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Performance of a turbine driven by train-induced wind in a tunnel

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ABSTRACT

A simulation of the turbine driven by a high-speed train-induced wind in the tunnel was performed using the IDDES method with the SST *k-w* turbulence model. A full-scale real train experiment was conducted, and the results from a previously published study were employed to verify the computational method and mesh used for the simulation of the flow fields around the train and the turbine. The results show that the differences between the experiment and simulation results are very small. Next, certain variations of the torque of the turbine, the vorticity, velocity, pressure and specific dissipation rate of the flow field around the turbine during the process of the train crossing a tunnel are analysed. The obtained results show that not only the wake of the tail car but also the flow around the head car exerts great influence on the turbine. Next, a series of comparative studies were performed. The relationship between the maximum torque of the turbine and the distances from the turbine to the entrance and the exit of the tunnel, which can be modelled as power functions, were proposed. It was observed that while the maximum torque of the turbine decreases when the length of a tunnel varies from 100 to 300 m, it increases with the increasing length of the tunnel for lengths between 300 and 800 m.

1. Introduction

Air pollutants and greenhouse gases emitted by human activities increase every year, harming the present and future of humanity (Moustafa, 2017). In fact, high concentrations of CO_2 and pollution in the atmosphere are caused by fuel combustion or other human activities (Dmitrienko and Strizhak, 2017; Niu et al., 2015). The use of renewable energy sources has been proposed as the solution for cleaner energy generation and consumption. Compared to other renewable energy sources, wind power is currently more commercial developed (Liao, 2016). Turbines are suitable for construction generally in coastal and dry arid zones or other areas where wind energy resources have good potential (Herbert et al., 2007). However, wind energy can also be provided in certain special occasions for driving turbines.

For instance, when cruising, a car will generate turbulence kinetic energy. A greater amount of energy is generated at a higher speed of the car (Musa et al., 2012). Therefore, some studies have considered the use of this kinetic energy for renewable energy generation. Additional power can be acquired through a wind turbine which is formed as a structure in the vehicle (Bao et al., 2012). Affixing a generator on the rear end of the car trunk also may enable the utilization of the energy of the wind impact the cars at high speeds (Chaudhary et al., 2017). Additionally, a turbine can be driven by the wake of a moving car when installed on the side of the road, and the relationship between the generating capacity and the speed of the car can be described by quadratic equations in this case (Tian et al., 2017).

Moreover, a high-speed train, which is faster, longer and has a larger cross-sectional area than a car, can provide a wake with higher speed and wider range during running. (Baker et al., 2001). The influence of a train's wake in the tunnel is especially strong (Fu et al., 2017). Thus, the wake of a high-speed train in a tunnel can be used for electricity generation.

As a matter of fact, owing to the presence of lighting and ventilation equipment, there is a demand for electricity in the tunnel. However, the voltage of the contact line is about 25,000 V, which can not directly be used for the necessities of tunnel facilities. Then some voltage converters have to be installed along the railway lines to provide specialized electric supply for the tunnel facilities. This may increase the loads and lower the stability of the electric power system. If there is another independent electric system, the power supply facilities of the high-speed train can be simplified, and the circuit of the contact line will be more safe and reliable. Generally, railway lines are located far from urban areas in order to avoid disturbing the residents, leading to the need for many tunnels for the railways in inaccessible mountainous areas. Hence the tunnels that always appear in mountain areas are far from residential regions, so lots of resources will be used if transferring

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the electricity.

Therefore, considerable resources are required to transfer electrical energy through wires into these tunnels, even though the power consumption requirements in the tunnels are not high. The maintenance cost of the wires for such transmission of electrical energy is also high. If the wake flow generated by the train passing through the tunnel can be used to generate electricity, resources can be saved, and the damage to the surrounding environment can also be reduced. However, using turbines can solve this electricity problem, as no extra wires are needed.

Notably, a contact-type electric power supply system limits the speed of the high-speed train in a way. Meanwhile, the contact line distributed along the railway consumes huge resources and destroys the environment. In the future, as the charging speed of large capacity batteries increases, the high-speed train may obtain the power using the large capacity batteries. At that time, using turbines installed in the tunnel to generate the electricity can become very popular for those tunnel facilities.

The use of a computational fluid dynamics (CFD) model methodology is widely adopted as a technique for analysing the surrounding flow field around high-speed trains or turbines. Based on the CFD method, in this work, the wind turbine is installed in the tunnel, and the process of the high-speed train passing through the tunnel and generating flowing air acting on the blades of the turbine is simulated.

2. Methodology

2.1. Physical models

The schematic diagrams of the simulated physical models are shown in Figs. 1 and 2. A model of a simplified high-speed train, which is composed of a head car, a middle car and a rear car, is shown in Fig. 1. The size of the model is consistent with the size of the actual train. In addition, bogies are omitted because the fine flow fields around the bottom of cars can be neglected. Table 1 lists the main geometric parameters of the train.

