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Dynamics of trailing vortices in the wake of a generic high-speed train

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The three-dimensional dynamics of a pair of counter-rotating streamwise vortices that are present in the wake of an ICE3 high-speed train typical of modern, streamlined vehicles in operation, is investigated in a 1/10th-scale wind-tunnel experiment. Velocity mapping, frequency analysis, phase-averaging and proper orthogonal decomposition of data from high-frequency multi-hole dynamic pressure probes, two-dimensional total pressure arrays and one-dimensional multi-hole arrays was performed. Sinusoidal, antisymmetric motion of the pair of counter-rotating streamwise vortices in the wake is observed. These unsteady characteristics are proposed to be representative of full-scale operational high-speed trains, in spite of the experimental limitations: static floor, reduced model length and reduced Reynolds number. This conclusion is drawn from favourable comparisons with numerical literature, and the ability of the identified characteristics to explain phenomena established in full-scale and scaled moving-model experiments.

1. Introduction

Modern high-speed trains (HSTs) have a unique geometry among ground-vehicles, having a streamlined nose and tail with no fixed separation points and slender (length $\gg$ height), small aspect-ratio (width:height ratio $\approx$0.75) bodies. The wake of a modern HST is in general expected to be a complex, unsteady, three-dimensional structure consisting of shear layers, vortex shedding, separation and recirculation regions, and a pair of counter-rotating streamwise vortices (Morel, 1980; Weise et al., 2006; Muld et al., 2012; Bell et al., 2014). These vortices move downwards and outwards as they progress away from the vehicle due to mutual induction and interaction with the image vortices beneath the ground (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). These coherent vortices consist of vorticity that is generated at the surface of the train, and result from the interaction between the flow around the sides of the train and the down-wash over the roof and tail.

The greatest slipstream velocities occur in the wake of a HST (Baker, 2010; Baker et al., 2012; Bell et al., 2014, 2015). Slipstream is the air flow induced by a vehicle's movement, which continues to be an important consideration for aerodynamic performance and safe operation. Such flows can be hazardous to waiting commuters at platforms and track-side workers (Pope, 2007) as well as track-side infrastructure, due to significant induced-pressure forces. Regulations are in place that limit the magnitude of slipstream velocities a HST can induce (European Rail Agency (ERA), 2008; CEN European Standard, 2009).

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The authors have previously identified the presence of a pair of streamwise counter-rotating vortices in the time-averaged wake as the cause of the peak slipstream velocities (Bell et al., 2014). The significance of these vortices to characterising the slipstream velocity of a HST has also been identified by other authors (Baker, 2010; Weise et al., 2006; Muld et al., 2012). The largest slipstream velocities are measured as the vortices move downwards and outwards beyond the passage of the train. The magnitude and location of the peak of instantaneous slipstream velocity in the wake has been shown to be inconsistent in numerical investigations (Muld et al., 2012; Pii et al., 2014; Hemida et al., 2014) and scaled moving-model experiments (Baker, 2010; Bell et al., 2015). Previous wind-tunnel experiments by the authors have indicated that 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 mitigating the slipstream risk of HSTs. Further, such insight could lead to improving the stability and drag of the vehicle as well as the comfort of passengers (Peters, 1983; Schetz, 2001).

Uncertainty exists over the existence of a coherent time-varying vortex pair in the wake of a HST. This was discussed by Bearman (1997) who provided evidence of the potentially large differences between the instantaneous and time-averaged wake of an automotive vehicle. It is possible that the vortex pair only become visible in results due to the necessary processing required for providing a time-averaged description of the near-wake. Heine et al. (2013) have performed a novel moving-model experiment, essentially firing a scaled HST model through a Particle Image Velocimetry (PIV) window. Their results showed some evidence of one streamwise vortex in the near-wake, proposed to be one of a pair established in the time-average wake, but existing in instantaneous flow, however this evidence was not conclusive.

