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Effect of train length on fluctuating aerodynamic pressure wave in tunnels and method for determining the amplitude of pressure wave on trains

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ABSTRACT

In this study, the aerodynamic performance of full-scale trains of different lengths going through or crossing each other in a tunnel was investigated using sliding mesh technology and a numerical algorithm developed and verified through a full-scale train test. The waveforms of the fluctuating pressure distribution on the train and in the tunnel were compared and analyzed, and the effect of the train length on the flow field in the tunnel examined. The results show that, because of the significant difference in pressure amplitude, long trains cannot be replaced by short trains when simulating trains going through or crossing each other in tunnels. However, some common regular patterns, such as the distribution of the peak values of the time evolution of pressure on the train and in the tunnel, can still be found in both cases. It was found that, for the evaluation of the fatigue effect induced by pressure on the train body, the equivalent load method based on the Paris formula is more secure and reliable than the root-mean-square equivalent load method. It was also discovered that, while analyzing the effect of the fluctuating aerodynamic pressure, it is better from the viewpoint of safety to consider the maximum pressure on the constant-section part of the train body as the representative parameter.

1. Introduction

With the increasing speed of high-speed trains, the security and comfort of train body structures, builders close to the railway tracks, and workers in tunnels are increasingly affected by the fluctuating aerodynamic pressure induced by trains going through tunnels or passing each other in a tunnel (Fujii and Ogawa, 1995; Raghunathan et al., 2002; Tian, 2015; Liu et al., 2017; Niu et al., 2017). Examples of the damage to the train and the tunnel resulting from the aerodynamic pressure are shown in Fig. 1. Therefore, an increasing number of scholars have studied the aerodynamics of the train and tunnel through different experimental, numerical, and theoretical methods (Howe et al., 2006; Zhang et al., 2017; Gilbert et al., 2013; Liu et al., 2016). At present, the scaled moving model test and numerical simulation are the main methods used to simulate the aerodynamic effects on trains running through tunnels (Liu et al., 2017, 2016; Niu et al., 2017; Howe et al., 2006; Zhang et al., 2017; Gilbert et al., 2013). Because of limitations of both the cost and size of test equipment, full-scale train tests are mainly conducted for verification (Niu et al., 2017; Zhang et al., 2017; Liu et al., 2016). The length of trains in the scaled train model test is short because it is restricted by the site and equipment of the test (Zhang et al., 2017; Yang et al., 2016). Therefore, it is very difficult to evaluate the aerodynamic effects on a train with long length running through a tunnel by using the scaled train model test. Considering that tests are usually performed under extreme operating conditions, for the cases of a train going through a tunnel or two trains crossing each other in a tunnel, the tunnel length is generally the most unfavorable aspect for conducting tests (Niu et al., 2017; Chen et al., 2017).

Many scholars have studied the effect of length on the train's aerodynamic performance. In reference (Huang et al., 2012); the drag distribution per car was studied using a wind tunnel; it was found that the tail car drag is smaller in two-car trains than in trains with three or more cars. In reference (Guo et al., 2016); the effect of train length on the train-induced air flow was studied using numerical simulations, and it was found that the velocity of the longitudinal component of the train-induced air flow increased with the increase in train length. Using a delayed detached-eddy simulation, Muld et al. (2014) found that the shedding frequency and length of vortices in the wake flow were mainly affected by the train boundary layer thickness. Based on a dynamic train model test, Bell et al. (2015) found that the train boundary layer thickness increased with the increase in train length. In reference (Mao et al., 2012); the aerodynamic performance of trains of different lengths

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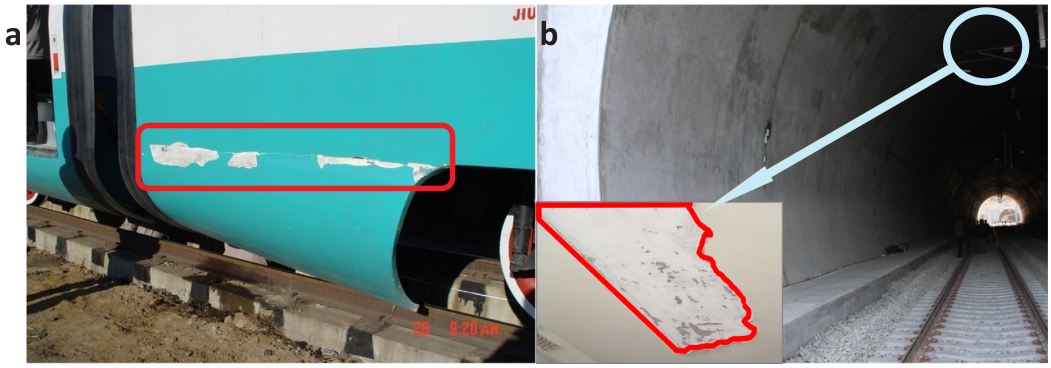

