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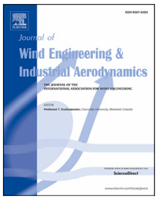

Numerical simulation and prediction of spatial wind field under complex terrain

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ABSTRACT

A computational fluid dynamics numerical simulation of a spatial wind field under a complex terrain was conducted, and a prediction model of wind characteristics was proposed based on the correlation of simulation results. A large eddy simulation turbulent model was employed to simulate the behavior of the turbulent flow of the spatial wind field by using OpenFOAM 4.0. Then, the prediction model of the spatial wind field was established according to the "triangle edge angle relationship" for the mean wind velocity and spatial correlation analysis for the fluctuating wind velocity. The predicted model was further validated by simulation velocity time histories, reaching good agreement with the simulated results, which indicated that the predicted model had a higher precision. Finally, the proposed model was utilized to predict natural wind field characteristics, and they were compared with field measurement data acquired from ultrasonic anemometers. A comparison of the fluctuating wind velocity time histories, mean wind speeds, and fluctuating wind velocity spectra indicated that the predicted model was practical.

1. Introduction

The impact of wind on national infrastructure projects, i.e., transmission tower lines, long-span bridges, and wind farms, both at the early project evaluation stage and during later operation, was considered. When arranging transmission tower lines and long-span bridges at the location of the least wind damage or locating wind farms in areas with the most annual average wind resources, an important precondition is to obtain accurate wind field information (Herbert et al., 2014). The most accurate way to obtain the local wind field information is to conduct a field measurement. However, this is very difficult and expensive, because the wind velocities for a high number of observations should be measured simultaneously. Generally, an alternative method, i.e., the numerical simulation method, is adopted.

Because the experimental study was limited to a model scale ratio, the numerical simulation method can capture the wind information of the entire space in the case of a full-scale condition. This has obvious advantages for the analysis of a wind field under complex terrain. The numerical simulation method can be divided into mesoscale and structural scale approaches that depend on the different scales of vortices that focus on the wind field. The mesoscale numerical model considers the multiphysics process (e.g., wind, temperature, humidity, water vapor) to simulate the wind field under a natural atmosphere and terrain (Papanastasiou et al., 2010; Huang et al., 2015). However, the mesoscale model seems to be too coarse for analyzing the wind field around a structure. As for this condition, a structure scale numerical model is a good choice (Kim et al., 2000; Feng and Shen, 2014). However, it would be too time-consuming if a computational fluid dynamics (CFD) numerical simulation were to be required for each case. Therefore, researchers studied several statistical models for efficiently obtaining the wind field. Alexiadis et al. (1998) proposed a spatial correlation predictor based on the measured data of adjacent sites. More than seven years' data of six sites were used to validate the model, and it performed well. The reduction of the prediction error by using a spatial correlation model was studied by Benchetrit and Levy (2002). The error of a single site was compared with that of an ensemble of wind farms, and it was found that

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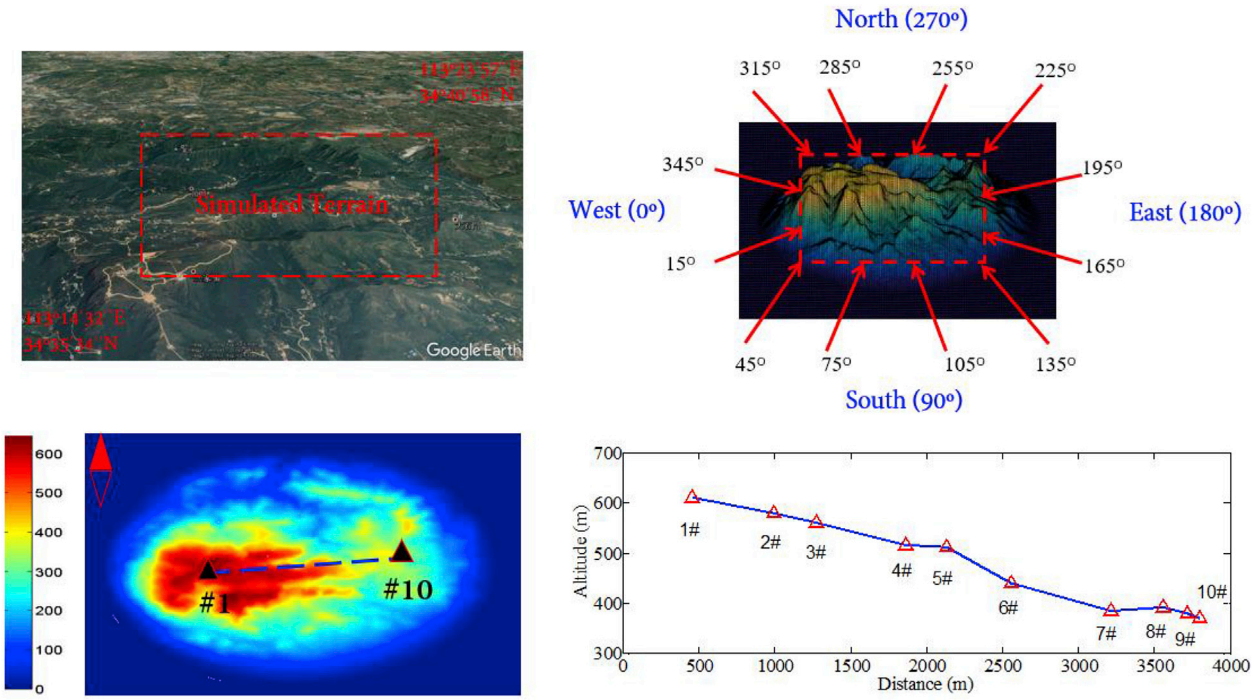

