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Moving model analysis of the slipstream and wake of a high-speed train

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ABSTRACT

A scaled moving model technique for analysing the slipstream of a high-speed train (HST) with the view of applying this methodology for checking TSI compliance in the design phase of a HST is assessed. Results from experiments are compared to full-scale field test results, and the sensitivity of slipstream to two of the limitations of scaled testing, Reynolds number and the length to height ratio (L/H), is presented. The results captured using this unique methodology provide insight into the transient flow around HSTs.

1. Introduction

The slipstream of a high-speed train (HST) continues to be an important aspect of aerodynamic performance and safe operation. Slipstream is the air flow induced by the train's movement as experienced by a stationary observer. Such flows can be hazardous to waiting commuters at platforms and track-side workers (Pope, 2007). The flows also present the risk of damage to track-side infrastructure. Regulations have been developed in Europe to reduce these risks; for example the European Railway Agency's (ERA) (2008) Technical Specifications for Interoperability (TSI) and the industry norms outlined by the European Committee for Standardization, herein referred to as the European Norms (EN) (CEN European Standard, 2009).

This paper investigates the slipstream of a HST under 'standard operation and configuration', defined here as a single train with one nose and one tail travelling on a straight track over flat ground with no crosswind present. This idealised train is modelled to isolate the slipstream characteristics generated by the train's essential generic geometry in an ideal environment. Under these conditions, the slipstream of a HST has a local peak velocity at the nose passing, a gradual increase in velocity as the boundary layer develops along the length of the train, followed by the largest peak in the near-wake of the vehicle (Baker, 2010; Baker et al., 2001, 2012a,b). These slipstream characteristics correspond to the description by Baker (2010) for flow around a HST having three distinct regions: the nose, boundary layer and wake regions. These general characteristics of a HST's slipstream, illustrated in Fig. 1, are referred to herein as the 'standard slipstream profile' and have been found by a number of researchers in full-scale track-side experiments (Baker, 2010; Baker et al., 2012a; Baker et al. 2012a,b).

Inter-carriage gaps have been found to cause perturbations to this general description as peaks, troughs or waves (Muld et al., 2014a; Pii et al., 2014), however these do not appear to significantly change the rate of increase of the boundary layer thickness. A local tail peak has also been identified in a number of HST slipstream profiles in full-scale experiments (Baker et al., 2012a), scaled experiments (Gilbert et al., 2013), and numerical simulations (Muld et al., 2014a; Hemida et al., 2013), but is not a standard feature and is likely dependent on geometry and measurement position. Both features are included in Fig. 1 as dotted lines to indicate that they are not standard, nor the focus of this research. Further, as the flow around HSTs is highly three dimensional, the slipstream profile as measured by a single streamwise line, as indicated in Fig. 1, is highly sensitive to measurement position, with the shape of the slipstream profile—even the relative magnitudes of the peaks—being susceptible to changes. However, in general the slipstream velocity decreases with increasing height above ground and distances away from train, as shown in full-scale experiments (Sterling et al., 2008) and numerical simulations (Hemida et al., 2013; Huang et al., 2014).

A number of known flow mechanisms can be identified in the wake of a high-speed train: shear layers, von Kármán-type vortex

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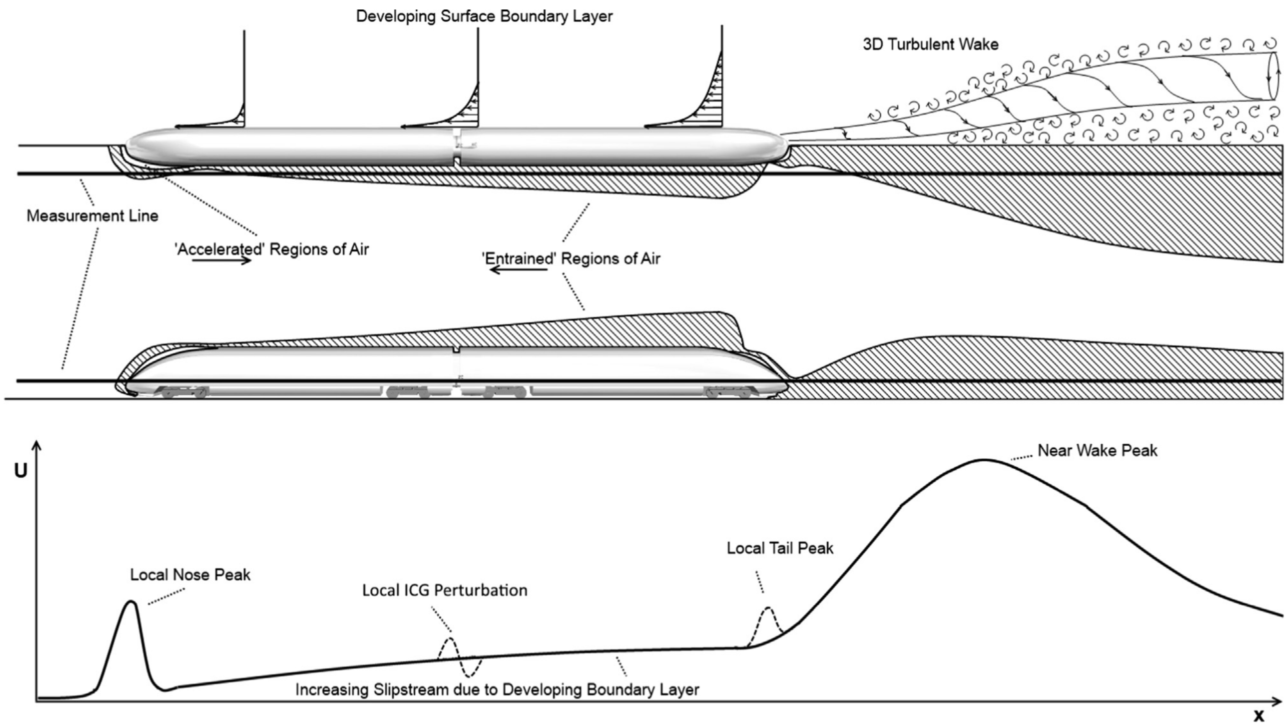

