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Numerical study of the influence of synthetic turbulent inflow conditions on the aerodynamics of a train

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ABSTRACT

The necessity of a more complete definition of the turbulent wind acting on a train is studied in this paper using computational fluid dynamics (CFD). A stochastic approach for the modeling of turbulent winds is proposed here. Synthetic winds are defined based on two different spectral models, namely the Kaimal spectrum and the Kraichnan spectrum. These are generated using Turbsim and ANSYS−FLUENT software, respectively. To complete the comparison, a third oncoming wind definition is considered, corresponding to a uniform (low-turbulence) wind. Large-Eddy Simulation (LES) and Scale-Adaptive Simulation (SAS) turbulence models have been used for the numerical simulation. Comparison is made of the average, standard deviations and extreme values of the loads calculated with the different methods. The corresponding flow fields are also studied and compared. The transient behavior is analyzed using the spectra of the velocity and loads, and the aerodynamic admittance curves. The results obtained for the last inlet condition are in good agreement with previous studies, while the importance of the spectral model choice is evidenced in the analysis of the velocity and force spectra, as well as in the aerodynamic admittance curves.

1. Introduction

Operational safety of high-speed trains has been investigated assuming steady uniform cross-winds, attracting much attention from researchers (Diedrichs, 2008; Cheli et al., 2010; Hemida and Baker, 2010; Choi et al., 2014), as well as in road vehicles (Guilmineau et al., 2011). However, in windy conditions, the natural atmospheric wind can exhibit strong lateral gusts. Indeed, the wind in the atmospheric boundary layer is known to be distinctively turbulent and non-stationary. Thus, for a more precise evaluation of the cross-wind stability, unsteady turbulent oncoming wind should be considered. Furthermore, it has been observed that there can be substantial differences between the aerodynamic data obtained from steady and unsteady cases, so that the interest of an analysis considering unsteady inlet conditions is evident.

Two approaches have been developed for the modeling of turbulent winds, namely deterministic and stochastic approaches. The former tackles the natural wind by means of an equivalent ideal wind gust that can adopt different shapes. These are the exponential shape (Larsen et al., 2003; TSI, 2008), the '1-cos' shape (Carrarini, 2006), the ramp function (Lippert, 1999), a combination of a damping, a saturation and a sinusoidal function (Krajnovic, 2008), or the most commonly

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applied 'Chinese hat' (Proppe and Wetzel, 2010; TSI, 2008). The stochastic approach involves a description of the turbulent wind by its power spectrum density, so that the uncertainty and variability of the natural wind is somehow taken into account. Experimentally, this approach has been applied for high-speed trains (HST) by Baker et al. (2004), Quinn et al. (2007), Sterling et al. (2009) and Tomasini and Cheli (2013); analytically (Cooper, 1984; Yu et al., 2014); and numerically (Baker, 2010). However, there is no reference where the stochastic approach is considered in a computational fluid dynamic (CFD) study concerning HST. Large-eddy simulation (LES) has been used for transient simulations of HST (Hemida and Krajnovic, 2010), and here we use this method for the study of the train stability under a stochastic description of the oncoming cross-wind.

The turbulent inflow problem, i.e. how to generate an artificial turbulent inflow condition for numerical simulations, has been faced considering a large variety of strategies. These may introduce different degrees of computational cost, and a review is given in the paper of Jarrin et al. (2006). More recent approaches rely on the fact that coherent structures embedded within the flow play a dominant role in the spatio-temporal dynamics of turbulent flows (Druault et al., 2004; Perret et al., 2008), where the generation of turbulent inflow boundary conditions is based on the use of an experimental database. Considering also a given reference turbulent flow, Hoepffner et al. (2011) have proposed a technique to produce a random field with exactly the same two-point two-time covariance as the reference one. Nevertheless, because of its relative simplicity, synthetic methods have reached a significant popularity. Kondo et al. (1997) create time series of velocity fluctuations by performing an inverse Fourier transform for prescribed spectral densities, where their phase is drawn randomly. The digital filtering technique is applied by Klein et al. (2003) and Xie and Castro (2008) for the superimposition of fluctuations, while Mathley et al. (2006) add perturbations from a 2D vortex method to a specified mean velocity profile. Based on the work of Kraichnan (1970), in the paper of Smirnov et al. (2001) a non-homogeneous turbulent flow field is obtained from simplified variants of a spectral method. The spectral synthesizer, implemented in ANSYS−FLUENT (ANSYS, 2013), is based on Smirnov's contribution. It involves scaling by some turbulent variables and applying orthogonal transformation operations to a continuous flow field generated by a superposition of harmonic functions, where the number of modes is limited to reduce the computational cost. Whereas the algorithm is relatively simple, the spectral density of the generated turbulent flow field only follows Gaussian's spectral model (Huang et al., 2010), so the energy in the inertial subrange and the dissipation subrange are too small compared to what is observed in real wind conditions. In contrast, other spectral models, like the von Karman (1948) or Kaimal et al. (1972) ones, do cover both the energy-containing and the inertial subrange. This characteristic is critical to ensure accurate LES for evaluation of wind effects on ground vehicles, as it is pointed out by Huang et al. (2010). Consequently, we compare the results obtained from the application of the spectral synthesizer with those considering the Kaimal spectral model. The latter has been simulated using the TurbSim (Jonkman, 2009) code, which is widely used in wind energy engineering. To complete the comparison, simulations have also been run with a uniform (low-turbulence) oncoming wind using the Scale-Adaptive Simulation (SAS) (Menter and Egorov, 2010) turbulence model. The motivation of using this turbulence model is based on previous works of the authors.

1.1. The scope of the study

- Transient and wind gusts simulations are not exactly novel, but to our knowledge, this is the first CFD study considering not a single ideal gust but a full turbulent cross-wind acting on a train. The complexity of experimentally setting a controlled fully turbulent cross-wind test emphasizes the interest of the numerical alternative. A description of the method, its requirements and capabilities are included.
- Three different scenarios are compared in the paper. These are a uniform oncoming cross-wind and two stochastic winds, namely a Gaussian-based and the Kaimal spectral model, covering in this paper the simplest and the most realistic approaches. The former and the Gaussian-based case correspond to a uniform mean wind profile, while in the Kaimal-based case a non-uniform mean wind profile, following a logarithmic law, is considered. The turbulence intensity is also varied in these three scenarios. In all the cases, the train is at rest, subjected to a synthetic turbulent wind at a 30° yaw angle.
- Substantial differences between the aerodynamic data obtained from steady and unsteady cases have been observed in other cases (Krajnovic et al., 2012), and one objective of the paper is to estimate and analyze these differences. Averaged aerodynamic quantities (mean, extreme values and the standard deviation of force and moments coefficients as well as pressure distributions) are used for this comparison, while the transient behavior is analyzed by the velocity and forces spectra, and the aerodynamic admittance curves.
- SAS and LES are used in this work for the transient simulation of the stated problem. For the validation of our simulations, results are compared with the experimental data given in the work of Wu (2004). While LES have been extensively used in train aerodynamics, SAS has not yet been applied for this particular problem, so it is encouraging the industrial interest it might cause.

2. Numerical method

A detailed description of the flow structures around a train subjected to a 30° cross-wind is given by Chiu and Squire (1992) and Hemida and Krajnovic (2009). Capturing the vortex shedding in flows around trains requires simulation methods