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Flow topology and unsteady features of the wake of a generic high-speed train

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ABSTRACT

The unsteady wake of a high-speed train is investigated experimentally. From a practical point of view, the wake region is of considerable importance as it is where slipstream velocities—velocities induced by the vehicles movement through air—are largest. In turn, this can create a considerable risk for passengers and track-side workers as the train passes. The flow is quantified in a 1:10 scale wind-tunnel experiment using high-frequency 4-hole dynamic pressure cobra probes, surface-pressure measurements and flow visualisation. The dominant feature of the time-average wake topology consists of a clearly identifiable counter-rotating streamwise vortex pair. Although the wake structure and evolution should perhaps be considered as a whole, the near wake exhibits periodic unsteadiness, at a Strouhal number of 0.2, that could be attributed to periodic shedding from the sides and to a lesser extent the top surface. This periodicity feeds into the trailing vortices, consistent with lateral and vertical displacement of the cores as they advect downstream and thus affecting maximum slipstream velocities.

1. Introduction

The geometry of modern high-speed trains (HSTs) is unique amongst ground-vehicles, having slender (length $\geq$ height), small aspect-ratio (width:height ratio ≈ 0.75) bodies, and a streamlined nose and tail with no fixed separation points. In general, the wake of a modern HST is expected to be a complex, unsteady, three-dimensional flow, consisting of shear layers, von Kármán-type vortex shedding, separation and recirculation regions, and a pair of counter-rotating streamwise trailing vortices (Morel, 1980; Weise et al., 2006; Muld et al., 2012; Bell et al., 2014). These vortices move downwards and outwards due to mutual induction and interaction with the ground as they advect downstream of the vehicle (Weise et al., 2006; Muld et al., 2012; Heine et al., 2013; Schulte-Werning et al., 2001; Yao et al., 2013; Bell et al., 2014). The vortices result from vorticity that is generated at, and advected along, the surface of the train, and then subsequently from the interaction between the downwash over the roof and tail of the train and the flow around the sides.

The wake of a HST is where the largest *slipstream* velocities are found to occur (Baker, 2010; Baker et al., 2012; Bell et al., 2014, 2015). Slipstream is the air flow induced by a vehicle's movement measured at a fixed distance from the vertical centreplane of the train. It is an important consideration for the aerodynamic performance but also for the safe operation of high-speed trains (HSTs). Such flows can be hazardous to commuters waiting at platforms and to track-side workers (Pope,

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2007) due to significant induced pressure forces. Regulations are in place that limit the magnitude of slipstream velocities a HST can induce (European Rail Agency, 2008; CEN European Standard, 2009).

The authors have previously associated high slipstream velocities in the wake to the presence of a time-averaged streamwise vortex pair (Bell et al., 2014). The contribution of these vortices to characterising the slipstream of a HST has also been identified by preceding research (Baker, 2010; Weise et al., 2006; Muld et al., 2012). As the vortices move downwards and outwards beyond the passage of the train, the largest slipstream velocities are measured. The magnitude and location of the peak of instantaneous slipstream velocity in the wake has been shown to be inconsistent in scaled moving-model experiments (Baker, 2010; Bell et al., 2015) and numerical investigations (Muld et al., 2012; Pii et al., 2014; Hemida et al., 2014). Previous work by the authors has indicated this is caused by periodicity in the wake (Bell et al., 2015). Understanding the source of this high variation, and peak instantaneous slipstream velocities provides the potential for mitigation of the slipstream risk of HSTs, as well as improving stability and drag of the vehicle and the comfort of passengers.

