showed little change. These findings contribute not only to the design of the metro train and tunnel system, but also to the guidance of the metro train operation.

1. Introduction

As a fast and efficient short distance transportation mean, the subway line has been built and expanded in an increasing number of cities. With the rapid development and increasing speed of metro trains, their aerodynamic characteristics are becoming increasingly prominent. The alternating pressure, piston effect and ride comfort has attracted the attention of an increasing number of people.

Several researchers are investigating the aerodynamic performance of trains and train-induced unsteady airflows in metro tunnels. Kim and Kim (2007) conducted both experimental and computational studies on unsteady pressure in a metro tunnel caused by a train, by using the sharp interface method for the moving boundary of an immersed solid, and found that the numerical results were in good agreement with the experimental data. The flow structure around the train in a tunnel is different from the one in the open air (Shin and Park, 2003). Gilbert et al. (2013) carried out scaled model experiments, in order to study transient air velocities and dynamic pressure loads generated by high-speed trains in three cases: confined spaces, partially enclosed spaces, and open spaces. The authors found that peak gust magnitudes increase in all of the confined cases, when compared to the open air, that the piston effect was the main cause of the increases in the peak gust magnitudes, and that the tunnel length significantly influenced the flow characteristics. A large amplitude compression wave and a dilatation wave are both caused by a train entering a tunnel (Baron et al., 2001; Mok and Yoo, 2001; Doi et al., 2010; Khayrullina et al., 2015). The high-pressure fluctuation in a tunnel caused by a train easily causes passenger discomfort (Raghunathan et al., 2002). Some scholars studied the influence of train and tunnel shapes on the aerodynamic effects in the tunnel (Xiang and Xue, 2010; Liu et al., 2010; Muñoz-Paniagua et al., 2014). Ricco et al. (2007) studied the influence of the tunnel parameters on the compression wave. The authors performed

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simulations by means of a one-dimensional numerical code, and found that the cross-sectional shape of the tunnel did not affect the pressure waves, but the influence of the blockage ratio on the pressure waves was significant.

In general, the operating environment of a metro train is primarily in the tunnel, and the operation mode of a metro train in the metro tunnel is generally constituted by three processes: acceleration, constant speed, and deceleration. Huang et al. (2012) studied the train-induced unsteady airflow in a tunnel of Seoul subway by means of Computational Fluid Dynamics (CFD). Choi and Kim (2014) compared and analyzed the effect of the train head shape and of tunnel cross-sectional area on the aerodynamic drag of the metro train by using CFD. Baron et al. (2001) studied the aerodynamic phenomena generated by a train running through a long tunnel of small cross-section, by means of a quasi-one-dimensional numerical simulation, and discussed the effect of several tunnel configurations at high on-train drag, pressure wave amplitude, and shock wave. The authors found that configurations consisting of twin tunnels connected by pressure relief ducts near stations and operated under partial vacuum should be preferred.

In order to improve environmental conditions in subways, some airshafts are set near metro platforms, with the aim of maintaining air circulation near the metro platform. The effect of the airshafts parameters on the aerodynamic characteristics of a metro train is also significant (Baron et al., 2001; Lin et al., 2008; González et al., 2014). Rabani and Faghih (2015) investigated the characteristics of train–tunnel interaction at a tunnel entrance numerically by using a moving boundary, and found that the maximum drag coefficient occurs when the train enters the tunnel, and that the air vents and enlarged hood at the portal decreased the pressure gradient and drag coefficient by about 28% and 36%, respectively. Miyachi et al. (2014) carried out a model experiment, to investigate pressure waves generated by a train passing through a tunnel with a branch, and found that the cross-sectional area ratio of the branch is the main factor determining the magnitude of the pressure waves in the tunnel and of the pulse waves radiated from the tunnel portals. Lin et al. (2008) studied the piston effects influenced by airshafts occurring in the underground tunnel ventilation, by measuring the transient air movement in a typical metro platform. The authors found that a larger sectional area resulted in a larger volume flow rate, but its percentage increase was less than the percentage increase in the sectional area, and that the length of the airshaft is also an important factor for efficient air exchange originated by piston effects. Xue et al. (2014) analyzed the three-dimensional unsteady airflow in a metro platform and tunnel by an experiment and a numerical simulation, and found that the influence of the airshaft on the piston wind is more significant when the airshaft is located before the platform than when the airshaft is located after the platform. González et al. (2014) built a 3-D computational model for a typical metro line located between two consecutive platforms, in order to simulate the air flow in a metro tunnel, and analyzed the influence of the piston effect in the longitudinal ventilation system of metro tunnels. The authors found that the attenuation of the shafts depends on the ventilation system, and that it is somewhat lower for two opposite trains than for a single train running in the tunnel. There is little literature on the study of the effect of the metro train acceleration and constant speed and platform spacing (the distance between two adjacent platforms) on the aerodynamic effects that occur in tunnels.