Fig. 1. The slipstream of a high-speed train. The flow induced can travel in two directions: 'Accelerated' flow—travelling opposite to the direction the train is travelling and 'Entrained' flow—travelling with the direction the train is travelling. Accelerated flow is primarily around the head and tail. Increasing thickness of the entrained flow exists over the roof and sides due to the thickening boundary layer. Similarly, a widening region of entrained flow occurs in the wake, expected to be due to the presence of coherent turbulent structures of different scales within the wake. The perturbation in the developing boundary layer—due to the inter-carriage gap—and the local peak at the tail are presented as dotted lines to indicate that they are not found in all HST slipstream profiles.

shedding, separation and recirculation regions and a pair of twin counter-rotating longitudinal vortices (Morel, 1980; Weise et al., 2006; Muld et al., 2012a; Hemida et al., 2013; Huang et al., 2014). The contribution of twin counter-rotating vortices to wake topology has been identified as a particularly important feature in characterising slipstream (Baker, 2010; Weise et al., 2006; Muld et al., 2012a). The counter-rotating vortices are created by the interaction between the down-wash over the roof and tail of the train and the flow around the sides of the train in the transition from a constant cross-section to the end of the tail. These vortices move downwards and outwards due to the mutual induction and interaction with the ground as they progress away from the vehicle (Weise et al., 2006; Muld et al., 2012a; Heine et al., 2013; Schulte-Werning et al., 2001; Yao et al., 2013), with some researchers predicting that they exhibit spanwise oscillations (Muld et al., 2012a; Yao et al., 2013; Schulte-Werning et al., 2003).

The use of a moving model methodology is assessed as a technique for analysing a HST's slipstream and checking for TSI compliance in the design phase. This is performed by comparison to full-scale field test results as well as investigation of the sensitivity of results to the two primary experimental limitations of a moving model methodology: reduced Reynolds number and reduced length to height ratio (L/H). The results obtained are also analysed through ensemble averaging, characterising individual runs, conditional averaging and proper orthogonal decomposition (POD) analysis to provide insight into the transient flow around a HST.

2. Methodology

2.1. Experimental set-up

The experiment was performed at Deutsches Zentrum für Luft- und Raumfahrt (DLR—German Aerospace Centre) Tunnel Simulation Facility (TSG), a moving model facility in Göttingen, Germany. A moving model method has the advantage of measuring slipstream with the same train-measurement probe and train-ground relative motion as full-scale field experiments. The test section, illustrated in Figs. 2 and 3, consisted of 8 m of flat ground, 4 m of which was forwards of the first measurement position. Also included was 6 m of 1/25th scale single track ballast and rail (STBR), 2 m of which was forwards of the first measurement position. Ground configuration is not specified in the EN for scaled model slipstream experiments, however a STBR was required for head pressure pulse investigations in the 2009 EN (CEN European Standard, 2009)—the 2013 EN (CEN European Standard, 2013) revision excluded the rails from this configuration—and crosswind investigations (CEN European Standard, 2010). Thus a STBR ground configuration was modelled in this experiment. A 1/25th scale model of an ICE3—a HST in operation throughout Germany—was used in the experimental work.

Two pairs of light gates (L1 & L2 and L3 & L4 in Fig. 2) were used to determine the model's velocity and acceleration. The model's velocity and acceleration were used to convert the measurements from the time domain to the spatial domain, in which all results are presented. The model's average velocity, U_t, was used to normalise the measured slipstream velocities.

Two modifications aimed at improving the level of detail were made to DLR's ICE3 model, which originally conformed to the EN. The first was to include the wiper geometry at the tail section (omitted at the nose for practical reasons), to ensure that the level of downwash and corresponding strength of the twin counter-rotating vortices was similar to full-scale. The second modification was made to the bogie skirts, coverage was increased to better represent operational ICE3 geometry. This was done to ensure shedding off the exposed region of the bogies, particularly the rearmost bogie, was as realistic as possible.