A number of numerical researchers applying different methodologies and investigating various, albeit similarly modern, HST geometries have predicted that the streamwise vortex pair in the wake of HSTs exhibits spanwise oscillations. Delayed detached eddy simulations (DDES) of an Inter-City Express 2 (ICE2) HST by. Muld et al. (2012), using Proper Orthogonal Decomposition (POD) and Dynamic Mode Decomposition (DMD), identified a persistent streamwise vortex pair as the dominant wake feature, in contrast to a separation-dominated wake (Morel, 1980; Ahmed, 1983) seen with some generic automobile-like geometries. The dominant modes exhibited spanwise oscillations of the vortices occurring at a non-dimensionalized frequency, based on the freestream velocity and hydraulic diameter, of $St_{HD} = 0.085$, which they proposed to be caused by vortex shedding. Schulte-Werning et al. (2003) identified similar features on the same HST geometry in their unsteady simulations. Surface streamlines showed the point of origin of a pair of vortices oscillating in the spanwise direction around the vehicle's nose at $St_{HD} = 0.14$.

Numerical simulations using the Lattice Boltzman Method (LBM) by. Pii et al. (2014) identified vortex shedding at $St_W = 0.18$, developing from the underbody due to interaction with the bogies, before being released into the near wake. The near-wake exhibited spanwise fluctuations in velocity and pressure but the dynamics of the vortex pair was not presented. The results from a scaled wind-tunnel experiment on an ICE2 HST (Bell et al., 2014) indicates potential agreement with the unsteady numerical findings, although without confirmation of the flow structures responsible, as frequency and probability distribution analysis indicated periodicity at the location of the time-averaged vortex pair. Explicit experimental confirmation of the spanwise dynamics in the near-wake of a HST and the mechanism, which causes such movement, has not yet occurred.

The counter-rotating pair of streamwise wake vortices are typical of automotive ground-vehicles, as established by (Ahmed, 1983) and others (Vino et al., 2005; Krajnović and Davidson, 2005; Strachan et al., 2007), who also identified movement downwards and outwards from the symmetry plane as the fluid advects downstream. Coherent unsteady features of automotive wakes have been found by a number of researchers both experimentally and numerically (Lienhart and Pêgo, 2012; Vino et al., 2005). In addition to the time-averaged streamwise vortex pair in the wake of a 25° backlight-angle Ahmed body, researchers have identified signs of predominantly 2D von Kármán-type vortex shedding in the vertical plane. This occurs as the shear layers over the roof and under-body roll up, partially feeding the upper and lower recirculating regions, with the remainder rolling up to form the periodic sheet (Wang et al., 2013; Vino et al., 2005). A similar unsteady flow mechanism has been described by (Gilhome et al., 2001) for a notchback automotive geometry.

This work, part of a collaboration between Monash University and Bombardier Transportation, aids in the identification, description and quantification of the flow mechanisms responsible for the slipstream characteristics that affect the safety and operation of modern HSTs. Ultimately, it is hoped that the insight provided by this work will aid in the design of future generations of HSTs.

2. Methodology

2.1. Experimental model

A 1/10th-scale simplified version of a Deutsche Bahn Inter-City-Express 3 (ICE3) high-speed train is the model investigated in the presented work. The external shape, and thus external aerodynamics, are the same as the Siemens Velaro HST. This HST is in operation throughout Germany, Netherlands, Belgium, Austria, Switzerland, Denmark, France, Spain, Turkey, Russia, and China. The HST Computer-Aided Design (CAD) model geometry is freely available from the TC 256 Secretariat held by the DIN Standards Railway Committee (FSF)(DIN Standards Committee Railway, 2014). The availability of the ICE3 geometry, its wide use throughout the world, and its modern aerodynamic shape that is similar to other current HSTs in operation makes it an ideal geometry for studying the flow structures proposed to be typical of modern HSTs.

The ICE3 model measured $5.0 \times 0.3 \times 0.4$ m^3 ($L \times W \times H$), with a cross sectional area of ≈ 0.12 m^2. The model had four sets of bogies, no pantographs, no inter-carriage gaps and no heating, ventilation and air conditioning (HVAC), as the essential geometry—the gross external shape—is the focus of this investigation. The model was supported by 6 pairs of 0.05 H (20 mm) diameter cylindrical supports in line with the wheels in the bogies.