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Numerical simulation of the Reynolds number effect on the aerodynamic pressure in tunnels

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ABSTRACT

With an increase in train speed, the aerodynamic effects caused by the train could escalate, especially for a train running in a tunnel. A number of large transient pressure waves are generated owing to the confined spaces within the tunnel, resulting in possible damage to the vehicle structure and the facilities in the tunnel. Therefore, it is necessary to study the aerodynamic performance of a train running in a tunnel. A scaled moving model test system was constructed to facilitate the simulation of the aerodynamic effects caused by a train running in a tunnel. In this study, the influence of grid density, calculation time step, and turbulence model on the pressure caused by the train entering the tunnel was analyzed, which is helpful for choosing suitable values of the aforementioned parameters to simulate the aerodynamic performance of the train in the tunnel. The impacts of Reynolds number effect on the distribution of the surface pressure and peak of pressure wave along the train, and the pressure waveform were also studied through numerical simulation on three scaled model trains (full scale, 1/8, 1/20, and 1/32 scaled). The findings aid in understanding the relationship between the Reynolds and pressure amplitude, and the results of the scaled test can be applied to a full-scale train.

1. Introduction

The Reynolds number effect is a complex subject. An online experiment with a full-scale train model is the closest to the practical operation of a train, but it is too expensive, and some test items can be difficult to obtain. With the rapid development of high-speed trains, the scaled model test has been widely used in wind tunnels for investigating the aerodynamics of a train in open air (Bocciolone et al., 2008; Cheli et al., 2010a,b; Schober et al., 2010; Bell et al., 2017). Considering that the impact of Reynolds effect on the aerodynamics of the train is evident, the Reynolds effect of the test must be in the self-simulation zone. Only thus, the Reynolds effect would be relatively small. In order to investigate this mechanism and the degree of influence of the Reynolds effect, some scholars have studied the influence of the Reynolds effect on the aerodynamic performance of a train over many years (Baker and Brockie, 1991; Kwon et al., 2001; Cheli et al., 2013; Niu et al., 2016). Based on the conclusions of past research, the scale of the train model in most current research and experiments is less than 1/20th. Bell et al. (2014) investigated the slipstream of a 1/10th scale model of high-speed trains via velocity flow mapping in the wake and streamwise measurements with dynamic pressure probes in an experiment, and presented the impact of the modeling ballast and rail or flat ground configuration on the wake structure and the corresponding slipstream results. Bell et al. (2017) also studied the effect of tail geometry on the slipstream and unsteady wake structure of high-speed trains in a 1/10th scale wind tunnel experiment. Niu et al. (2017a,b) studied the effect of turbulence conditions on the aerodynamic force and pressure of the train by using a 1/8th scale train model in a wind tunnel.

However, in the case of trains running in a tunnel or passing by each other, the aerodynamic performance of the train could not be replicated in the wind tunnel test. And there is obviously difference in flow flied around the train between tunnel and open air (Faramehr and Hemida, 2016). According to previous research (Dorigatti et al., 2015; Premoli et al., 2016), it was determined that there is a difference between the aerodynamic performances of stationary and moving trains in open air, but the difference is not very large, and is in the acceptable range. In

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order to solve the above problems, a scaled moving model test system was constructed to simulate the aerodynamic performance of a train. Some scholars used the scaled moving model test to study the aerodynamics of trains. Bellenoue et al. (2002) studied the generation of the initial compression wave and the three-dimensional effect of the entrance, and determined that the scale effect mainly changed the amplitude of the pressure wave in the tunnel, but did not the affect its gradient; further, they proposed an axisymmetric model based on the results of this study, and it can be beneficial in replacing the three-dimensional model. Kim and Kim (2007) simulated the aerodynamic performance of a metro train running in a tunnel using numerical simulation and a 1/20th scale moving model test, and analyzed the influence of acceleration and deceleration of the train on the amplitude and distribution of pressure in the tunnel. They determined that the deceleration of the train is faster when it is close to the tunnel exit, and the difference between the numerical simulation and test is in the range of 12.3%–17.2%. Liu et al. (2010) studied the influence of different kinds of hoods and their parameters on the pressure in the tunnel and the micro-pressure wave at the tunnel exit using a moving scale model test and numerical simulation, and established the relationship between the amplitude of the micro-pressure wave and the parameters of hood, including length, expanding section area, window area etc. Doi et al. (2010) developed a $1/30^{th}$ scale train model moving test that can realize a high-speed train passing through a tunnel with a speed of 500 km/h, and studied the effect of the shape of tip of the train on the intensity and formation of the pressure wave in the tunnel. Gilbert et al. (2013) studied the three-dimensional velocity distribution in the tunnel using a 1/25th scale dynamic model experiment and a Cobra probe, and determined that the piston effect is the main reason for the rise in gusts caused by the train in the tunnel, and the flow characteristic of the tunnel is affected by the tunnel length. Heine and Ehrenfried (2014) identified an extended, vented tunnel portal, which reduces the pressure gradient of the initial compression wave by approximately 45% in a 1/25th scale moving model experiment. Yang et al. (2016) designed a scaled (up to 1/8th) moving model facility, whose power was supplied by a compressed air gun, and the speed of model with a weight of 106 kg in the facility can be up to 500 km/h; further, a scale model braking in 70 m can be achieved using permanent magnets. Using sensors and a mining system, the pressure wave of the scaled train model running in open air and a tunnel can be obtained in this facility. Nevertheless, there are few studies on the Reynolds effect on the aerodynamic effects caused by trains running in a tunnel.

