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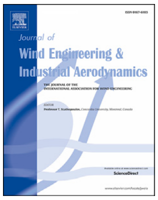

Impact of ambient wind on aerodynamic performance when two trains intersect inside a tunnel

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ABSTRACT

In this study, the aerodynamic performance of two trains that intersect inside a tunnel under ambient wind conditions is investigated. A full-scale test is conducted to verify the computational method and mesh, and then a series of numerical simulations are performed to investigate the pressure variation and the aerodynamic force coefficient by comparing with the condition of no ambient air. The difference between the results with/without ambient wind in a tunnel is analysed. The results indicate that if Train A travels downwind, the positive pressure of train surface increases and the negative pressure decreases as the wind velocity increases, and the arrival time of the maximum positive pressure lags on average 0.024 s and 0.058 s for wind velocities of 20 m/s and 40 m/s, respectively. For the tunnel wall measuring points, the maximum positive pressure increases as the wind velocity increases. The maximum drag coefficient of downwind Train A decreases by 4.7% and 10.1% for wind velocities of 20 m/s and 40 m/s, respectively, whereas that of upwind Train B increases by 5.7% and 15.8%, respectively. The maximum positive side force coefficient of downwind Train A increases by 20.8% for an ambient wind velocity of 40 m/s, whereas the same coefficient decreases by 16.7% for upwind Train B.

1. Introduction

The determination of the aerodynamic performance, including the change in flow structure, the pressure wave and the aerodynamic forces coefficient resulting from two trains intersecting inside a tunnel, is a complicated and prominent issue (Fujii and Ogawa, 1995; Raghunathan et al., 2002). Two trains that pass each other inside a tunnel can cause a pressure surge and transient load that acts on the trains and tunnel, which impacts the structural safety of trains and tunnels and causes many aerodynamic problems (Howe, 1998; Uystepruyst et al., 2011). Based on the numerical simulation of the three-dimensional compressible Euler/Navier-Stokes equations, Fujii and Ogawa (1995) explored a three-dimensional flow field induced by two trains passing each other inside a tunnel. A domain decomposition method with a fortified solution algorithm (FSA) interface scheme was employed to address the moving-body problem. The results indicated the occurrence of a complicated phenomenon surrounding the interaction of the flow induced by the two trains. The maximum suction force occurred when the two trains were aligned side by side. The effectiveness of the numerical method for calculating moving boundary problems was also verified. Hwang et al. (2001) considered the nose shape and the tunnel and train lengths, investigated the flow field around high-speed trains that pass each other along a double-track using a three-dimensional inviscid numerical method, meanwhile, the effects of the train speed, the gap between the trains and the blockage ratio were also analysed. The results indicated that the side force during the crossing is proportional to the square of the train speed without the effect of viscous flow. A new method that utilizes the user-defined function (UDF) language of the Fluent commercial software was proposed by Zhao and Sun (2010) to simulate the problem in which two trains simultaneously pass each other. A two-dimensional test case was employed for validation; the results indicated that this method can satisfy the computational requirements and be easily extended to a three-dimensional simulation. Chu et al. (2014) employed a three-dimensional, compressible, RNG $k-\varepsilon$ turbulence model and the sliding mesh method to investigate the influence of the tunnel length, the blockage ratio, the train speed and the intersecting location on the interactions of the aerodynamic waves generated by two trains that pass each other in a tunnel. The pressure change of the tunnel centre axis was analysed at different times. The results revealed that the pressure and drag coefficient of the train reach a maximum at the midpoint of the tunnel; the pressure and drag coefficient increase as the train speed and blockage ratio increase; the side force is primarily dependent on the train/train interaction and the maximum occurs when the two trains are aligned side by side.

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Many studies have investigated the interaction influence of train/tunnel pressure waves and force coefficients for a single train passing through a tunnel and two trains crossing inside a tunnel by numerical simulation (Wang et al., 2015; Liu et al., 2017a), moving model test (Miyachi et al., 2016; Zhang et al., 2017) and full-scale test (Ko et al., 2012; Liu et al., 2017b). The aerodynamic effect on high-speed trains that travel in the open air and are exposed to wind has also been investigated by many researchers (Liang et al., 2006; Yu et al., 2016). From 2014 to 2015, for the successful launch of the Lanzhou-Xinjiang high-speed railway, some full-scale tests were performed to investigate the aerodynamic performance of high-speed trains that operate in windy areas and tunnels. According to the requirements and test procedures for aerodynamics in tunnels (BS EN 14067-5, 2010), no initial airflow should exist in a tunnel for the full-scale measurement of pressure changes. However, if initial airflow is present, its influence on the measurements should be determined. The Xinjiang railway operates in a windy area, and the number of days with level 8 winds (17.2 m/s-20.8 m/s) exceeds 200. Thus, a weak or strong wind existed during the tests. When full-scale tests were performed in windy areas, a greater wind speed was measured along the line when the ambient air was affected by the terrain and windbreak, which created a larger airflow in the tunnel. Consequently, the train was impacted by the combined effect of the initial airflow and train-induced airflow. Thus, the flow field around trains in this region is more complex, especially for two trains that intersect inside a tunnel. To accurately evaluate the aerodynamic effect caused by two trains that intersect inside a tunnel in ambient wind, the effect of ambient wind on pressure waves in the tunnel must be considered using relevant numerical simulations and field test data. However, few studies have addressed this problem. Therefore, the objective of this study is to investigate the problem using the sliding mesh method. The simulation results are analysed to understand the influence of ambient wind on the pressure waves and aerodynamic forces of trains inside a tunnel.