Fig. 1. Damage on train and tunnel: (a) Crack on the train. (b) Fall of lining structure.

in cross winds was investigated, and a non-dimensional relationship was established between the train drag coefficient and the number of cars; it was determined that the use of the aerodynamic force of the head car to evaluate the aerodynamic safety of the whole train tends to be a conservative approach. It is well established in the CEN European Standard (2003) that the train length is an important factor in determining the airflow in tunnels. Some scholars also found correlations between the train length and the compression wave in tunnels. Using dynamic train model tests, Ricco et al. (2007) found that, for longer trains, the first compression wave not only has a higher amplitude but also lasts longer. In reference (Martínez et al., 2008), the authors found that the peak of the first compression wave produced by a long train is higher than that produced by a short train, and that the tail-generated expansion wave reaches the head of short trains earlier than in the case of long trains. Muñoz-Paniagua et al. (2014) optimized the nose shape of a high-speed train entering a tunnel using a genetic algorithm, and analyzed the influence of other design variables of the train nose on the train aerodynamic drag. However, literature is scarce on the effect of train length on the waveform, amplitude, and distribution law of pressure waves in the tunnel.

In this paper, the effect of train length on the pressure wave is studied in detail, and the relationship between the train length and amplitude of fluctuating pressure in tunnels is established. Based on the relationship between the train length and fluctuating pressure in tunnels with the most unfavorable length, we can obtain the basic waveform and amplitude of the fluctuating pressure, which helps not only in the design of the system of train and tunnel, but also in guiding the train operation and formation. Based on the waveform and equivalent load method in fatigue-analysis techniques, a method for choosing the amplitude of the pressure wave on trains is determined. Therefore, it is of great significance to establish the relationship between the train length and fluctuating pressure in tunnels with the most unfavorable length.

2. Numerical simulation

2.1. Train and tunnel models

The high-speed train shown in Fig. 2a was used as the model in this study. The train model was simplified for numerical simulation in accordance with the CEN European Standard (2010), as shown in Fig. 2b. As is well known, high-speed trains are composed of different numbers of identical cars (except for the head and tail cars), and the number of cars in a train can be increased or decreased depending on the number of passengers. The train dimensions are shown in Fig. 2c and d. The height (H) of the full-scale train model is 3.7 m, and N is the number of middle cars. The overall train length (L_{tr}) can therefore be calculated as L_{tr} = (7.16H) × 2 + (6.76H) × N. In this study, four different train lengths are considered: 78 m (3 cars), 128 m (5 cars), 203 m (8 cars), and 403 m (16 cars).

The fluctuating pressure in the tunnel is most unfavorable when the tunnel length has a critical value (Wang et al., 2012; Sun et al., 2014). The tunnel lengths used in the numerical simulations are therefore calculated with Eqs. (1) and (2) (CEN European Standard, 2010) and correspond to the most unfavorable lengths from an aerodynamic viewpoint. These equations are used for two types of conditions: one train traveling through the tunnel (Eq. (1) and two trains crossing each other in the tunnel (Eq. (2). The resulting tunnel lengths are listed in Table 1 for different train lengths.

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

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

where U, U_1, and U_2 are the train speeds (83.33 m/s is considered here in all cases); c is the local sound velocity (340 m/s in this paper); L_{tr}, $L_{tr,1}$, and $L_{tr,2}$ are the train lengths; and $L_{tl,crit}$ is the critical tunnel length.

As shown in Fig. 3, the effective clearance area of the tunnel in this simulation was 100 m^2, and the distance between the two railway lines in the tunnel was 5.0 m. Fig. 3a shows the layout of the measurement points on the train surface. Three monitoring points were arranged on each of the middle cars. Further, as shown in Fig. 3b, there were several

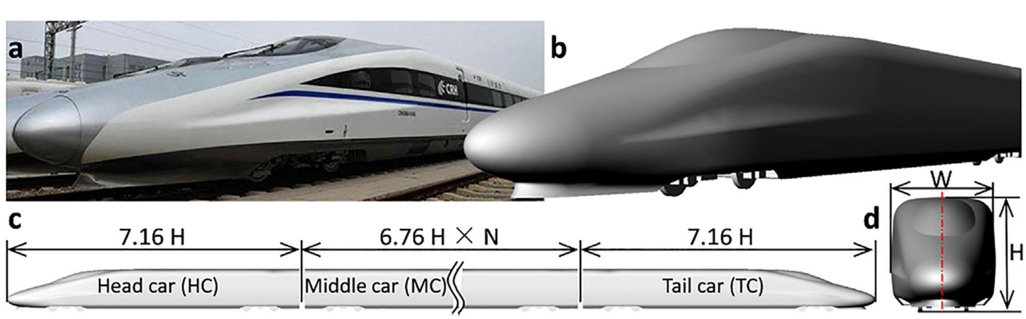

Fig. 2. (a) Train model. (b) Digital train model for numerical simulations. (c) Lateral dimensions of the train model. (d) Front view of the digital train model.