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A new method to measure the aerodynamic drag of high-speed trains passing through tunnels

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ABSTRACT

Due to the infeasibility of using a wind tunnel to measure the aerodynamic drag coefficient of a high-speed train entering and passing a tunnel, a new moving model test method is proposed. A photoelectric sensor is fixed at the bottom of the train to scan the printed zebra stripes which are pasted along the track, from which the train displacement is obtained and the speed and acceleration can be calculated. The train aerodynamic drag coefficient before entering the tunnel and the drag coefficient of a train running inside the tunnel can be obtained based on Newton's Second Law. The results show that the aerodynamic drag coefficient of the train before entering the tunnel barely changes at different positions which can be considered as constant, but the value decreases as the train passes through the tunnel. This phenomenon is caused primarily by the transient airflow inside the tunnel. Comparisons with the verified numerical simulations are performed and good agreement with difference less than 7% is reached, which implies that the moving model method proposed in this paper is feasible and reliable.

1. Introduction

High-speed railways have become a popular and important mode of transportation in modern society due to its advantages of high speed and efficiency, which draws increasing attention worldwide (Shen, 1997). The total worldwide length of high-speed railway lines is expected to reach 0.59 million kilometres by 2025. In China, the high-speed railway operation mileage has reached 22,000 km at the end of 2016, at the forefront of the world (Gao and Zhang, 2016). However, as train speeds increases, the train aerodynamic drag increases dramatically, resulting in huge energy consumption (i.e., the energy consumed by high-speed trains with speed of 345 km/h can reach 385.21 kJ/(t.km), approximately 2 times of trains with speed of 225 km/h, and majority of the energy are consumed to overcome the running resistance (Wang, 2012)). In particular, when a train passes through a tunnel, the aerodynamic resistance will accounts for at least 90% of the total resistance for a train speed of 300 km/h (Kwon et al., 2001) and occupies the leading position of all resistance mechanisms, even at low train speeds in tunnels. (Baron et al., 2001).

Unlike the case of a train running in open air, the aerodynamic drag changes continually as a train passes through a tunnel (Schetz, 2001). Since the train model in the wind tunnel test is stationary and fixed on the ground, the wind tunnel tests are unsuitable for studies of the aerodynamic performance of trains in tunnels. The full-scale field test is the most reliable but costly way, this method is easily affected by environmental factors and cannot be conducted during the early shape design phase of high-speed train manufacturing, whereas information concerning the aerodynamic drag is incredibly valuable in that stage (Wang and He, 1994; Golovanevskiy et al., 2012). Numerical simulation is the most popular method adopted in the research of tunnel aerodynamic performance because of its efficiency and relative low dependency on environmental factors. Numerical simulations of the train transient aerodynamic drag in tunnels when two trains pass each other in the same tunnel have been performed, and the dynamic aerodynamic drag curve has been obtained (Iida and Maeda, 1990). The relationship between the train aerodynamic drag and the transient pressure was calculated using a one-dimensional unsteady pressure model and laminar transient viscous heat transfer model (Vincent, 1999). By using the uncompressible viscous model, the aerodynamic drag of the train running in a circular tunnel is smaller than in rectangle tunnel, and the maximum aerodynamic drag of a train in a tunnel is approximately 2.5 times that of a train in open air (Wang et al., 2012).

Because the wind tunnel experiment cannot simulate the ground effect of a high speed train and the relative motion between the train and the tunnel, a moving model rig on which the train model runs along a track has been developed (Tian, 2007). This method can more accurately

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simulate the relative movement of the train, air, and ground without any interference from any floor boundary layer (Pope, 1991; Humphreys and Baker, 1992; Sun, 2012). Moving model rig techniques currently used in testing include compressed air type and rubber ejection type. The compressed air moving model rigs are mainly located in South Korea (Jang et al., 2009; Kim and Kang, 2011), Japan (Doi et al., 2009), the Netherlands (De Wolf and Demmenie, 1997) and Southwest Jiaotong University in China (Luo, 2003; Zhao, 2004). While for rubber ejection moving model rigs, one set is owned and operated by the University of Birmingham in Derby of UK (Dorigatti et al., 2015) and the other set belongs to Central South University in China (Miao et al., 2012).

Multiple moving-model experimental studies have been performed (Hara and Okushi, 1962; Li et al., 2010; Li et al., 2011). However, all these studies focus on the aerodynamic characteristics when multiple trains pass each other or run through tunnels, but no study has addressed the aerodynamic drag of trains running through tunnels. This paper proposes a new moving model test method to measure high-speed train aerodynamic drag, which will provide a new and valuable resource for estimation this parameter.

