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Effects of ground configurations on the slipstream and near wake of a high-speed train

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ABSTRACT

The effects of ground configurations on the slipstream and near wake of a high-speed train are numerically investigated with improved delayed detached eddy simulation (IDDES). Both time-averaged and instantaneous near wake structures and the associated distribution of slipstream velocity are compared for two ground configurations, i.e., stationary ground (SG) and moving ground (MG) conditions. The ground configuration has pronounced effects on the tail vortex structures and the associated slipstream velocity distribution. For both ground configurations, the large scale longitudinal vortices in the near wake are always associated with high slipstream velocity. These tail vortices oscillate more violently for the SG case relative to the MG case. Thus, they transport the fluid with high slipstream velocity departing from the central wake region more efficiently, which explains why the slipstream velocities at the TSI monitoring points are significantly larger for the SG case. The difference of slipstream velocity between the two ground configurations becomes more significant with the bottom wall approached.

1. Introduction

Slipstream is the flow induced by the train's movement, which is generally characterized as a highly turbulent non-stationary air flow (Sterling et al., 2008). High slipstream velocity has direct impacts on the passengers waiting on platforms, trackside workers, loadings on the nearby structures, and also the aerodynamic stability of trains passing by each other (Pope, 2007; Baker et al., 2014a, b). These effects of slipstream become more important with the increasing running speed of the HSTs in recent years (Yang et al., 2015; Ding et al., 2016) and thus need to be taken into account in the development and authorization of new trains (Baker et al., 2014a). Recently, in the full-scale test on the Zheng-Xu high-speed railway line in China, two HSTs (CRH-0207 and CRH-0503) passed by each other with the running speed reaching 420 km/h, respectively. Obviously, the slipstream played the dominant role in the lateral stability of the HSTs in this experiment.

Different techniques, e.g. full-scale field test (Baker et al., 2014a,b), reduced scale moving model test (Baker et al., 2001; Gilbert et al., 2013; Bell et al., 2015), wind tunnel test (Weise et al., 2006; Bell et al., 2014, 2016a,b) and computational fluid dynamics (CFD) simulation (Muld et al., 2012; Hemida et al., 2005, 2014; Yao et al., 2013; Huang et al., 2016; Pii et al., 2014), have been utilized to investigate the slipstream and near wake flow of HSTs. Among which, the full-scale field test is a reliable method for measuring the slipstream of a HST (TSI HSRST, 2008), although it is rather costly. It is worth mentioning that, the field measurements are very sensitive to the environmental conditions, e.g. surrounding circumstance, natural wind, etc. A series of full-scale tests have shown high run-to-run variance with complex surrounding conditions (Baker et al., 2014a). Furthermore, this technique cannot be adopted during the design stage of a HST, since a real running train is needed for the field measurement.

An alternative technique is the reduced-scale moving model test, which becomes more and more popular because of its low cost and simplicity relative to the full scale field measurement (Nayeri, 2013). Particularly, the environmental conditions, including ambient wind, track shape, train-track relative motion, etc., are easier to control in the reduced-scale model tests. It is the recommended experimental technique for the design of a train (CEN, 2013). On the other hand, a number of challenges are also aroused for the moving model test. For example, a complex mechanism system is necessary for accelerating the model,

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maintaining a cruise speed for the model and braking the model (Pii et al., 2014). In addition, the measurement is also sensitive to the experimental setup and the possible flow-induced-vibration of the probes (Pii et al., 2014).

Another way to measure the slipstream is the conventional wind tunnel test with stationary train model, whose primary benefit is the convenience to map the time-average and instantaneous flow structures (Bell et al., 2014). For instance, particle image velocimetry (PIV), smoke or oil-film visualization, hot-wire array and Cobra probe can be easily utilized in the wind tunnel experiments to get detailed information for the slipstream and near wake structures of a HST (Weise et al., 2006; Bell et al., 2014). Moreover, the cost is relatively lower for a wind tunnel experiments than that for a moving model rig and full-scale field measurement. Wind tunnel test was performed by Weise et al. (2006) to analyze the specific region of the slipstream and near wake of a HST. Their flow visualization found two typical flow patterns, i.e. separation bubble and vortex shedding, may occur alternately in the near wake of a train, depending on the geometries of the train tail. Based on wind tunnel experiments with stationary train model and ground wall, Bell et al. (2014) quantified the near wake characteristics and identified the causes of slipstream. They associated the peak of the spectrum of the slipstream velocity with the counter rotating vortices that move outwards from the HST tail. More recently, Bell et al. (2016a,b) found that the near wake of a HST exhibits periodic unsteadiness, which could be attributed to periodic vortex shedding from the side and top surfaces of the train. These periodic vortices feed into the trailing vortices as they moving downstream, thus affecting the distribution of slipstream velocities.

