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Unsteady flow structures in the wake of a high-speed train

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ABSTRACT

This paper reports an experimental investigation on the wake of a 1/50th-scale high-speed train (HST) with a slenderness ratio, L/W, of 15.7 (L and W are the length and width of the train model, respectively). Hot-wire anemometry, flow visualization and particle image velocimetry (PIV) measurements are conducted in a close-loop low-speed wind tunnel at a Reynolds number of 1.3×10^5, based on the free stream oncoming flow velocity U_∞ and W. The results of both the frequency spectrum analysis and flow visualization suggest that the instantaneous near wake of a slender HST is dominated by a pair of large-scale counter-rotating streamwise vortices, which are shed alternatingly. Utilizing the proper orthogonal decomposition (POD) analysis for the PIV measurement results, the dynamic characteristics of the near wake are clarified. The first six POD modes, corresponding to the dominant coherent structures, are described in more detail. Each of the large-scale streamwise vortices presents increase/decrease alternatingly in size along with oscillating behaviour in both lateral and vertical direction, which is ascribed to the tilted vortex shedding from the bogie section of the trailing carriage. Moreover, the interaction between the streamwise vortices and the ground is also discussed.

1. Introduction

The flow around a high-speed train (HST) has recently been laid more emphasis on, especially its near wake complexity. Due to the unique geometry of a HST with ground proximity, e.g. the slender and streamlined nose/tail, the instantaneous flow separation points are not fixed. In term of the time-averaged flow, a pair of counter-rotating streamwise vortex, viz trailing vortices, has been identified in the wake of a HST. They move initially towards the ground and then away from each other due to the mutual induction and interaction with the ground [1–3]. The periodic unsteadiness and oscillation of this streamwise vortex pair cause a slipstream velocity peak in the near wake of a HST [4–7]. Slipstream is the flow induced by the movement of train, which is generally characterised by a highly turbulent non-stationary air flow [8]. High slipstream velocity has direct impacts on the passengers on platforms, trackside workers, and loadings on the nearby structures [9–12], which become more important with the increasing running speed of the HSTs in recent years [13,14] and thus need to be taken into account in the development and authorization of new trains [11,15,16].

Previous numerical and experimental studies indicate that the wake of a HST is highly three-dimensional and characterised by the presence of shear layers, vortex shedding, separation and recirculation regions, and a pair of counter-rotating streamwise vortices [4,5]. Schulte-Werning et al. [17] identified lateral oscillations of the vortices occurring at $St = 0.14$ ($St = fU/D$, D is the hydraulic diameter) by URANS simulations, which coincided with the periodic of the side force. Two typical dominant flow modes were identified in the wake by Muld et al. [18] using DES and decomposition methods (POD and DMD), i.e., vortex shedding and the bending of the counter-rotating vortices. Numerical simulations using the Lattice Boltzmann Method (LBM) by Pii et al. [19] identified vortex shedding at $St = 0.15–0.18$ ($St = fU/W$, W is the train's width), developing from the underbody due to interaction with the bogies, before being released into the near wake. The velocity and pressure in the near wake exhibits lateral fluctuations, however, their inherent connection to the vortex dynamics has not been thoroughly understood yet. Xia et al. [7,20] investigated the effects of ground configurations on the near wake and slipstream of a HST with improved delayed detached eddy simulation (IDDES). They suggested that the vorticity is diffused much more rapidly for the streamwise vortex pair embedded in a turbulent boundary layer, leading to the more intensive oscillation of the wake for the stationary ground case relative to the moving ground case. Additionally, they elucidated the relationship between the slipstream peak and the instantaneous streamwise vortex pair.

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Wind tunnel test was performed by Weise et al. [21] to analyse the specific region of the slipstream and near wake of a HST. Their flow visualization results identified two typical flow patterns, i.e. separation bubble and vortex shedding, which occur alternatingly in the near wake of a train, depending on the geometries of the train tail. Based on wind tunnel experiments, Bell et al. [3] quantified the near wake characteristics and identified the causes of slipstream. They associated the peak of the spectrum of the slipstream velocity with the time-averaged counter rotating vortices that move outwards from the train tail. More recently, Bell et al. [4–6] found that the near wake of a HST exhibits periodic unsteadiness, which could be attributed to periodic vortex shedding from the side and top surfaces of the train. These periodic vortices feed into the trailing vortices as they moving downstream, thus dominating the distribution of slipstream velocities. They also proposed that the unsteady wake topology of a HST is characterised by sinusoidal, antisymmetric motion of the pair of counter-rotating streamwise vortices.

As mentioned, there are only a few experimental studies of the wake topology of a HST and there are still open questions about this wake flow. For example, the instantaneous flow structures, the unsteady dynamics, the mechanism causing the wake swing as well as the link between slipstream and unsteady wake behaviours have not been fully understood. Moreover, previous experimental studies have not clearly depicted the instantaneous and spatial evolution of the unsteady flow structures in the wake, due to the limited measurement methods [3–6,21].

