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Numerical study of the aerodynamics of a full scale train under turbulent wind conditions, including surface roughness effects

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HIGHLIGHTS

- Aerodynamic behavior of a full scale train under synthetic crosswind.
- Large-Eddy Simulation (LES) with a wall function in the near-wall region.
- Both smooth and rough train surfaces are contemplated in this paper.
- Average, standard deviations and extreme values of the loads are compared.
- The synthetic wind is defined based on the Kaimal spectrum.

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ABSTRACT

A numerical simulation of the aerodynamic behavior of a full scale train under synthetic crosswind is presented. Both smooth and rough train surfaces are contemplated in this paper. The synthetic wind is defined based on the Kaimal spectrum, which is generated using Turbsim. The flow description is based on numerical simulations obtained using Large Eddy Simulation (LES) with the commercial code ANSYS-Fluent. Considering a very-high Reynolds number for our train model with LES requires the use of a wall function in the near-wall region. In this way, it is removed the need to resolve any turbulent eddies in the inner part of the wall layer, and the entire inner-layer dynamics are represented by a single value of the wall shear stress. The simulation gives a time history of the force and moments acting on the train; this includes averaged values, standard deviations and extreme values. Of particular interest are the spectra and admittances of the forces and moments. Comparisons are made with numerical and experimental results obtained for a small scale model fixed to the ground in a wind tunnel.

1. Introduction

A very intense research activity around train aerodynamics has been observed during the last years, and recent publications like Dorigatti et al. (2015), Fragner et al. (2015), Garcia et al. (2015) and Catanzaro et al. (2016) have put in evidence this topic is still of major relevance. Among all the aerodynamic problems of high-speed trains (HST), crosswind stability is probably one of the most demanding, involving the impinging flow on the windward side, curved flow along the vehicle surfaces, successive detachment and reattachment lines or the wake flow on the leeward side. The unsteadiness of

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the separated flow in the leeward side and the presence of trailing vortices in the flow make Reynolds-Averaged Navier–Stokes (RANS) models not suitable, and suggest that a turbulence resolving approach like Large-Eddy Simulations (LES) is a better option. The use of this approach has been extended for train aerodynamics and studies have been published both for HST, (Hemida and Krajnovic, 2009; Garcia et al., 2015), or freight trains, (Hemida and Baker, 2010; Östh and Krajnovic, 2014; Liu et al., 2014). However, although eddy-resolving methods like LES have shown their potential for this case, their computational cost remains an issue that limits in short term their use in realistic configurations and at Reynolds numbers close to those of real HST. Indeed, previously mentioned references consider Reynolds numbers in the order of 0.2×10^6 to 1.4×10^6, compared to 10^7 of real HST. Consequently, care has to be taken when extrapolating results from simulations to operational Reynolds numbers, (Loose et al., 2006; Krajnovic, 2014). In Baker and Brockie (1991), extrapolation errors from model scale (1/76 to 1/20) to full scale of up to 33% has been reported. The limitation of Reynolds number for a LES simulation has also an influence on the flow description. As explained in Copley (1987), depending on the Reynolds number, the flow may present a different behavior. Indeed, it may separate from the roofside windward corners without reattachment, may separate and reattach forming a separation bubble or the bubble may be suppressed and the flow is fully attached over the roof until it detaches at the leeward side upper corner. So, it is observed the need of a simulation at Reynolds numbers (still) closer to real conditions.

