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Cluster-based reduced-order modelling of the flow in the wake of a high speed train

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ABSTRACT

The flow field in the wake of a high-speed train is studied by cluster analysis and a cluster-based reduced-order model (CROM) is derived. The CROM strategy is a generalization of the Ulam–Galerkin method for the approximation of the finite-rank Perron–Frobenius operator and constitutes a data-driven approach to extract physical mechanisms in an unsupervised manner. Time-resolved data is first clustered into groups by using the *k*-means clustering algorithm to yield a small number of representative flow states, the cluster centroids. Then, the cluster transitions are modelled as a Markov process. A further analysis of the derived dynamic model provides information on the interaction of the dominant structures in the flow. The flow field around a generic high-speed train model, here the Aerodynamic Train Model, is obtained from a large-eddy simulation. This train model is designed to reproduce the geometrical features of the ICE2 train. The extracted flow structures can be associated with longitudinal vortices and vortex shedding. Furthermore, these structures are found to be associated with either states of low or high drag of the train.

1. Introduction

Examples of aerodynamics issues concerning railway systems are numerous (Raghunathan et al., 2002). The flow field beneath the train can cause the gravel stones to dislodge (ballast flight), which might cause damages on the train (Quinn et al., 2010; Jönsson et al., 2012). When trains enter a tunnel, pressure waves are formed at the nose of the trains (Heine et al., 2012; Uystepruyst et al., 2011; Muñoz Paniagua et al., 2014). These waves propagate inside the tunnel with the speed of sound. One part of the waves is radiated to the surrounding environment at the opposite tunnel entry. The other part is reflected and travels back inside the tunnel. The first part contributes to noise pollution of the surrounding environment, and the second reflected part hits the train inside the tunnel causing increased mechanical stress on the train as well as vibrational discomfort for the passengers. Travelling inside tunnels also increases the drag of the train significantly (Kim, 1997).

Aeroacoustically produced noise is another source of environmental noise pollution during train operations. The source of the noise is flow separation caused by either the detachment of the boundary layer on the train or by vortex shedding from protruding structural elements on the train. For instance, the vortex shedding behind the pantograph causes a monotone noise that propagates far away from the railway. The strength of the noise is proportional to the train speed by a power of 6–8 (King, 1996). Thus, noise alleviation is of immense practical importance as train speed increases.

Aerodynamically induced drag on the train contributes to the overall energy demand for the railway system. For high speed trains (HST), largest contribution to the aerodynamic drag comes from viscous friction along the train body (Orellano and Sperling, 2009). The second largest contributor is the pressure difference between the nose and the tail of the train.

Another issue is the slipstreams (Muld, 2012), i.e., the air during traction that is being dragged along by the viscous friction on the train. Induced wind gusts are sweeping over platforms when trains pass. Too strong wind gusts can cause danger to passengers standing on the platforms. Therefore, the train industry is subjected to regulations concerning the allowed slipstream velocities around trains. Sterling et al. (2008) summarized experimental

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work on slipstreams for high speed and freight trains. Four regions of the flow around the train are the main constituent part of the slipstream: the flow upstream and around the nose of the train, the boundary layer along the train, the near wake and the far wake. For high speed and freight trains, the largest velocities occur in the boundary layer region and in the near wake (Sterling et al., 2008; Muld et al., 2012, 2013).

The flow around high speed trains is inherently unsteady. During cross winds, a longitudinal vortex is formed along the leeward side of the train that induces large transients in the side and lift forces (Hemida, 2008). The moments exerted by these forces can in extreme cases cause overturning of the train. The flow in the wake depends on the geometrical configuration of the tail. For configurations with a steep tail slope, the flow organizes as a bluff body wake flow with a quasi-steady separation bubble with flow separating from all the four rear edges. For configurations with a flatter slope, two longitudinal counter-rotating vortices emerge from the flow separating at the sides of the tail. This phenomenon is the same as observed for the flow in the wake of axisymmetric cylinders when varying the slant angle (Morel, 1980) and the C-pillars vortices at the base of passenger cars with a slanted rear (Ahmed et al., 1984; Krajnović and Davidson, 2005a,b).