Fig. 1. Simulated region and observation points.

the error of the spatial correlation model was less than that of a single site, because of the spatial smoothing effect. The error reduction was mainly decided by the region size and the site number. Damousis et al. (2004) proposed a temporal prediction model based on a fuzzy method accompanied by a spatial correlation. This prediction model was applied to a flat terrain and a complex terrain. It was found that the data from the remote sites did improve the forecasting accuracy over the flat terrain. However, for the complex terrain, it made the forecast worse. The spatial correlation model did not have a good effect. Barbounis and Theocharis (2007a,b) found that a model utilizing the wind direction conditions could get better performance than a model that did not consider the wind direction.

The focus of the above prediction models is the temporal domain. A significant correlation of hourly or daily mean wind speeds has been recognized for distances of 20-to-100 km (Damousis et al., 2004). The prediction models could only predict the mean wind speed when considering the time delay in a straight line, whereas spatial wind field forecasting did not perform well. It should be noted that the correlation decreased with a horizontal distance (Corotis et al., 1977) and topographical elevation difference (Beyer et al., 1993). It also decreased when the orientation of the distance vector differed from the wind direction (Palomino and Martín, 1995). The correlation coefficient is related to the wind direction, terrain roughness, and height above the ground (Chan et al., 1983).

The current spatial wind field prediction models are mainly aimed at the mean wind information, and the consideration of topography, terrain roughness, and wind direction is insufficient. Thus, a highly efficient spatial wind field prediction model derived from CFD simulation results was proposed, and the influence of the above factors on the predicted model were included. Then, the prediction model could obtain the entire wind field only with finite spatial observation data.

The structure of this paper is as follows. In section 2, a computational model of a wind field is introduced. In section 3, the basic wind characteristics are analyzed. In section 4, a spatial wind field prediction model is proposed and is validated by simulation results. In section 5, the proposed prediction model is used to predict the natural wind field by using a few items of observation data. Finally, the conclusion is given in section 6.

2. Simulation settings

The simulated region is the range of longitude 113.2397°–113.2943°E, latitude 34.58150°–34.63605°N, in Henan province in the middle of China. The area of the terrain is about 6 km × 6 km, and a topographic elevation map of this region is shown in Fig. 1. Several ultrasonic anemometers were installed at the transmission towers, i.e., #1–#7 to monitor wind velocities. The wind field distribution is very important for designing and constructing high-voltage transmission tower lines in this region.

To evaluate the wind characteristics in different wind yaw directions, a total of 12 angle cases, i.e., 15° to 345°, with an increment of 30° were chosen for the present simulation, as shown in Fig. 1. The definition of the direction of the computational domain from west to east is 0°, from south to west is 90°, from east to west is 180°, and from north to south is 270°. The simulation results in each wind direction showed a certain similarity. Therefore, a representative case, i.e., the north-northwest direction 345° was selected to show the detailed wind field characteristics in the following sections.

For all simulated cases, the total calculation time is 1000 s, and the inflow running through the calculation domain needs almost 400 s. Therefore, simulated results from only 400–1000 s (i.e., 10 min) were used to analyze the wind field characteristics after the wind field was fully developed.

2.1. Terrain topology and computational domain

The terrain used in the present numerical simulation was taken from the Geospatial Data Cloud (http://www.gscloud.cn). A world digital elevation data product, i.e., the advanced spaceborne thermal emission and reflection radiometer global digital elevation model, was employed to extract the ground elevation with a horizontal resolution of 30 m and vertical resolution of 20 m. The simulated terrain is 6 km × 6 km (X × Y, west–east × south–north), and the largest elevation is 0.646 km.

Because the terrain in the simulated region is very complex and the geography resolution is limited, there is great steepness in the terrain. To avoid calculating divergence and to obtain a free wind field, the boundary of the simulated region should be extended and processed