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Flow between the train underbody and trackbed around the bogie area and its impact on ballast flight

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ABSTRACT

The aerodynamic behaviour of flow past a simplified high-speed train bogie including the ground underneath with ballast particles at scale 1:10 is studied numerically. It is found that the flow around the bogie is highly unsteady due to strong flow separations and flow interactions developed there. Generally, the ballast particles distributed inside the wheels are situated in the stronger turbulent flow and are subject to much higher aerodynamic forces than the particles located outside the wheels. Moreover, these aerodynamic forces increase when the ballast particles are located downstream of the bogie cavity and reach the peak values close to the bogie cavity trailing edge. The force time-series are produced based on the simulations of an array of the ballast particles in a wind-tunnel setup and it shows that the ballast flight is apt to happen as the rear part of the bogie cavity passing by the ballast bed. When the ballast particles become airborne, the fluctuating forces generated increase significantly. Therefore, the stronger unsteady flow developed around the bogie cavity, especially in the cavity trailing edge region, will produce larger fluctuating forces on the ballast particles, which will be more likely to cause ballast flights for high-speed railways.

1. Introduction

High-speed railways are being developed rapidly around the world. Much progress has been made in the understanding of the aerodynamic phenomena associated with high-speed trains (Baker, 2010, 2014; Hemida and Krajnovic, 2010; Jönsson et al., 2009; Schetz, 2001). Recently, the flow behaviour and the corresponding aerodynamic noise generation mechanisms of a scaled isolated wheelset and simplified bogie have been investigated, which is found to be closely linked with the flow aerodynamics around the bogie (Zhu et al., 2014, 2016). Related to the underfloor carbody aerodynamics, a phenomenon of ballast flight under normal meteorological conditions occurs more frequently in associated with the operation of high-speed railways (Quinn et al., 2009). In addition to ballast flight, the physical background of ballast projection encountered on the railway networks has been investigated in Japan and Korea (Kaltenbach et al., 2008). Ballast projection is revealed as a sporadic occurrence and causes impact damage to both train and track. Its developing starts from the aerodynamic initiation of motion of some larger ballast particles becoming airborne which later strike the vehicles, vehicle-mounted or trackside equipment and thereby bounce back onto the trackbed and eject additional ballast particles. In France, ballast flight and projection have recently received more attention in view of the planned increase of train operational speed up to 350 km/h (Kaltenbach et al., 2008). The planned High Speed 2 (HS2) in the United Kingdom will run at the speed around 360–400 km/h in the ballasted track. Thus, improved understanding of the flow behaviour of ballast flight would be useful for decision making and safe running of the railway.

It is generally recognized that the damage generated on the rail running surface by wheel-rail interaction is a major maintenance cost for any railway network (Cannon et al., 2003). With the development of high-speed railways, the railhead damage known as 'ballast pitting' has become more frequent (Quinn et al., 2009). This rail defect is caused by the small ballast particles becoming trapped between the rail running surface and the vehicle wheels. Thus, the sub-rail foundation experiences greater impact under heavy cyclic train loads particularly for high-speed railway lines. Due to such progressive deterioration, the residual deformation of the ballast is produced and leads to poor ride quality and loss of track support as a consequence of the voids formed between the sleepers and the ballast (Zhu et al., 2011).

In order to understand the mechanism of the ballast flight, field experiments were carried out to investigate the aerodynamic and

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mechanical forces acting on ballast particles which were generated during the passage of a high-speed train (Quinn et al., 2009). Additionally, an analytical model was established to identify the factors causing the small ballast particles being ejected from the trackbed. It was found that ballast flight could arise from a combination of both aerodynamic and mechanical effects and the process was stochastic (Quinn et al., 2009).

The aerodynamic loads on the trackbed causing ballast projection have also been investigated (Kaltenbach et al., 2008; Deeg et al., 2008). The wind tunnel experiments showed that the trackbed geometry, i.e. the type of sleepers and the level of the ballast bed surface, had a strong influence on the initiation and intensity of ballast particle dislodgement. However, obtained under idealized conditions in the laboratory, these results could not be correlated directly to the situations with realistic trackbed. Based on the experiments with a ballast catapult dealing with the impact of particles on the ballasted trackbed, a linear relation between the number of ejected granules and the kinetic energy of the impacting grain has been obtained (Kaltenbach et al., 2008).

The basic characteristics of the flow between the underbody of a high-speed train and the ground have been studied numerically based on a turbulent Couette flow model to simplify the calculation (García et al., 2011). The influence of the parameters (height of the gap, Reynolds number and roughness of the upper wall) on the equivalent surface roughness was analyzed. It was found that an equivalent roughness of the trackbed made of sleepers and ballast could be obtained based on this analytical method. However, the configurations with more detail geometries between the train and the ground are needed for the flow calculation.

A full-scale computational fluid dynamics (CFD) simulation based on Reynolds-averaged Navier-Stokes (RANS) investigation of the ICE3 (inter-city express, German high-speed train) geometry using the nonlinear $k-\varepsilon$ turbulence model together with a wall function approach was performed. The results showed that the thick boundary layers were developed considerably in the train underfloor region due to the generation of turbulence and secondary flow in the vicinity of the bogies. Additionally, the skin friction was increased significantly immediately downstream of the inter-car gap. The RANS results from this study didn't correspond well with the experimental measurements (Kaltenbach et al., 2008). Improvement on CFD results is needed for better understanding of the train underbody aerodynamics and its influence on the ballast flight.

