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Experimental study on the effect of Reynolds number on aerodynamic performance of high-speed train with and without yaw angle

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ABSTRACT

The influence of the Reynolds number on the aerodynamic force and pressure of a train was investigated experimentally at yaw angles of 0° and 15°. Two kinds trains were scaled at 1:8 and 1:20, respectively, and the Reynolds number, based on the train height, ranged from 3.02×10^5 to 2.27×10^6. The pressure distribution along a train at yaw angles of 0° and 15° was researched, and the results are compared herein. The difference in Reynolds number effect between the head and tail cars is also discussed. The results show that the lift coefficient of a train increases with an increase in Reynolds number at a yaw angle of 15°, and the other force coefficients decrease with an increase in Reynolds number. There are significant differences between the positive and negative pressures in terms of the Reynolds number effect. The yaw angle weakens the Reynolds number effect on the pressure coefficient on the head car, whereas the influence of the yaw angle on the Reynolds number effect on the pressure coefficient for the tail car is relatively complex.

1. Introduction

A wind tunnel test is one of the most widely used methods in the study of train aerodynamic characteristics. It has the advantages of a ripe experimental theory and method, high measurement accuracy, and ease of airflow parameter control, and is basically unaffected by weather. However, the train model used in a wind tunnel is scaled down, and thus the Reynolds number effect on a scaled model in a wind tunnel test poses a significant problem, and is far less than that of a full-scale test. Although the Reynolds number enters a self-simulation zone, and the Reynolds number effect is relatively small, no accurate conclusions can be made regarding the range and degree of influence of the self-simulation zone, i.e., whether the results of a scaled test can be applied to a full-scaled train. The variations in the laws of aerodynamic force and pressure on different positions of a train surface with the Reynolds number are unclear. This problem is of great importance for all types of vehicles, and has resulted in significant attention from experts and scholars, with a number of phenomena and research results having been found; however, there are still certain aspects that have received little attention at present, for example, the impact of the Reynolds number effect on the surface pressure of the streamlined zone of a high-speed train.

Baker and Brockie (1991) studied the effect of different types of ground simulation and varying Reynolds number on the wind tunnel measurements of the aerodynamic drag of trains, and found that the errors involved in extrapolating the values of the drag coefficient, from a model scale to a full scale, are significantly greater than the possible errors caused by an inadequate ground simulation. Willemsen (1997) studied the drag coefficient for different train head shapes and certain pressure taps located at the train head at varying Reynolds number, and found that both the drag coefficient and positive pressure coefficient on the train head decrease with an increase in Reynolds number. Kwon et al. (2001) tested the drag coefficient for two models of different scales in a wind tunnel using various moving ground simulation techniques (the established Reynolds number is within the range of 4×10^5 to 8.5×10^5), and found that there is almost no Reynolds number effect on the drag coefficients. Schober et al. (2010) tested a 1:15 scale model in an automotive wind tunnel at a Reynolds number of between 0.5 and 0.7 Re_{max} and found that a change in the roll moment coefficient around the leeward track with an increase in the Reynolds number is below 3% for all investigated cases, and that there is a different law of change between the roll moment coefficient around the leeward track and the Reynolds number for a true flat ground, and for a ballast and rail configuration and an embankment configuration. Cheli et al. (2013) studied the change in aerodynamic force coefficient based on the yaw angle (0° to 90°), as well as changes in the pressure coefficient, for a varying Reynolds number (1.3×10^5 to 7×10^5), and found that the lateral

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coefficient increases with an increase in Reynolds number at the different yaw angles, that the difference in the lateral force coefficient for a varying Reynolds number is obvious at a yaw angle of 40° to 70°, and that the yaw angle interrupts the law of change regarding the vertical force coefficient with the Reynolds number. Li et al. (2014) researched the Reynolds number effect on the aerodynamic characteristics and the vortex-induced vibration of a twin-box girder, and found that, with increases in the Reynolds number, the transition point from a laminar flow to a turbulence flow, and the reattachment point of the separated shear layer, gradually move upstream, and the bubble size shrinks. Many scholars (Schewe and Larsen, 1998; van Hinsberg, 2015) have carried out research on the Reynolds number effect on the flow around a cylinder, square column, and bluff bridge. Qiu et al. (2014) studied the mean wind loads on cylindrical roofs with a consideration of the Reynolds number effect and found that the drag and lift coefficients of a semi-cylindrical roof are significantly influenced by the Reynolds number range where the laminar-turbulent transition of the separated shear layer occurs. Schewe (2001, 2013) determined that the Reynolds number effect is caused by changes in the topological structure of a separated flow, which occurs mainly on the lower side of the bridge section, and also found that the effect is stronger in an asymmetric flow than in a symmetric flow. It can be assumed that, because of the symmetry of the time-averaged flow, the effects on the upper and the lower side compensate each other.