The purpose of the investigation reported in this paper was to analyze the impact of the Reynolds effect on the aerodynamic pressure of the train and the pressure wave generated by the train in the tunnel. A series of numerical simulations on four scaled model trains (full scale, 1:8, 1:20, and 1:32 scaled) were conducted for a range of Reynolds from 0.54×10^6 to 17.2×10^6. The impact of the Reynolds effect on the distribution of pressure along the train, pressure waveform, and the distribution of peak of pressure wave in the tunnel along the train are also briefly described.

2. Numerical simulation

2.1. Train and tunnel models

In this study, a high-speed train (Fig. 1a) was used as a model, which was simplified for the purpose of numerical simulation in accordance with the CEN European Standard (2003), and the model in Fig. 1b was used in this simulation. The height (H) and width (W) of the full-scale train model were 3.7 m and 3.38 m, respectively, as shown in Fig. 1c. The overall train length (L_{tr}) of the full-scale train model with eight cars was approximately 203 m, length of the head car and tail car was 26 m, and length of each middle car was 25 m.

In order to facilitate comparison with experimental data, the model in numerical simulation was established according to the size of the full-scale experiment. The effective cross-section area of the tunnel used in this study was 92 m^2, and the distance between the two railway lines in the tunnel was 4.6 m, as shown in Fig. 1e. While the tunnel length is critical, the pressure wave in the tunnel is the most unfavorable (Wang et al., 2012; Sun et al., 2014). The critical tunnel lengths in these numerical simulations were 1 465 m and 944 m, respectively. These lengths were calculated using Equations (1) and (2) (CEN European Standard, 2010), and correspond to the critical (or most unfavorable) lengths from an aerodynamic point of view. These equations are used for two types of conditions: a train traveling through the tunnel (Equation (1)), and two trains crossing each other in the tunnel (Equation (2)).

$$L_{tl,crit} \approx (L_{tr,1}/4)(c/U_1)(1 + c/U_1) \tag{1}$$

$$L_{tl,crit} \approx (c/2)/(L_{tr,1}/U_1 + L_{tr,2}/U_2) \tag{2}$$

where U_1 *and* U_2 are the train speeds (69.44 m/s); c is the local sound velocity (340 m/s in this study); $L_{tr,1}$ *and* $L_{tr,2}$ are the train lengths; $L_{tl,crit}$ is the critical tunnel length.

2.2. Numerical algorithm and parameters

2.2.1. Choice of turbulence models

The κ-ε turbulence model in the Reynolds-averaged Navier-Stokes (RANS) method has been widely used to simulate the aerodynamic performance of trains (Ogawa and Fujii, 1997; Baron et al., 2001; Yao et al., 2014). In recent years, with the improvement of computing capability, large eddy simulation and detached-eddy simulation are being widely used in numerical simulations of train aerodynamics (Muld et al., 2012; Niu et al., 2017a,b; Wang et al., 2017). However, for numerical simulations of pressure wave caused by a train entering a tunnel, RANS is still the first choice in these methods, and the effect of RANS is still remarkable (Mok and Yoo, 2001; Xue et al., 2014; Liu et al., 2010, 2017; González et al., 2014; Niu et al., 2017a,b). Huang et al. (2010, 2012), Rabani and Faghih (2015) adopted the Renormalization Group (RNG) κ-ε turbulence model and N-S equations to simulate the aerodynamic

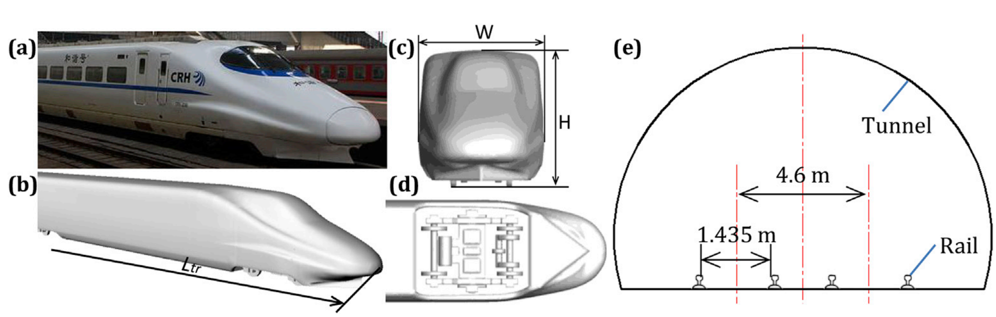

Fig. 1. (a) High-speed train model. (b) Digital train model for numerical simulations. (c) Lateral dimensions of the train model. (d) Bogie of train model. (e) Two-dimensional map of the tunnel.