The streamwise vortex pair in the wake of HSTs has been predicted to exhibit spanwise oscillations by a number of numerical researchers applying different methodologies and investigating various, albeit similarly modern, HST geometries. 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 streamwise vortex pair as the dominant flow regime. This is in contrast to high level of separation dominated flow regime (Morel, 1980; Ahmed, 1983). The dominant modes showed 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 tail at $St_{HD} = 0.14$. Numerical simulations using the Lattice Boltzman Method (LBM) by Pii et al. (2014) identified vortex shedding off the vehicles sides at a frequency based on the freestream velocity and body width of $St_W = 0.18$ developing in the underbody due to interaction with the bogies, before being released into the near-wake. The near-wake exhibited spanwise velocity and pressure fluctuations, however, the resulting dynamics of the vortex pair was not presented. Results from a scaled wind-tunnel experiment on an ICE2 HST (Bell et al., 2014) indicate a potential agreement with the unsteady numerical predictions, however, without confirmation of the flow structures responsible, although frequency and probability distribution analysis indicated periodicity at the location of the time-averaged vortex pair. Thus, experimental confirmation of the near-wake dynamics of a HST and the mechanism causing the oscillation have not been explicitly identified or explained.

The counter-rotating pair of streamwise vortices in a HST's wake are common to a number of analogous flows. Such vortices are found in generic automotive ground-vehicles as established by Ahmed (1983) and others (Vino et al., 2005; Krajnović and Davidson, 2005; Strachan et al., 2007) that also identified movement downwards and outwards from the symmetry plane. Unsteady features of automotive wakes have been found by a number of researchers 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 vortex shedding in the vertical centre plane. This occurs as the shear layers over the roof and under-body roll up, feeding the upper and lower recirculating regions, but also rolling up to form the periodically shed vortex structures (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.

Alternating vortex shedding, commonly known as Kármán shedding, occurs as two separated shear layers are alternately entrained into large-scale vortices that grow and eventually shed from a body (Gerrard, 1966). In addition to existing in automotive wakes, this type of vortex shedding has been identified at Reynolds numbers of $50 - 1 \times 10^7$, behind generic bodies such as two-dimensional cylinders (Tombazis and Bearman, 1997; Roshko, 1961; Williamson, 1996). The Kármán wake is due to a global instability, due to a region of local absolute instability that affects the entire flow. In contrast, the unsteady separating shear-layers are locally convectively unstable acting as amplifiers for disturbances as they advect downstream (Huerre and Monkewitz, 1990). The streamlined, highly 3D geometry of a HST tail presents a very different geometry for trailing-edge vortex shedding to automotive and even cylindrical bodies. Despite this, signs of shear-layer separation at the sides and the tail tip of a scaled model Inter-City-Express 3 (ICE3) HST have been identified (Bell et al., 2016), suggesting that vortex shedding still occurs even in this case.

Some researchers have identified unsteadiness of streamwise vortex pairs in automotive vehicle wakes. In a scaled wind-tunnel experiment, Sims-Williams et al. (2001) determined that the unsteady wake of a Rover 200 automotive vehicle, using a reconstruction technique from point measurements (Sims-Williams and Duncan, 1999), had two periodic features: the strengthening and the weakening of the pair of vortices together at a frequency based on the freestream velocity and square root of the frontal area of $St_{\sqrt{FA}} = 0.31$, and an alternating, asymmetric mode of strengthening/weakening of the vortex pair at $St_{\sqrt{FA}} = 0.10$. This experiment and analysis was also performed with a 25° backlight Ahmed body (Sims-Williams and Duncan, 2003), however, only the symmetric oscillation in strength and position of the vortex pair at a $St_{\sqrt{FA}} = 0.51$ was identified. This was attributed to vortex shedding from the bottom of the model base. Kohri et al. (2014) specifically investigated the dynamics of the pair of trailing vortices in the wake of the 27.5° backlight Ahmed body in scaled wind-tunnel