A NUMERICAL SIMULATION OF FLOW FIELD IN A WIND FARM ON COMPLEX TERRAIN

Myungsung Lee¹, Seung Ho Lee¹, Nahmkeon Hur¹, Chang-koon Choi²
¹ Department of Mechanical Engineering, Sogang University, Seoul 121-742, Korea,
² Department of Civil and Environment Engineering, KAIST, Daejeon 305-701, Korea

ABSTRACT

A three-dimensional flow simulation is performed to investigate the wind flow around the wind-power generation facilities in mountainous area of complex terrain. A digital map of the wind farm area located in the eastern mountainous area of Korea is used to model actual complex terrain. Rotating wind turbines are also modeled in the computational domain with detailed blade shape using the frozen rotor method. Wind direction and speed to be used as a boundary condition are taken from local meteorological reports. The numerical results show the details of flow field distribution in the wind farm, the variation in the performance of the wind turbines due to the location of the turbines in complex terrain, and the effect of the upstream turbine on the performance of the downstream one. The methodology presented in the present study may be used in selecting future wind farm site and wind turbine locations in the selected site for possible maximum power generation.

KEYWORDS: WIND ENGINEERING, WIND FARM, WIND TURBINE, COMPLEX TERRAIN, CFD (COMPUTATIONAL FLUID DYNAMICS), FROZEN ROTOR METHOD

Introduction

Global warming becomes a threat to the mother earth so that search for the clean and renewable energy generation has long been sought. Among the renewable energy sources, the wind energy is one popular form of the energy which can be relatively easily converted to the electric power compared to other form of renewable energy. Since the output of wind power is proportional to the cube of the velocity, the wind farm successfully located can provide significant output of energy (Murakami et al., 2003). For that reason, many experimental and analytical studies have been conducted in order to estimate wind resource using meteorological data. Helmis et al. (1995) carried out a field experiment in order to examine the wind flow characteristics concerning the upwind area and the wake region behind a single wind turbine using remote sensing techniques. As results of their study, wind speed acceleration and channeling effects are founded due to complex topography and the nonlinear interaction between the wake and the turbine tower is also revealed. Barthelmie et al. (1996) examined the coastal meteorology at the world’s first offshore wind farm in Vindeby, Denmark with observations such as wind speed differences between land and sea, wind speed profiles, diurnal variability and turbine wake effect. These experimental studies, however, consume much time and effort to investigate the flow structure in a wind farm. Morfiadakis et al. (1996) established a procedure for applying the von Karman formulation to the measured spectra of the three velocity components measured in the wind farm in the island of Andros, Greece. This analysis reveals that von Karman spectrum is suitable for the structure of the
turbulence measured at some location in free stream condition. However, intense topography effects like flow separation and wake effects are not adequately modeled by this formulation.

The methodology of wind resource assessment has relied on a combination of field data and software tools based on statistics and linear models of the fluid flow equations (Palma et al., 2008). This practice has proved its suitability in case of relatively flat terrain, being able to resolve the flow structure at areas of moderate slope (e.g. Landberg et al., 2003; Ayotte and Hughes, 2004 among others). Finardi et al. (1998) verified a mass-consistent model (MINERVE) which satisfies mass conservation with linearized space-interpolation to reconstruct the wind field features. They compute the space distribution of wind speeds and their variation with height so as to identify the areas suitable for wind turbine sites. Wind Atlas Analysis and Application Program (WAsP) is also based on the concept of linearized flow model for the purpose of predicting the wind resource for sitting of wind turbine singly or in farms. Lange and Højstrup (2001) evaluated the WAsP for offshore applications using available data of measurements at wind farm site in Danish Baltic Sea region. The wind resources estimated from measurements are widely good agreement with the WAsP-predictions. They, however, also found deviations in the directional wind speed predictions to correspond with the length of the sea fetch. Many of the procedure in WAsP are strictly applicable only under idealized and limited range of conditions. The most severe problem of these linearized models is encountered in mountainous terrains due to the importance of dynamics, which are not accounted in this model. The WAsP has been the commonly used computational tool in only flat terrain such as Denmark and northern Germany. In complex and very rugged terrains such as Korea and Japan, however, WAsP could lead to results outside an acceptable range (Şahin, 2004).

