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The effect of the ground condition on high-speed train slipstream

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A B S T R A C T

Understanding the induced movement of air as a high-speed train passes (*slipstream*) is important for commuter and track-side worker safety. Slipstream is affected by the movement of the train relative to the ground, but this is difficult to include in wind-tunnel tests. Using simulations based on the Improved Delayed Detached Eddy Simulation model, this study investigates the effect of relative ground motion on slipstream for three different ground/wheel configurations: a stationary ground with stationary wheels, a moving ground with stationary wheels, and a moving ground with rotating wheels.

By examining the interaction between the train-induced flow structure and ground boundary layer, this study identifies two ways that the ground boundary layer changes slipstream: through directly altering the high slipstream velocity region due to the ground boundary-layer development, and through indirect widening of the wake by deformation of the trailing vortices. The altered aerodynamic loading on a train due to relative ground motion is visualised through the surface pressure distribution, allowing the resultant impact on drag and lift to be assessed. For wheel rotation, it is concluded that its effect is mainly restricted to be within the bogie regions, with limited influence on the wake behind the train.

1. Introduction

Slipstream quantifies the induced air movement of a high-speed train (HST) as it passes. In terms of regulations, the slipstream velocity is quantified by the resultant induced horizontal velocity in the stationary reference frame measured at a specific point or points from the train vertical centreplane. With technological development, the speed of HSTs has dramatically increased over the past decades, with typical current cruising speeds of approximately 300 km/h. Given these extreme speeds, as slipstream velocity is proportional to train speed, it can be a serious safety hazard to commuters and trackside workers, and can also cause damage to infrastructure along track lines. Because of these dangers, many countries have enforced regulations to limit the maximum permissible slipstream velocity, for example, countries in Europe through the European legislation and standards (European Union Agency for Railways, 2014; Railway Applications, 2013). Therefore, slipstream poses one of the considerations for HST design, especially if the train is to operate in the higher speed range. As the induced slipstream velocity depends on the flow development around the train and in the wake, an accurate prediction of the flow structure is essential for understanding slipstream characteristics. Compared with conventional road vehicles, HSTs have more streamlined shapes with no fixed flow separation points, a much larger length-to-width ratio, and they travel close to the ground at a significantly higher speed. Therefore, the flow around a HST is unique, and existing knowledge of neither conventional road vehicles aerodynamics nor aircraft aerodynamics can be directly utilised to understand HST aerodynamics.

Much effort has been channeled into studying train aerodynamics from many aspects, such as slipstream assessment (Bell et al., 2014), shape optimisation (Shuanbao et al., 2014), cross-wind instability (Krajnović et al., 2012) and underbody flow (Zhang et al., 2016). Similar to road vehicle aerodynamics, accurate modelling of the ground motion relative to vehicle is an important consideration. Currently, the most widely-used methods for studying HST aerodynamics are full-scale testing, moving-model testing, wind-tunnel experiments and numerical simulation. For physical experiments, full-scale and moving-model testing inherently employ a realistic ground boundary treatment, whilst in order to obtain an effective ground representation in a wind tunnel, either ground simulation techniques (such as boundary-layer suction) are essential or use of a moving-belt is recommended (Fago et al., 1991). Even though full-scale and moving-model testing utilise a more realistic stationary reference frame, the measurements are sensitive to the full-scale environmental conditions, e.g., ambient wind conditions. In any case, it is very difficult to undertake detailed measurements of the

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flow field around a moving model and to conduct unsteady statistical analyses, such as flow mapping of the mean or phase-averaged wake.

In contrast, wind-tunnel experiments adopt the vehicle reference frame, making it much easier to undertake measurements of the flow structure around the train model and in the wake. In general, it is both difficult and expensive to equip a wind tunnel with a moving floor for train aerodynamics research.

Compared with conventional road vehicles, HSTs typically have a much larger length-to-height ratio, typically around $50 \sim 100$. Additionally, HSTs appear to have a longer coherent wake structure than road vehicles. For example, the region of interest for road vehicles is typically within 3 vehicle heights, since drag is the primary consideration, while the region of interest for HST slipstream assessment can be up to $5 \sim 10$ train heights behind the tail because sideways wake movement/oscillation can have a strong effect on slipstream. For example, Bell et al. (2017) reported that the train wake disturbance was significant up to around 20 train heights (the peak slipstream velocity was recorded at approximately $5 \sim 10$ train heights) behind the tail according to the wind tunnel, moving model rig and full-scale testing experiments, all based on an ICE3 train model. As a consequence, even if a moving floor is implemented, a significantly longer moving-belt is required to represent the relative motion, not only along the long train but also in the extended wake region. Additionally, according to the CEN guidelines (Railway Applications, 2013), the aerodynamic performance of a HST needs to be studied not only on a flat ground configuration, but also on an elevated ballast configuration. The introduction of a moving ballast makes employing a moving-belt technique almost impossible for wind-tunnel experiments. Therefore, understanding the potential differences that can be introduced by adopting a stationary floor is essential.