This paper mainly studies the aerodynamic characteristics caused by a metro train running between two platforms, and aims to analyze the effect of the acceleration and constant speed of the metro train and platform spacing on the aerodynamic characteristics in the metro tunnel using CFD. Furthermore, the pressure inside the train is calculated by a rapid and efficient computation program that is used to evaluate the passenger's discomfort. In order to simulate the relative motion between the metro and the tunnel, the sliding mesh method is used in the numerical simulation.

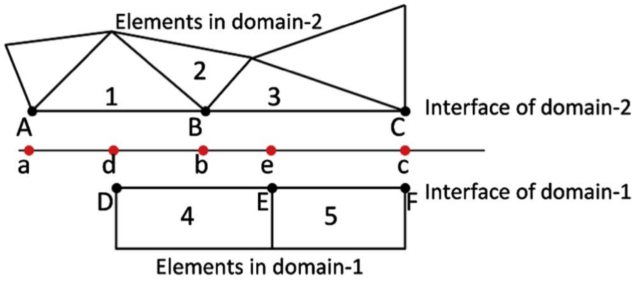

Fig. 1. Principle of sliding mesh.

2. Numerical methods

2.1. The simulation method and the turbulence model

The relative motion between the train and the tunnel can be realized by using a dynamic mesh method (Muñoz-Paniagua et al., 2014), and a sliding mesh method (Xiang and Xue, 2010; Muñoz-Paniagua et al., 2014). However, as the train is running, the grids around it need to be reconstructed in the dynamic mesh method. The information exchange between the fluid field around the train and the fluid field in the tunnel can be done through an exchange surface in the sliding mesh method, which means that the grid does not need to be reconstructed. Therefore, the sliding mesh method is used to simulate the relative motion between the train and the tunnel. The motion of the train is controlled by a user defined function (UDF) in Fluent.

The principle of the sliding mesh is presented in Fig. 1. Domain-1 and domain-2 are two parts of the computational domain, and they have relative motion in relation to each other. The interfaces of domain-1 and domain-2 are composed of A-B-C and D-E-F, respectively. In the simulation of the flow field, a pair of exchange surface (a-d-b-e-c) is formed by the interfaces of domain-1 and domain-2. The information regarding the flow field in both sides of the exchange surface (a-d-b-e-c) can be exchanged through the exchange surface (a-d-b-e-c), and the information on elements 1, 2, 3, 4 and 5 on the interface is exchanged by each other using the interpolation method.

When the metro train is running in the tunnel, the air inside the tunnel is not free to flow and is squeezed. This fact needs to be considered, as it is relevant for the viscosity and compressibility. Because the minimum constant train speed is 40 km h^{-1}, and the height of the train (H) is treated as the characteristic length, which is 3.85 m, the Reynolds number of the flow field around the train is higher than 3.3×10^6. Therefore, the flow around the train is in a turbulent state. The Reynolds number is calculated by formula (1).

$$Re=\frac{\rho v_{tr} H}{\mu} \tag{1}$$

where the air density ρ is 1.225 kg/m^3, v_{tr} is the train speed, and the air viscosity coefficient μ is 1.8×10^{-5} Pa s.

The simulation method based on Reynolds-averaged Navier–Stokes (RANS) equations has been widely used in simulating the aerodynamic performance of trains running in a tunnel (Ogawa and Fujii, 1997; Baron et al., 2001; Mok and Yoo, 2001; Xue et al., 2014; Yao et al., 2014). In recent years, large eddy simulation (LES) and detached eddy simulation (DES) have been widely used in the numerical simulation of train aerodynamics, resultant of the improvement of computing capability (Muld et al., 2012a,b; Niu et al., 2017). LES has been used to simulate the process of a train passing through a tunnel (Khayrullina et al., 2015), and can accurately simulate the change in flow structure around the train in the tunnel, but the alternating pressure was not studied by (Khayrullina et al., 2015). However, as the requirement of LES and DES regarding the grid and the time step is too high, they are not suitable for the work described in the present paper. The κ-ε turbulence model was used by Liu et al. (2010) and González et al.