Recent development in CFD enables us to predict the flow field in area of mountainous region with very complex terrain. Murakami et al. (2003) developed local area wind prediction system based on computational wind engineering for the purpose of selecting suitable site for wind-power plants. A new linear type $k$-$\epsilon$ turbulence model and the tree canopy model were used for accurate prediction of local area wind energy distribution. The predicted results agrees better with the measured data than that by WAsP in two-dimensional cliff (front-step), hill model, and a practical size of domain (3000 m x 1800 m x 200 m) considering the conditions of ground surface. Palma et al. (2008) studied the wind flow over a coastal region by field measurements with cup and sonic anemometer, and computer simulations using linear and nonlinear (CFD) mathematical models of the fluid flow equations. They showed that CFD techniques are useful and capable of identifying the separated flow region clearly unsuitable for installation of wind turbines. Few papers have been published on the assessment of wind flow in the complex terrain of mountainous region. Moreover the flow field through the operating wind turbines on the complex terrain has not been studied extensively, which gives the detailed information on the effect of the terrain and the adjacent turbines on the performance of the wind turbine. The present study aims to investigate the effect of the complex topography and the turbine wake in the full-scale wind farm on the performance of the power generation.

**Numerical methods**

The mountainous terrain was discretized by a mesh generation program which reads digitized map with contour heights at every 10 m and maps the 2-D flat surface mesh onto the digitized map to get the height information by searching and interpolation algorithm. The 2-D rugged surface mesh is then used to generate 3-D volume mesh above the surface. In the present study an area of 10 km x 12 km is considered for simulation, and the upper boundary is set at 6 km above the sea level as shown in Figure 1. This figure also shows a wind farm
consisting of 49 wind turbines installed on the mountainous region. As seen from the figure, all wind turbine is located on ridges of mountains, and each position of turbines is denoted with numbers. The details of computational meshes are shown in Figure 2, where the horizontal mesh spacing is 20 m, and the vertical height of the computational cells above the ground surface is around 3 m. In order to resolve the flow through the turbine blades, detailed mesh has been generated automatically from the CAD data with polyhedral cells for the volume of a single wind turbine, and this turbine mesh has been copied to compose the whole wind farm mesh. The wind turbine considered in the present study has three blades of 40 m radius, and the height of the turbine hub is 80 m above the ground level. Since many wind turbines adopt a tilted rotor axis in order to provide sufficient clearance between the rotor blades and the tower, a tilt angle of 7° is considered in the present analysis (Hau, 2005).

At inlet boundary plane a logarithmic boundary layer profile with free stream velocity of 15 m/s is imposed from the meteorological reports for last nine years (Climate information for wind velocity, 2000-2008). From the same data of field measurements the dominant wind direction is west of 38% in occurrence frequency, and followed by easterly wind of 12% frequency for the 9-years period. Simulations were performed for westerly and easterly winds for a matter of primary interest. There were total of four different cases, accounting on
additional southerly and northerly wind directions, whose frequency of around 5%. Figure 3 shows the computational cases with four different wind directions. In the present analysis, it is noted that all wind turbines have the same direction of the rotating axis paralleled to the incoming flow. Figure 3 also illustrates boundary conditions adopted in each case. The outlet condition was applied on the opposite plane of the inlet boundary. At other boundaries symmetric condition is imposed in the assumption that the boundaries are located far away from the area of interest so that the flow structure at boundaries may have minimal effect on the flow field near wind turbines.

Frozen rotor method was used by setting multiple reference frames in the present analysis to consider the rotational effect of the wind turbine. In this method a rotating speed is considered by 6 RPM as nominal operation of the wind turbine. To evaluate the performance of wind turbine generators, the torque acting on the turbine blades are calculated with final solutions of each computational case. Total 22,000,000 computational cells are used in the domain possessing the wind farm consisting of 49 wind turbines. STAR-CD V4.08 (Computational Dynamics Ltd., 2008) was employed to simulate the flow field in the wind farm. A steady incompressible full 3-D Navier-Stokes equation was solved with standard k-ε model for turbulent flow. For the simulation, a 20-CPU Linux cluster with Intel Xeon Quad-Core 2.5 GHz 64-bit processor was used for parallel computation. The typical computation time was around 2 days to achieve converged solution over 1,000 iterations.

**Results and discussion**

A significant output of wind energy can be achieved by installation of wind turbines in an appropriate site. However, it is not an easy task to arrange the turbines in the wind farm, since many factors have to be taken into account for optimal performance. Among the various factors, the flow structure in the wind farm is one of the most important matters for effective operation. In the present study, the flow field in the wind farm on the complex terrain is investigated with four different wind directions and the performance of the wind farm is also evaluated.