Relative to HSTs, the effect of incorrect relative ground motion has been extensively studied for road vehicles. The previous research of the underbody flow with different ground conditions have shown that the moving ground configuration can increase the mass flux underneath the vehicle in the streamwise direction and decrease it in the spanwise direction, and this alters the aerodynamic loading on the underbody structure (Krajnović and Davidson, 2005). However, different studies with different geometries, do not provide a consistent trend on the aerodynamic loading and flow. For example, Krajnović et al (Krajnović and Davidson, 2005) reported that floor motion reduced drag by 8% and lift by 16% on a simplified car with a typical fastback geometry, while Burgin et al. (1986) found an increase in drag for flow past a bluff body with a moving ground. Additionally, Sardou (1986) found a significant alteration to the rear wake with/without ground motion, while Krajnović et al (Krajnović and Davidson, 2005) found that the wake flow was relatively insensitive.

For future development of HSTs, a fuller understanding of the flow around and behind a HST is becoming more important, and to achieve that the inclusion of an accurate ground boundary condition would seem important. If this is not possible, an understanding of at least the semi-quantitative effects that can be caused by different ground motion configurations would seem necessary.

Some previous research has been channelled into investigating the effect of ground motion. Kwon et al. (2001) studied the performance of two ground simulation techniques, a moving-belt system and a tangential blowing system, based on a Korean HST. The results showed that a moving floor could increase the aerodynamic drag by approximately 15%, and this was explained as the result of the increase in both friction and pressure drag. Specifically, the altered boundary-layer profile beneath the train increased the friction drag on the train underbody, and the pressure drag was increased due to the stronger vortical wake structures. Xia et al. (2016a,b), compared the effect of a stationary and moving ground on the flow structure and aerodynamic loading on a Chinese HST (CRH3) on a flat ground configuration using CFD. An identical dominant wake structure was determined for both cases, while the moving ground case showed a narrower wake with slower vortex shedding, as compared to the one with a stationary ground. Additionally, a significant variation to underbody pressure was identified due to the ground motion, which resulted in a large deviation for drag and lift predictions between stationary and moving grounds, and raising the train model, which was thought might reduce differences, could not effectively eliminate this variation. Zhang et al. (2016) further examined the combination effect of the ground motion and wheel rotation on underbody flow and aerodynamic loading. They found that the moving ground case showed a higher total drag on the train compared with stationary ground; however, the application of rotating wheels did not show an identifiable further increase in drag. Additionally, the impact of rotating wheels was only seen on the local pressure distribution within the bogie region, and showed as an increase of the drag of the wheels. A moving ground with rotating wheels boundary condition was concluded as necessary, especially for studying the underbody flow of a HST.

According to previous research, the ground motion has been verified to have a significant effect on the HST aerodynamic loading and the surrounding flow field. Even though the effect of the ground motion has been identified and partially investigated, a comprehensive understanding of the mechanism on how it alters the train slipstream development is yet to be undertaken and this has motivated the present study.

Indeed, the aim of current study is to investigate the effect of the ground motion on the slipstream development around a generic HST model, including identifying the mechanism by which it alters the flow structure around the train and within the wake region. Additionally, the effects of ground motion on slipstream assessment and aerodynamic loading are studied. Specifically, for a systematic comparison and determination of the effect introduced by the ground motion and the wheel rotation, three cases with different ground/wheel motions are studied: (i) Stationary Ground with Stationary Wheels (SGSW), (ii) Moving Ground with Stationary Wheels (MGSW) and (iii) Moving Ground with Rotating Wheels (MGRW).

This paper is structured as follows. The numerical set-up, including defining the train geometry, the computational domain and corresponding boundary conditions, the meshing strategy, the turbulence models and solver settings, are introduced in the *Methodology* Section. In the *Results and Analysis* section, the effect of ground motion is studied from the following three perspectives: slipstream assessment (Section 3.1), flow structure (Section 3.2), and aerodynamic loading (Section 3.3). In Section 3.1, the slipstream assessment is implemented under the TSI specifications (European Union Agency for Railways, 2014), including the analysis of unsteady statistics of the slipstream velocity profiles and gust phenomenon. Additionally, the flow field at the slipstream measurement location is investigated to reveal the mechanism on how ground motion alters the slipstream measurement. In Section 3.2, further investigations of the ground motion effect on the flow structures are conducted. For explicitly studying the ground motion effect at each stage of train slipstream development, the overall flow field is divided into two regions: the flow development region and wake propagation region. The altered aerodynamic loading is visualised through the train surface pressure distribution, and the resultant force variation (drag and lift) is presented in Section 3.3. The findings are summarised in Section 4.

2. Methodology

2.1. Geometry

The geometry used for this study was based on a Deutsche Bahn InterCity-Express 3 (ICE3) high-speed train, a widely operated train model in Asian and European countries. ICE3 has a representative external shape, and its Computer-Aided Design (CAD) model is freely available from the DIN Standards Railway Committee (FSF) (DIN, 2014). This makes ICE3 an ideal model for generic HST aerodynamic research, and a comparison between the full-scale ICE train and numerical model is illustrated in Fig. 1. Important geometric features that have a strong influence on the slipstream are retained, i.e. the bogies and snowploughs, although the CAD model is simplified. Geometric features like pantographs (Ambrósio