Obviously, in the above mentioned wind tunnel experiments with stationary model, the relative moving between the train and ground is not considered. The effects of the stationary ground configuration on the slipstream have not been quantified yet (Bell et al., 2014, 2016a,b). Nayeri (2013) pointed out the obvious limitation of the conventional wind tunnel test with stationary train model and bottom wall is the boundary layer developed on the wall, which may have high interference with the underbody flow of the HST model (Xia et al., 2017a, b; Zhang et al., 2016). Moreover, the relative motion between the HST and the ground wall cannot be reproduced in the conventional wind tunnel test, unless the techniques, such as moving ground wall and boundary layer suction, etc., are utilized (Hucho, 1998; Kwon et al., 2001; Tian, 2007). Maybe due to the complexity of these techniques, the influence of ground configurations (stationary and moving ground) on the slipstream and near wake of a HST has not been thoroughly studied in literatures. This influence is expected to be more significant when the HST becomes slender (high length to height ratio) and the ground clearance becomes smaller.

With the increasing availability and accuracy, computational fluid dynamics (CFD) has become a viable tool for the investigation of HST aerodynamic. Generally, CFD can overcome the limitations of practical wind tunnel test. For instance, the moving ground can be simulated easily and models or approximations exist to handle high Reynolds number cases. Furthermore, CFD provides much more detailed information of the flow, which is helpful for understanding the inherent physics and mechanism of the issues concerned (Hemida et al., 2005). Detached eddy simulation (DES) has been successfully used to predict the slipstream and crosswind assessment of complex trains (Muld et al., 2012; Yao et al., 2013, 2014; Huang et al., 2016). Two typical dominant flow modes were identified in the wake by Muld et al. (2012) using DES, i.e., vortex shedding and the bending of the counter-rotating vortices. A pair of longitudinal vortices in the time-averaged flow has been identified by several researchers (Baker, 2010; Hemida et al., 2014; Muld et al., 2012; Xia et al., 2017b; Yao et al., 2013), which move initially towards the ground and then away from each other. However, the instantaneous longitudinal vortices and the relevance between the slipstream and the unsteady wake are not fully understood.

The main objective of the present work is to compare the slipstream and the near wake structures of a HST with a stationary ground (SG) and a moving ground (MG) using the improved delayed detached eddy simulation (IDDES). Distribution of the slipstream around of a HST, vortex shedding frequencies and both time-averaged and instantaneous near wake structures will be addressed, to get a comprehensive understanding of the effects of ground configurations.

2. Methods

2.1. Computational model and domain

A 1/8th scale CRH3 high-speed train model with three coaches was used in the simulation, which included two head coaches and one middle coach. The train model was 9.567 m long (L) × 0.407 m wide (W) × 0.453 m high (H), with a cross section area of 0.172 m^2, as shown in Fig. 1. A lot of details were considered in the HST model, including cowcatchers, bogies, windshield, inter-carriage gaps and air conditioning fairings, etc. In addition, the two railway tracks under the HST were also considered in the simulation.

As shown in Fig. 1, the computational domain was 37H (length) × 26H (width) × 18H (height), where H is the height of the HST model. Fig. 1 also shows the definition of the coordinate system (x, y, z), with the origin 0 on the ground. The boundary conditions were specified as following: velocity inlet for the inlet; pressure outlet for the outlet; non-slip wall condition for the train body and the stationary ground; moving wall with the same velocity as the inlet for the moving ground; slip wall condition for the rest boundaries. The oncoming flow velocity U_∞ was 61.11 m/s, corresponding to the Reynolds number, based on U_∞ and W, of 1.65 × 10^6, which is far higher than the minimum Re (0.25 × 10^5) recommended by CEN (2013) for model-scale slipstream tests.

2.2. Numerical method

All the simulations presented were completed in the commercial code STAR-CCM+9.04.009, developed by CD-Adapco. The time-dependent IDDES (based on SST k-ω model) used in this paper is a hybrid RANS-LES model (Shur et al., 2008), which combines the advantages of the delayed detached eddy simulation (DDES) and the wall-modelled large eddy simulation (WMLES). The DDES provides shielding against grid-induced separation (GIS) caused by the grid refinement beyond the limit of the modelled stress depletion (MSD) (Spalart, 2009). One the other hand, the WMLES model is designed to reduce the Reynolds number dependency and to allow the LES simulation of wall boundary layers at much higher Reynolds numbers than the standard LES models (Shur et al., 2008; Huang et al., 2016). In the present IDDES, a new subgrid length-scale is defined in Eq. (1), including explicit wall-distance dependence, which is different from the traditional LES and DES involving only the grid-spacing. The primary effect of Eq. (1) is to reduce Δ and also to give it a fairly steep variation, leading to a similar trend in the eddy viscosity (especially with the Smagorinsky model, as opposed to transport-equation models), which is likely to de-stabilize the flow (Shur et al., 2008).

$$\Delta = \min\{\max[C_w d_w, C_w h_{max}, h_{wn}], h_{max}\} \tag{1}$$

In Eq. (1), d_w is the distance to the wall, h_{wn} is the grid step in the wall-normal direction, and C_w is an empirical constant which is equal to 0.15 based on a wall-resolved LES of channel flow (Shur et al., 2008). $h_{\max}$ in Eq. (1) is defined as the largest local grid spacing, as shown in Eq. (2). The complete formulations for the IDDES are not shown here for simplicity. Readers may refer to Shur et al. (2008) for further details.

$$h_{max} = \max\{h_x, h_y, h_z\} \tag{2}$$

The present simulations employed a segregated incompressible unstructured finite-volume solver. To discretize the convective terms of the momentum equations, a hybrid numerical scheme (Travin et al., 2000)