A global view of the flow pattern for four different wind directions is presented in Figure 4. This figure shows the space distribution of the wind speed at the hub height of the wind turbine, which is useful information with a view to estimate the wind potential. The complex mountainous terrain is depicted with contour levels at every 50 m. As expected, the results were strongly correlated with the terrain elevation and the high velocity regions appeared at ridges of the mountain chain, where many wind turbines are installed. The wind speed increases during the uphill in the mountainous region, and decreases in the downhill. Mountain chain modeled in the present study is developed mostly in south-north direction,
and the larger areas of uphill and downhill are appeared in west-east direction. Since the wind speed increases during the uphill and becomes maximal at topographical peak, many wind turbines are arranged at ridges in S-N direction for higher speed of incoming flow. With a view of relation between the topographical configuration and the wind speed, the southerly and northerly wind conditions are easy to induce less flow acceleration because the direction...
of wind flow is perpendicular to the slope of the mountain chain. For the above reason, average wind speed in southerly and northerly wind conditions is quite lower than west and east cases. In the results of west and east wind simulations the wind turbines located at ridges where the predicted wind speed is high above 10 m/s, are expected to generate sufficient output of power. It can be also observed that the area with flow deficit lower than 9.5 m/s as depicted by A and C in the figure. This low speed of incoming flow may lead to a low performance of the wind turbine. It is also noted that the wind turbines as indicated with B and D may suffer incoming flow defect since they are in the wake region induced by the upstream turbines.

Figure 5 shows the local areas with flow deficit due to the topography and the wake of upstream turbines under westerly wind condition. In left-side of the figure, wind turbine (hereafter referred to as WT) 25 is located in the downhill, where wind speed decreases, so that lower performance of the WT 25 is expected. The effect of the wake induced by upstream turbines is also obvious as shown in right-side of the figure. As seen from the figure, WT 31 and 32 are in the wake region of the upstream turbines 29 and 30 respectively. These turbines

![Figure 5: Local flow deficit induced by topography (left) and wake of upstream turbines (right).](image)

![Figure 6: Comparison of vertical profiles of streamwise velocity at various positions ahead of hub axis in westerly wind simulation.](image)
also may have trouble to generate sufficient output power. Figure 6 shows the vertical profiles of the longitudinal velocity component between WT 25, 31, and 32 at various positions from the hub axis. Non-dimensional velocity component is used with the free stream speed of 15 m/s. Since the velocity profile of WT 31 is relatively small compared with WT 25 and 31, the worst performance of WT 31 is expected among these turbines.

By integrating the torque acting on the turbine blades the power output was estimated in order to examine the variations in the performance of wind turbines as shown in Figure 7. This technique enables us to evaluate the performance of the wind turbine qualitatively. As shown in the graph, wind turbine 39, 40 under easterly wind shows the worst performance among the turbines due to the wake by upstream turbines, and turbine 31 also shows poor performance in westerly wind condition since the incoming wind speed passing through the wind turbine is low due to the topographical effect. In the graph, the results of southerly and northerly winds are ruled out because the incoming flow speed calculated in these cases is quite lower than cut-in speed which turbine begins to operate.

The details of flow structure induced by the complex terrain as predicted in the present study cannot be obtained by any point measurement technique or linearized flow model like WAsP. Moreover most significant result of the present study is that some turbines are affected by the wake of the upstream turbines, which can only be predicted by simulation of operating turbines in the wind farm on the complex terrain. Therefore should the present analysis have been performed before the selection of the location of the turbines, alternative location for turbines which are affected by low speed of incoming flow could be chosen for better performance of the wind farm.

Concluding remarks

A three-dimensional flow simulation is performed to investigate the wind flow in a wind farm in mountainous area of complex terrain. A digital map of the mountainous wind farm area is used to model actual complex terrain. Rotating wind turbines are also modeled in the computational domain with detailed blade shape using the frozen rotor method. Detailed flow structure in the wind farm is obtained and the method presented in the present study can be applicable for optimal arrangements of turbines in the wind farm.

**Figure 7:** Performance of wind farm as evaluated by integrating torque acting on turbine blades.
References


Climate information data from the management system of Korea Meteorological Administration, Hoenggye, Gangwon Province, Korea.


STAR-CD Version 4.08 Manuals, (2008), Computational Dynamics Ltd.