Cluster-based reduced-order modelling (CROM) (Kaiser et al., 2014) is a recently developed method for extraction of flow structures and Reduced-Order Modelling. CROM combines the cluster analysis (Burkardt et al., 2006) and transition matrix models in fluid dynamics (Schneider et al., 2007). This approach constitutes an alternative to flow decomposition methods such as the Proper Orthogonal Decomposition (POD) and the Dynamic Mode Decomposition (DMD) as well as to reduced-order modelling techniques such as POD models. CROM processes a time-resolved sequence of spatially resolved flow snapshots in two steps. First, the snapshot data are clustered into a small number of representative states, called centroids. The probabilities of the snapshots of the instantaneous flow to be in the centroids are determined, and the centroids are sorted by analysis of a transition matrix. This transition matrix determines the probability of the flow to transition from one centroid to the others. Secondly, the transitions between the states are dynamically modelled using a Markov process. Physical mechanisms are then distilled by a refined analysis of the Markov process.

In this work, the flow in the wake of a generic high speed train model is studied by CROM. The time-resolved flow around the high speed train model needed for the cluster analysis is obtained by large eddy simulation (LES). Previously, many generic vehicle bluff body flows have been investigated using LES (Krajnović, 2002, 2009; Östh, 2014), such as the flow around a squared backed Ahmed body (Krajnović and Davidson, 2003; Östh et al., 2014), the flow around a simplified heavy vehicle (Östh and Krajnović, 2012), the flow around generic high speed trains (Hemida and Krajnović, 2009; Hemida et al., 2012, 2010) and the flow around freight trains (Hemida and Baker, 2010; Östh and Krajnović, 2014; Liu et al., 2014).

The paper is organized as follows: Section 2 presents the train model, the flow configuration, the numerical set-up of the LES, as well as a brief presentation of the flow field obtained from the LES simulation. Section 3 describes the CROM algorithm. The results from the cluster analysis applied to the LES data are presented in Section 4, and the work is finally concluded in Section 5.

2. Configuration

The section describes firstly the generic high speed train model in Section 2.1. The flow configuration and the numerical wind tunnel are then described in Section 2.2, and the LES method used to simulate the flow around the train configuration is outlined in Section 2.3. A brief overview of the flow field and the forces acting on the train, as obtained from the LES simulation, is presented in Section 2.4.

2.1. The high speed train model and the computational grid

The generic high speed train model used in the present work is presented in Fig. 1(a). The model is a generic ICE2 train, also know as the "Aerodynamic Train Model" (ATM) (Orellano and Schober, 2006). Different configurations of the ATM are studied in the literature. The differences between the configurations are the length of the train and the inclusion or exclusion of details such as the boogies and gap. In the numerical work by Muld et al. (2009, 2012, 2013, 2014) on the ATM, boogies and gaps were included. In that work, Detached Eddy Simulation (DES) was used to simulate the flow around the trains. In this work, LES is used. As LES generally requires higher spatial resolution and consequently more computational degrees of freedom in the computational grid, and since the focus of the present work is on the flow structures in the wake, a completely smoothed model is considered, as depicted in Fig. 1(a). The configuration of the model used in the present work was also used in the numerical study on cross winds by Hemida and Krajnović (2009). The height of the model is $H=0.358$ m, the width of the model is $W=0.302$ m and the length equals $L=3.560$ m$=9.94H$. These dimensions correspond to a 1:10 relationship with the real dimensions of a train. Although the ATM model previously has been studied in experimental and numerical work, no direct comparison with the configuration studied in the present work is available. Therefore, in order to assess the grid dependence on the results two computational grids were employed. A coarse grid containing 21 million grid points and a fine grid containing 34 million grid points. Fig. 1(b) shows the fine grid in the wake. The grids contain only hexahedral elements and were constructed the block-structured technique in Ansys Icem CFD.

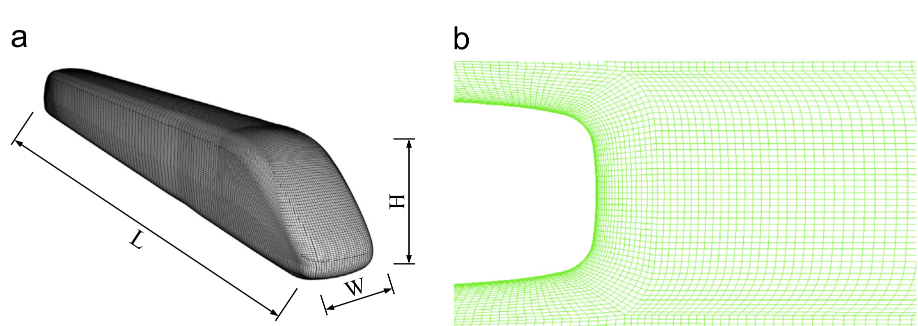

Fig. 1. (a) The train model seen from behind in a perspective view. The train surface is viewed together with the computational grid on the surface. (b) The computational grid in the wake.