The present work reports an experimental investigation on the unsteady flow structures in the near wake of a HST. The main objective here is to investigate the wake dynamics, i.e. the formation and development of the unsteady vortex structures. Hot-wire anemometry was used to explore the frequency characteristics. The instantaneous flow structures was visualized by laser-induced fluorescence (LIF). Moreover, particle image velocimetry (PIV) and proper orthogonal decomposition (POD) technique were utilized to reveal the dynamics of the near wake flow. Experimental details are given in § 2. The snapshot POD method is described in § 3. The time-averaged flow structures are presented in § 4.1. The captured frequency characteristics and the corresponding unsteady flow structures are unveiled in § 4.2. The POD analysis of the wake dynamics is elucidated in § 4.3. A physical model of the unsteady flow structures in the wake of a HST is proposed in § 4.4. This work is concluded in § 5.

2. Experimental details

2.1. Wind tunnel and train model

The experiment was performed in a close-loop low-speed wind tunnel, with its test section of 2 m (Length) × 0.555 m (Width) × 0.333 m (height), as shown in Fig. 1(a). The longitudinal turbulent intensity at the exit of the contraction section was less than 0.5%, which is consistent with similar wind tunnel experiments for a HST [22]. The axial static pressure gradient in the test section was less than 0.005 Pa/m. The high-speed train model was a 1/50th-scale China Railway High-Speed 3 (CRH3) with a slenderness ratio L/W of 15.7,

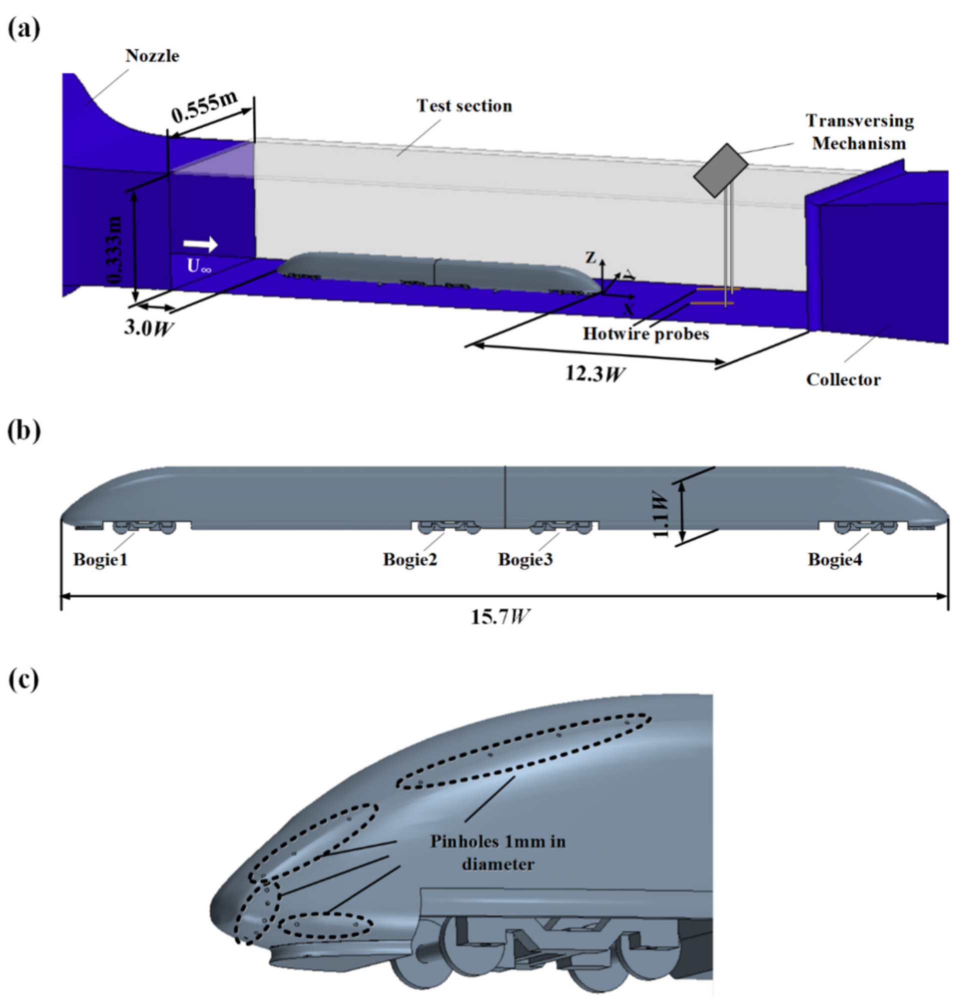

Fig. 1. (a) The 1/50th-scale CRH3 model, (b) Schematic of experimental arrangement and (c) Smoke release points in flow visualization experiments.