2. Moving model test principle of train aerodynamic drag coefficient

The total resistance of a train comprises the mechanical resistance and aerodynamic resistance (Raghunathan et al., 2002), which can be expressed using different equations, among which the Davis equation is widely accepted and applied (Rochard and Schmid, 2000). The Davis equation can be described as

$$R = A + BV_t + CV_t^2. \tag{1}$$

where, R is the total operating resistance of the train. V_t is the train speed. A (N), B (N·s/m), and C (N·s^2/m^2) are the coefficients generally obtained from the coasting experiment. A is the mechanical operation resistance caused by the wheel and track friction and is proportional to the train mass and BV_t includes all the other mechanical resistances, including transmission loss, braking resistance, and air momentum resistance. When a train operates normally, the circulating engine heat, cooling system, and the on-board air conditioner absorb and discharge air. The air momentum resistance is related to the air intake and discharge. CV_t^2 is the train aerodynamic drag and is proportional to the square of the train speed (Schetz, 2001).

However, Davis equation can be used only in straight line conditions in open air without natural wind, for trains that tun through tunnels, the equation is modified as follows:

$$R = A + BV_t + T_f CV_t^2 \tag{2}$$

where T_f is the additional coefficient caused by the tunnel and $T_f \geq 1$. The additional coefficient T_f is affected by factors of blocking ratio, train speed, train length and tunnel length.

The coefficient of the aerodynamic term $T_f C$ can be expressed as:

$$T_f C = \frac{1}{2}\rho S_x C_{tx} \tag{3}$$

Here, $\rho = 1.225$ kg/m^3 is the air density. S_x is the reference area that generally corresponds to the train cross section and C_{tx} is the total aerodynamic drag coefficient of the train in the tunnel. Since the difference of the train mechanical resistance inside and outside the tunnel is small, the aerodynamic drag coefficient C_{tx} can be expressed as:

$$C_{tx} = 2T_f C/(\rho S_x) \tag{4}$$

Then the additional tunnel coefficient T_f can be calculated as:

$$T_f = C_{tx}/C_x \tag{5}$$

Here, C_x is the train aerodynamic drag coefficient outside the tunnel. Based on the coasting experiment principle and Newton's second law, the relationship between the train operation resistance and the train operation acceleration can be described is

$$R = A + BV_t + T_f CV_t^2 = Ma \tag{6}$$

where M is the mass of the high-speed train and a is the train operation acceleration.

For a train that runs outside a tunnel, the additional tunnel coefficient $T_f = 1$. Thus, the measurement of the aerodynamic drag coefficient can be transformed into a measurement of the train model speed and acceleration.

Three methods are available to measure the train model acceleration: (1) Directly using an acceleration sensor in the coasting test. (2) Calculating the first derivative of the velocity versus time. (3) Calculating the speed difference between a time interval and dividing this difference by the time interval.

Although the first method is the simplest and most direct, it involves an irreconcilable contradiction that the train model will be lunched by the power system to achieve the train speed and stopped by the braking system in a very short time (0.25–0.35s) (Zhou et al., 2014), resulting in huge acceleration which can reach 50 g for the train model itself, whereas the actual acceleration caused by air resistance is much less than 1 g, thus the selected acceleration sensor range is significantly larger than the target measured value and inertia of the train model itself, which will result in large experimental errors. Therefore, the indirect measurement method should be used.

Expressing the motion displacement as a function of time as $s(t)$, then the train model velocity at a certain time can be calculation as:

$$v(t) = \frac{ds}{dt} = \lim_{\Delta t \to 0} \frac{s(t+\Delta t) - s(t)}{\Delta t} \tag{7}$$

Then the acceleration can be obtained as follows:

$$a(t) = \frac{dv}{dt} = \frac{d^2 s}{dt^2} \tag{8}$$

In additional, the average acceleration can be expressed as

$$\bar{a} = \frac{v(t+\Delta t) - v(t)}{\Delta t} \tag{9}$$

Based on this principle above, the moving model test system to measure the train aerodynamic drag coefficient was developed and series of experiments were conducted.

3. Facility and system of the moving model test

3.1. Moving model rig

Experiments were conducted on the moving model rig at Central South University in China. As shown in Fig. 1, the experimental line is a compound line with a total length of 164 m which is divided into an accelerating section, a testing section and a braking section. This moving model experiment system includes the experimental table, power system, acceleration system, control system, test system, brake system, data processing system, and experimental model. The experimental table can simulate the above ground line operation conditions of the train, however due to the space restriction, structures of ballast and subgrade with rails that a real train operated on are not precisely constructed, which may underestimate the contribution of the underbody aerodynamic drag but accounting for relative very small part of the train total aerodynamic drag. The acceleration system of the moving model device uses the multilevel aerodynamic pulley acceleration mechanism, which can achieve a maximum experimental speed of 500 km/h (Tian, 2015). To prevent electromagnetic disturbance of the onboard system and high impact