The mechanisms of the ballast flight or projection are not well understood (Quinn et al., 2009; Kaltenbach et al., 2008). Since the flow beneath a high-speed train running on a ballasted track is highly unsteady and turbulent, it is still very difficult to numerically predict the ballast flight or projection. The bogies and the train underbody cavities are the main components in the train underbody regions and contain many geometries exposed to flow with little or no streamlining, leading to complex flow structures which affect the flow behaviour around the trackbed. As a first step, the flow behaviour under the train carbody with some ballast particles attached on and close to the trackbed around the bogie region is investigated based on the numerical simulations performed for a simplified bogie situated in the bogie cavity with the ground underneath.

2. Numerical method

Aerodynamically, high-speed trains are operating within the low Mach number flow regime, for example at 300 km/h the Mach number is about 0.25. The incoming flow simulated here is at low Mach numbers (0.09 corresponding to 30 m/s) and thereby the compressibility effects are small and therefore can be neglected to the hydrodynamic airflow field. Therefore, the unsteady, incompressible Navier-Stokes equations are used to solve the flow field. The continuity and momentum equations in tensor notation are

$$\frac{\partial u_i}{\partial x_i}=0 \quad , \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j} = f_i - \frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu\frac{\partial^2 u_i}{\partial x_j \partial x_j} \quad , \tag{2}$$

where x_i represents the Cartesian coordinates in the three directions for $i = 1,2,3$. p is the pressure, ρ is the density, ν the kinematic viscosity, f_i is the body force components and u_i the flow velocity components. Here ρ and ν are constants for incompressible flow. The open source software OpenFOAM-2.2.1 is employed to solve the governing equations. A second-order accurate scheme is utilized for the convection and diffusion terms of the spatial derivatives and the temporal discretization follows a second-order fully implicit scheme. The pressure-velocity algorithm PIMPLE, combining PISO (pressure implicit with splitting of operator) and SIMPLE (semi-implicit method for pressure-linked equations) algorithms (OpenFOAM, 2015), is applied to solve iteratively the resulting discretized linear-algebra equation system. The delayed detached-eddy simulation (DDES) model based on the Spalart-Allmaras (S-A) turbulence model is employed for the current flow calculations. The S-A model is a one-equation model which solves a convection-diffusion equation for the modified turbulent kinematic viscosity, $\tilde{\nu}$. The transport equation is defined as

$$\frac{\partial \tilde{\nu}}{\partial t} + u_j\frac{\partial \tilde{\nu}}{\partial x_j} = G_\nu - Y_\nu + \frac{1}{\sigma_{\tilde{\nu}}}\left[\frac{\partial}{\partial x_j}\left((\nu+\tilde{\nu})\frac{\partial \tilde{\nu}}{\partial x_j}\right) + C_{b2}\left(\frac{\partial \tilde{\nu}}{\partial x_i}\right)\left(\frac{\partial \tilde{\nu}}{\partial x_i}\right)\right], \tag{3}$$

where the three terms on the right-hand side are the production term, destruction term and diffusion term of the model variable $\tilde{\nu}$. Details of the formulations were introduced in (Spalart and Allmaras, 1992).

As a hybrid technique, detached-eddy simulation (DES) combines unsteady Reynolds-averaged Navier-Stokes (URANS) modelling in the near-wall regions to resolve the boundary layer, with large-eddy simulation (LES) in the massive separated outer flow regions to capture the large-scale structures (Spalart et al., 2006). The applications of DES in the fully turbulent mode have been confirmed by the benchmark problem results with different codes (Spalart et al., 2011). Delayed detached-eddy simulation has been developed to avoid grid-induced separation and preserve the RANS mode throughout the boundary layer. The CFD simulation results using DDES with layered grid show good agreement quantitatively with the experimental data (Spalart et al., 2006).

3. Simulation setup

The three-dimensional model at 1:10 scale consisting of a simplified bogie, a section of the train underbody and trackbed with ballast particles is displayed in Fig. 1 where the incoming flow with freestream velocity U_0 is also indicated. The simplified bogie is the same bogie as used in (Zhu et al., 2016). To reduce the simulation cost, the most representative components that generate vortex shedding and turbulent wake, such as the wheels, axles and the frame, are kept in the simplified bogie model. The axle has a diameter (d) of 17.5 mm and the wheels have a diameter (D) of 92 mm. The wheelbase (centre-to-centre length of two axles) is 252 mm which is about 14 times the axle

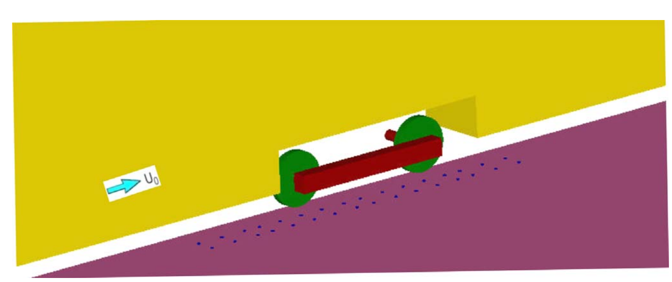

Fig. 1. Simplified model of train underbody and trackbed with ballast particles.