The near-wall region in high Reynolds number turbulent flow contains streaks that are dynamically important to the flow but which have dimensions that make it impractical to resolve in numerical problems, (Cabot and Moin, 1999). This near-wall problem of LES has been object of study for the last five decades, and to deal with the necessity of simulating the flow around a HST at (very) large Reynolds numbers while balancing the accuracy and cost of RANS and LES, hybrid RANS–LES methods postulate as the solution. Although different definitions are considered for the hybrid RANS–LES term, here it is used for any method that uses both approaches to simulate the flow, no matter how much is solved or modeled in the boundary layer, (Larsson et al., 2016). The most common alternative in HST aerodynamics is the use of Detached-Eddy Simulation (DES). This approach has been applied in Wu (2004) and Morden et al. (2015). In both the classic version (Spalart et al., 1997) or more advanced (Spalart et al., 2006; Gritskevich et al., 2011), turbulence is modeled all over the boundary layer. In order to reduce the influence of the RANS model in hybrid RANS–LES methods, wall-modeled LES (WMLES) has been proposed. In this case, the turbulence is modeled just in the inner part of the boundary layer, which is the main responsible of the expensive computational cost of LES simulations at high Reynolds numbers, (Larsson et al., 2016). For an extense review of WMLES, the reader is referred to Piomelli and Balaras (2002) or more recently Larsson et al. (2016). Two main branches of WMLES can be identified, namely hybrid RANS/LES methods or wall-stress model methods. In all the cases, removing the need to resolve any turbulent eddies in the inner part requires the entire inner-layer dynamics to be represented by a single value of the wall shear stress. The latter approach has been applied in cases where local adverse pressure gradients, separation and impinging flow are observed, (Wu and Piomelli, 2016), or configurations with wall-curvature or separated flows, (Jaegle et al., 2010), while off-wall boundary conditions have also been applied in Direct Numerical Simulation (DNS), (Mizuno and Jiménez, 2013). Here we consider the use of wall-stress model WMLES for the crosswind stability study of a HST. Wall functions in conjunction with LES have been used in Howard and Pourquie (2002) Minguez et al. (2008) and Serre et al. (2013) for the Ahmed body, but to our knowledge, this would be the first time it is used for HST. Here we use an equilibrium model that follows the law-of-the-wall on all solid cells. This has shown some success to predict wall stresses even in separated flow cases, although needs to be improved to predict the location of separation and reattachment points, (Cabot and Moin, 1999). Nevertheless, as pointed in Larsson et al. (2016), equilibrium models are still applicable in non-equilibrium flows.

Natural atmospheric wind is known to be distinctively turbulent and non-stationary. Thus, following our objective of a more precise evaluation of the cross-wind stability, unsteady turbulent oncoming wind is considered. The stochastic approach involves a description of the turbulent wind by its power spectrum density, and this approach has been applied for HST experimentally, (Baker et al., 2004; Sterling et al., 2009; Tomasini and Cheli, 2013), analytically, (Cooper, 1984; Yu et al., 2014) and we have used it numerically in Garcia et al. (2015). Here we consider the Kaimal spectral model, (Kaimal et al., 1972), as this covers both the energy-containing and the inertial subrange, which is critical to ensure accurate LES for evaluation of wind effects on ground vehicles, as it is pointed out by Huang et al. (2010). The Kaimal spectral model is simulated in this paper using the TurbSIM (Jonkman, 2009) code, which is widely used in wind energy engineering.

Finally, another novel issue proposed in this work is to study the influence of a rough train surface. Turbulent flows over rough walls has been object of study in Jiménez (2004). To sustain the analysis of roughness effect, changes in the aerodynamic force coefficients and flow topology in the near wake can be studied by comparing it with results from a hydraulically smooth train surface case, which is the habitual approach in the literature. Similar research has been proposed in Rodriguez et al. (2016) for a circular cylinder. Here, a roughness height of $z_0 = 0.03$ mm is chosen, which is equivalent to a hydraulic roughness of $k_s = 1$ mm and corresponds to some material like cast iron, according to classical textbook tables for the use of Moody diagram. This value is about two orders of magnitude larger than the limit criterion to still consider a flat plate hydraulically smooth, (Schlichting, 1979). So, it is justified to contemplate the train surface as fully rough.

The paper is organized as follows. The numerical method and the numerical set-up and boundary conditions are described in Sections 2 and 3, respectively. In the latter, the most significant features of our paper, namely the boundary condition at the walls and the inlet turbulent wind, are detailed. Qualitative and quantitative results are presented in Section 4, where it is given the averaged, standard deviations and extreme values of the forces and moments acting on the train. Besides, an analysis of the instantaneous flow structures, the spectra and admittances of forces and moments is done. Comparisons with experimental and numerical results already published in Garcia et al. (2015) for the small scale model for our smooth and rough train walls are also performed. Finally, Section 5 is devoted to conclusions.