The purpose of the investigation reported in this paper was to analyze the influence of the Reynolds number effect on the aerodynamic force and pressure coefficients both qualitatively and quantitatively, contributing to the results of a scaled test that can be applied to a full-scale train. A series of wind tunnel tests with simultaneous multi-pressure and force measurements on two scaled model trains (1:8 and 1:20 scaled) were conducted for a range of Reynolds number of 3.02×10^5 to 2.27×10^6 in a uniform flow with low turbulence. The effects of the Reynolds number on the pressure distributions and aerodynamic force are also briefly described.

2. Methodology

2.1. Experimental setup

Tests were conducted in a high-speed test section of a wind tunnel at the National Engineering Laboratory for High Speed Railway Construction. As shown in Fig. 1, the cross-sectional area of the test section is 3×3 m^2, the length of the test section is 15 m, the minimum and maximum flow speeds in this wind tunnel test are 20 and 60 m/s, respectively, and the turbulence intensity is less than 0.5%. In addition, the maximum scale and yaw angle are 1: 8 and 15°, respectively. Considering the roadbed and floor, the blocking ratio is less than 5%. Thus, the test results do not need to be corrected.

A two-car formation train, scaled at 1:8 and 1:20, is used as the test model, as shown in Fig. 2a and b. As shown in Fig. 2b, the lengths of the head and tail cars are both 6.9*H*, the total length of the train is 13.9*H*, and the distance from the nose tip of the train to the ballast front is 6.0*H*, where *H* is the height from the top surface of the rail to the roof of the train, and is also the characteristic length. The Reynolds number is calculated through formulation (1). Because the wind speed in this test was from 20 to 60 m/s, the range of Reynolds number was 3.02×10^5 to 2.27×10^6. Fig. 3 shows the two types of scaled trains and subgrades used. A ground configuration adhering to the EN (CEN European Standard, 2009, 2010) was modeled.

$$\mathrm{Re} = \rho U_{ref} H/\mu, \tag{1}$$

where the air density ρ is 1.225 kg/m³, U_{ref} is the average speed of the incoming flow, H is the height of the train model and used as a characteristic length, and the air viscosity coefficient μ is 1.8×10^{-5} Pa s.

As shown in Fig. 3, a steel angle is used to make the frame under the plate so as to reduce the blocking ratio and enhance the frame stability. In this experiment, the flow direction cannot be changed by the wind tunnel itself. Thus, to change the direction of the wind direction, we can only rotate the test platform (see Fig. 3a). First, we installed 16 pairs of pulley wheels at the bottom of the bracket (see Fig. 3a), which can help us rotate the test platform quickly and conveniently. The 16 pairs of pulley wheels installed at the bottom of the bracket facilitate the movement of the large plate and the lower bracket. We then designed the side support at the bottom of the bracket, shown in Fig. 3a, which is used to connect the bracket and wind tunnel floor, and some bolts are used to fix them so as to ensure the stability of the test platform during the test. As shown in Fig. 3b, the flat edges are processed into a wedge shape to minimize the influence of the edge shape on the flow field.

2.2. Measurements

As shown in Fig. 4b and c, a TFI Cobra probe 270 was installed at the end of a steel pole 15 mm in diameter, which was fixed to a three-dimensional numerically controlled moving frame

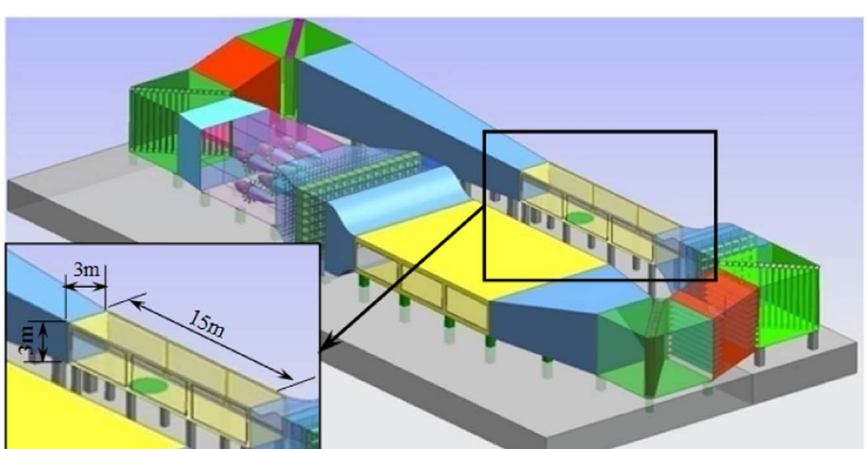

Fig. 1. Double enclosed test section wind tunnel.