Section 2 of this paper describes the numerical analysis method, the computational geometry model and grid, and other computational details. The results from the simulations and their validation are presented and discussed in Section 3. The paper is concluded in Section 4.

2. Numerical analysis

2.1. Methodology for train/tunnel numerical simulation

Different numerical methods for studying train/tunnel aerodynamics are available, including one-/two-/three-dimensional, incompressible/compressible, and steady/unsteady flow methods (Ozawa, 1992; Mei, 1997; Yu, 2004; Saito and Iida, 2006; Choi and Kim, 2014; Uystepruyst et al., 2011; Muñoz-Paniagua et al., 2014). According to the recent literature (Chu et al., 2014), and considering the real conditions of this study and the computational accuracy and effectiveness, a three-dimensional, compressible, unsteady, RNG $k-\varepsilon$ two-equation turbulent model and decomposed sliding mesh method are utilized.

2.1.1. RNG $k-\varepsilon$ turbulent model

In terms of train/tunnel aerodynamics, the $k-\varepsilon$ turbulent model is extensively applied because of its effectiveness and reliability. The standard $k-\varepsilon$ turbulent model is the simplest and most adaptable model for a simple geometry and flow (Pope, 2000) and is extensively employed for flows with a high Reynolds number. The components of the Reynolds stress for the standard $k-\varepsilon$ turbulent model are isotropic, which is an unrealistic hypothesis. To remedy this flaw, an RNG $k-\varepsilon$ turbulent model was developed by Yakhot and Orszag (1986). The RNG $k-\varepsilon$ turbulent model differs from the standard $k-\varepsilon$ turbulent model as follows: the standard model considers the rotational flow in the mean flow by amending the turbulence viscosity, while the RNG model has an additional term in the function and reflects the main flow time-average strain rate (User’s Guide, FLUENT, 2003). These improvements improve the credibility and accuracy of the RNG $k-\varepsilon$ turbulent model in an extensive flow field analysis. The governing equations of the RNG $k-\varepsilon$ turbulent model are as follows:

Turbulent kinetic energy k equation:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\alpha_k \mu_{eff}\frac{\partial k}{\partial x_j}\right]+G_k+\rho\varepsilon \tag{1}$$

Turbulent dissipation rateεequation:

$$\frac{\partial(\rho \varepsilon)}{\partial t}+\frac{\partial(\rho \varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\alpha_\varepsilon \mu_{eff}\frac{\partial \varepsilon}{\partial x_j}\right]+\frac{C_{1\varepsilon}^{*}\varepsilon}{k}G_k-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{2}$$

where ρ is the air density; u_i is the velocity component in the i direction; $\alpha_k=\alpha_\varepsilon=1.39$ is the turbulent Prandtl number in the k equation and the εequation, respectively; μ_{eff} is the effective dynamic viscosity; G_k is the generation of the turbulent kinetic energy based on the mean velocity gradients; and $C_{1\varepsilon}^{*}$ and $C_{2\varepsilon}$ are model coefficients, where $C_{2\varepsilon}=1.68$.

In addition,

$$\mu_{eff}=\mu+\mu_t \tag{3}$$

where$\mu$is the dynamic molecular viscosity of the air, μ_t is the turbulent viscosity and

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon} \tag{4}$$

$C_\mu=0.0845$ is the model coefficient. Another model coefficient, $C_{1\varepsilon}^{*}$, is given as

$$C_{1\varepsilon}^{*}=C_{1\varepsilon}-\frac{\eta(1-\eta/\eta_0)}{1+\beta\eta^3} \tag{5}$$

where$C_{1\varepsilon}=1.42$, η_0=4.377, and $\beta=0.012$ are the model coefficients and η is described as

$$\eta=\left(2E_{ij}\cdot E_{ij}\right)^{1/2}\frac{k}{\varepsilon} \tag{6}$$

where$E_{ij}$is the main flow time-average strain rate, which is defined as

$$E_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \tag{7}$$

2.1.2. The decomposed sliding mesh method

To replicate the relative movements of the train/train and train/tunnel scenarios, the two primary methods used are the dynamic mesh method and the sliding mesh method. For a three-dimensional compressible numerical simulation, the dynamic mesh method can simulate the relative motion more realistically than the decomposed sliding mesh. However, the effectiveness and computational sources of the dynamic mesh method are costly, and the mesh distortion is complex and difficult to control because of the mesh reconstruction. The computational effectiveness and the use of sources and time of the sliding mesh method are superior to those of the dynamic mesh method, and the computational results can generally satisfy the requirements (Choi and Kim, 2014). Therefore, the decomposed sliding mesh method is employed in this study.

The decomposed zones of a train travelling through a tunnel are shown in Fig. 1. The computation zone is divided into five zones: Zone 1 is the ground zone, which has a high aspect ratio, in which the mesh can be established in a structured grid. Zone 2 moves with the train; the grid inside this zone is unstructured because of the complex train geometries. The densest grids need to be established in Zone 2, as the flow field near the train surface is complex. To control the number of grids, this zone should not be too large. Zone 3 also moves with the train. In contrast with Zone 2, in regions near the train in Zone 3, the grid can be slightly dense,