Moreover, a common Savonius or Darrieus turbine has only two or three blades, making them unsuitable for used in the tunnel because the flows generated by the train will affect the turbine in various directions. A smaller number of blades mean a larger angle between the adjacent blades which, in turn, means that the threshold direction of flow and speed of wind for starting the turbine will be more unstable. To ensure that the turbine can work in the environment of flows in various directions, a model of a Banki-Michell turbine (Sammartano et al., 2013) consisting of 2 plates with 24 circularly symmetrical 0.05 m thick blades, is shown in Fig. 2, while Table 2 lists the main geometric parameters of the turbine.

2.2. Method of simulation

Even though the Mach number in this simulation is smaller than 0.3, the compressibility of air cannot be negligible owing to the compression waves induced by the moving train in the tunnel (Liu et al., 2016).

The governing equations of the flow fields include continuity, Navier-Stokes and energy conservation equations (Versteeg and Malalasekera, 1995). These equations are as follows:

$$\frac{\partial\rho}{\partial t} + \mathrm{div}(\rho\boldsymbol{u}) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \mathrm{div}(\rho u_i\boldsymbol{u}) = \mathrm{div}(\mu\,\mathrm{grad}u_i) - \frac{\partial p}{\partial x_j} + S_k \tag{2}$$

$$\frac{\partial}{\partial t}(\rho T) + \mathrm{div}(\rho\boldsymbol{u}T) = \mathrm{div}(k\frac{k}{c_p}\mathrm{grad}T) + S_T \tag{3}$$

where ρ is the air density, $\boldsymbol{u}$ is the velocity vector, u_i is the component of the velocity vector, p is the pressure on the fluid microelement, S_k is the generalized source term of the momentum conservation equation, c_p is the specific heat, k is the coefficient of heat transfer, T is the temperature and S_T stands for the viscous dissipation.

The IDDES method which is a model consisting of two sub-branches, namely, Wall Modelling LES (WMLES) and Delayed Detached Eddy Simulation (DDES) (Šekutkovski et al., 2016), is adopted in this work to obtain the instantaneous and accurate slipstream around the high-speed train and the turbine. The IDDES method originates from the incipient DES method (Spalart et al., 1997), which combines the advantages of RANS and LES and distinguishes them in each node by the discriminant function $\widetilde{d}$ (Spalart, 2009).

$$\widetilde{d} = \min(d,\ C_{des}\Delta) \tag{4}$$

where C_{des} is the model coefficient that is usually equal to 0.65, and Δ is the filtering length. In the near-wall regions, $d < C_{des}\Delta$, so $\widetilde{d} = d$, and the RANS model is adopted. Conversely, in the far-wall regions, $d > C_{des}\Delta$, $\widetilde{d} = C_{des}\Delta$, and LES is adopted. Hence, two calculation methods can be smoothly converted in both the near-wall and far-wall regions. However, the calculation accuracy is extremely dependent on the size of mesh, which is the key to determining the pattern of LES or RANS.

To overcome the shortcoming of DES, the DDES method was proposed using a delay function (Spalart et al., 2006). The discriminant function $\widetilde{d}$ can be modified as

$$\widetilde{d} = d - f_d\max(0,\ d - C_{des}L_g) \tag{5}$$

where f_d is the delay function given by Eq. (3).

$$f_d = 1 - \tanh[(c_d r_d)^3] \tag{6}$$

where $c_d = 8$ is an empirical content value. r_d is the ratio of the model

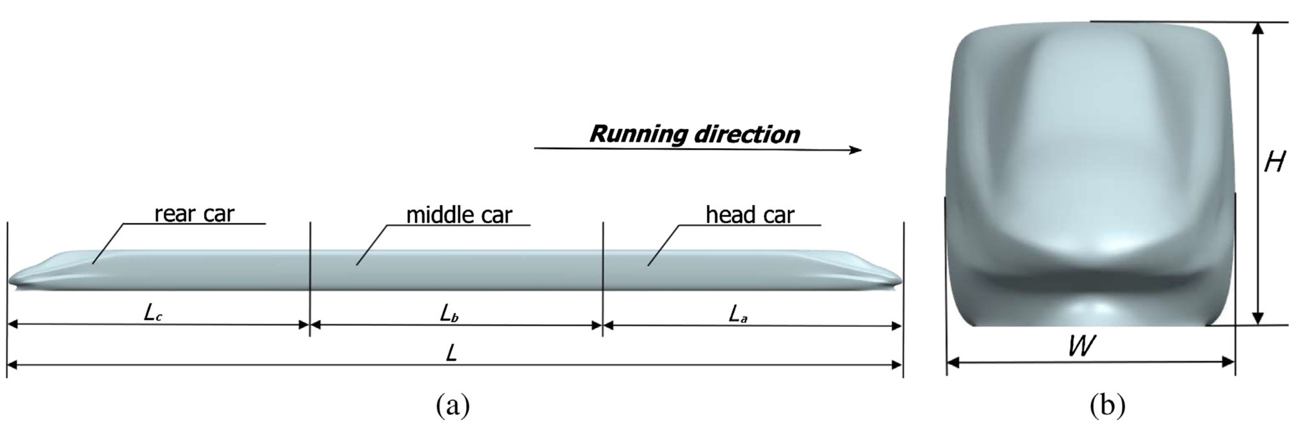

Fig. 1. CFD model of the train: (a) side view; (b) front view.