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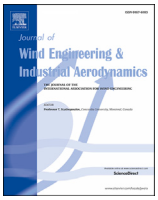

# Experimental study on the effect of wind angles on pressure distribution of train streamlined zone and train aerodynamic forces

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ABSTRACT

The influences of wind angles on the behavior of a high-speed train were investigated using a scaled-down wind tunnel model (1:8 scale) at the wind angles of 0°, 5.14°, 10.2°, 15.11°, and 19.8°. Based on the experimental results elicited at different Reynolds numbers ($9.44 \times 10^5$, $1.26 \times 10^6$, $1.57 \times 10^6$, and $1.89 \times 10^6$, corresponding to the wind speeds of 30 m/s, 40 m/s, 50 m/s, and 60 m/s, respectively), the speed of 60 m/s was determined as optimal for wind tunnel tests. The effects of the incoming flow angles on the pressure distribution of the train's streamlined zone and the aerodynamic forces of the train were analyzed. Results show that the pressure coefficients on the leeward side and the symmetrical plane profile curve of the streamlined zone decreased as the wind angle increased. However, the change in the windward side was opposite to that of the leeward side. The lateral and the absolute value of the lift forces increased rapidly as a function of the wind angle, while the drag force was maximized when the wind angle was 15.11°, followed by subsequent decreases at increasing wind angles.

## 1. Introduction

In recent decades, the optimization of the train's shape has become one of the main approaches used to satisfy the increasing requirements for low-energy consumption, increased safety, and stability for high-speed railway operations. In particular, the optimization of the parameters relevant to the streamlined zone of the train's head has become the focus of optimization investigations. The streamlined part is essential to the aerodynamic performance of the high-speed train that can be effectively improved by optimizing the train's head shape (Baker, 2010a; Willemsen, 1997). However, the airflows around the streamlined zone of the train's head are very complex, and even a minor change of the parameters determining the streamlined shape can result in an obvious variation of the pressure distribution on the surface of the streamlined part, especially when the high-speed train is cruising in cross-wind conditions (Khier et al., 2000; Yao et al., 2014). The change of the pressure distribution induced by the winds at different yaw angles may lead to an obvious variation of the aerodynamic loads on the train, especially for the lift and lateral forces. The increased lift and lateral forces can be hazardous to the operational stability of the train, and even lead to the "train shaking" phenomenon and overturning (Baker, 2009). The effects of wind angles on the pressure distribution of the streamlined part are unclear, and the experimental tests of the influences of the wind angles on the train's aerodynamic forces in a wind tunnel continues to be an important research aspect for the safe operation of high-speed trains.

Numerous investigations have been performed on the aerodynamic performances of trains induced by cross-winds, based on wind tunnel experiments, full-scale tests, and CFD (Computational Fluid Dynamics) simulations, in the UK (Baker, 2003, 2010b, 2013; Baker et al., 2004; Ding et al., 2008; Dorigatti et al., 2015; Hemida et al., 2013; Hemida and Baker, 2010; Sterling et al., 2008), Italy (Bocciolone et al., 2008; Cheli et al., 2010a,b,c, 2011, 2012; 2013; Tomasini and Cheli, 2013), Sweden (Dierichs et al., 2007; Krajnović et al., 2012), Germany (Carrarini, 2007; Hoppmann et al., 2002; Khier et al., 2000; Wetzel and Proppe, 2010), China (Niu et al., 2016, 2017; Xu and Ding, 2006) and Australia (Bell et al., 2014, 2015; Golovanevskiy et al., 2012). Specifically, in the standard EN 14067–6 (CEN European Standard, 2010), a deterministic methodology based on the "Chinese Hat'' wind gust model has been proposed to evaluate the dynamic response of a railway vehicle to cross-wind action. What is more important is the fact that an outline of the stochastic wind model has been included in Annex J in the standard EN 14067–6 (CEN European Standard, 2010; Yu, 2016). However, the wind tunnel test is

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one of the most extensively used methods in the study of the train's aerodynamic characteristics. It has the advantages of a well-developed experimental method, increased measurement accuracy, and ease of airflow parameter control, and is basically unaffected by the weather (Baker, 2002; Bocciolone et al., 2008; Cheli et al., 2011; Chen and Liou, 2011; Niu et al., 2016; Yu, 2016).

The wind and wind angles can affect the atmospheric boundary layer of the train when it passes through wind areas, and can cause a rather complex turbulence around the train. The strong randomness characteristics of turbulence under different wind angles often result in disorderly turbulent flow fields around the train, thereby leading to tremendously increased aerodynamic forces acting on the train that may seriously affect the stability of the train's operation. They may even cause train derailment and rollover accidents (Hemida and Baker, 2010; Niu et al., 2017; Zhang et al., 2016). A 1:20 scale ETR 480 train model adopted by Bocciolone et al. (2008) was used in a wind tunnel experimental test to analyze the crosswind actions on rail vehicles and evaluate the influence of crosswind angles (0°–90°) on the aerodynamics of the railway vehicle. The results indicated that when the train model was set on the viaduct, the drag force coefficient of the head car firstly increased as a function of the wind angle, and reached its maximum value at approximately 70°. Then drag force decreased as a function of the wind angle. Meanwhile, the absolute value of the lateral force coefficients and the rolling moment of the head car yielded the same trend with that of the drag force, and also reached its maximum value at 70°. Cheli et al. (2010a) measured the aerodynamic coefficients of the ETR500 train model (1:10 scale) based on wind tunnel tests. The drag, lift, and lateral forces, and the rolling moment values for the standard TSI infrastructure scenarios (flat ground with and without ballast and rail, and an embankment that was 6 m high), and for a typical Italian viaduct, were presented when the wind angle increased from 0° to 90°. Results indicated that the infrastructure scenarios had significant influences on the relationship between the aerodynamic coefficients as a function of the wind angles. The lateral forces of the train were measured in wind tunnel experiments performed by Suzuki et al. (2003). The lateral forces of four types of trains with different shapes were compared in this study, within the wind angle range of 30°–150°. Results showed that the lateral force of the train first increased with increase of the wind angle, and reached its peak when the wind angle was 60°, followed by decreases at increasing wind angles. However, the lateral force measured in this study was for the middle car, and the streamlined shape of the train was not taken into consideration. Orellano and Schober (2006) studied the aerodynamic forces of the high-speed train ICE2 using a 1:10 scaled model in the wind tunnel. Attention in this study was confined to the aerodynamic loads on the first car when exposed to a range of yaw angles (−30°–60°). Thus, the second car (tail car) model was incomplete, and only included the streamlined section and a portion of the train body. Results showed that the drag coefficients increased with increases of the wind angles (within the range of 0°–60°), and the lateral force coefficients had the same trend in this wind angle range. However, the lift force coefficients decreased with increases of the wind angles in the wind angle range of 0°–60°, but the decrease observed for angles in the range of 0°–10° was unobvious. Catanzaro et al. (2010) analyzed the aerodynamic forces of the ETR500 train measured in the wind tunnel using a 1:15 scaled model. Results showed that the lateral force coefficient and the overturning moment increased with increases of the wind angle. Although six cross-sections were adopted for the set of pressure taps used on the surface of the streamlined zone, two sections were taken for analysis to validate the numerical simulation results, and illustrate the pressure distribution on these two sections. Wind tunnel measurements on a high-speed train model at a scale of 1:25 were carried out at different turbulence conditions by Nayeri et al. (2010). The rolling moments of the head train were measured within a wind angle range of 0°–90°, and the results showed that the rolling moment of the head train increased with increases of the wind angle. However, this study focused on the influence of the wind tunnel grid turbulence on the aerodynamic coefficients of the trains to describe an approach to reduce the undesired Reynolds number effects by changing the turbulence conditions of the flow. Golovanevskiy et al. (2012) measured the frontal air drag of several train configurations using 1:40 scaled train models in a wind tunnel, and found that the drag force increased rapidly with increases of the wind angle in the range of 0°–20°. However, this study was concerned with the optimal model configuration for aerodynamic modeling of long, open cargo railway trains. Cheli et al. (2013) carried out experimental tests to measure the aerodynamic forces on the vehicles at different wind angles. The effects (related to the wind flow turbulence) on the mean force coefficients were investigated by means of atmospheric boundary layer simulations, and the mean force coefficient values were measured only for the wind angles of 30°, 45°, 60°, and 90°. Results showed that the lateral force and the rolling moment coefficients had the same trend. That is, within the range of 30°–60° these values increased at increasing wind angles, and then decreased at wind angles higher than 60°. Additionally, the lift force coefficient values decreased at increasing wind angles, while the decreased values exhibited within the range of 30°–45° were more obvious than the decreased values within the range of 45°–90°. However, the head of the train model used in this experiment was nearly a bluff body, and the analysis of the pressure distribution was focused on the train body, not the train head.

For the pressure distribution, Cheli et al. (2010b) then measured pressure changes of the streamlined zone using a 1:15 scaled train model in the wind tunnel, and the wind angle range was −30° to 30°. Five cross-sections were adopted on the streamlined zone, but the pressures of the pressure taps located on these five cross-sections obtained in the wind tunnel test were used for the evaluation of the cross-wind velocity acting on the train model. Niu et al. (2016) measured the pressures distributed on the surface of the streamlined zone of the train, and the aerodynamic forces of a two-car grouping train were also obtained in this test. Two wind angles (0° and 15°) were considered in this study, and results showed that the pressure coefficients of the pressure taps on the symmetric plane of the train's streamlined zone decreased when the wind angle increased from 0° to 15°. However, this study focused on the effects of the Reynolds number on the pressure distributions and aerodynamic forces. Moving model and static experiments were carried out by Dorigatti et al. (2015) using a 1:25 scaled model of a Class 390 Pendolino. The pressure distribution on the nose region of the train was observed in the experimental tests when the wind angle was 30°. In this study, three cross-sections on the streamline zone of the train were adopted for the arrangement of the pressure taps, and fourteen pressure taps were set on each loop curve of the three cross-sections. Results showed that when the wind angle was 30°, the pressure coefficients of the pressure taps on the windward side increased at increasing heights, but the change of the pressure coefficients with the height of the tap position on the leeward side was inversed. Additionally, the pressure reached its negative peak on the leeward edge of each loop's roof. However, the purpose of this study was to compare the static and moving experiments, and this comparison was only performed at a wind angle of 30°. There are still many investigations on assess the influence of the wind and the train's relative velocity based on wind tunnel tests, even with moving model test rigs (Baker, 2002; Bocciolone et al., 2008). Other wind tunnel experimental studies focused on the analysis of the slipstream and the wake of the train, or the turbulence around the train (Bell et al., 2014, 2015; Niu et al., 2017).

The main focus of this wind tunnel experimental investigation was to analyze the influence of the wind angles on the pressure distribution of the streamlined zone, and evaluate the aerodynamic forces of the train. In addition to the results of the train model tests at a scale of 1:8 in the wind tunnel, a series of additional tests were carried out at the China Aerodynamics Research and Development Center. The test results can provide a reliable scientific basis for the design and manufacture of China Railways High-speed (CRH) trains. Tests of pressures for all pressure taps located on the streamlined zone, and aerodynamic force tests were conducted on the high-speed train model at a wind speed $V = 60$ m/s.