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A numerical simulation of flow field in a wind farm on complex terrain

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Abstract. A three-dimensional flow simulation was performed to investigate the wind flow around wind-power generation facilities on mountainous area of complex terrain. A digital map of eastern mountainous area of Korea including a wind farm was used to model actual complex terrain. Rotating wind turbines in the wind farm were also modeled in the computational domain with detailed geometry of blade by using the frozen rotor method. Wind direction and speed to be used as a boundary condition were taken from local meteorological reports. The numerical results showed not only details of flow distribution in the wind farm but also the variation in the performance of the wind turbines due to the installed location of the turbines on complex terrain. The wake effect of the upstream turbine on the performance of the downstream one was also examined. The methodology presented in this 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.

1. 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 effect were found due to complex topography, and the nonlinear interaction between the wake and the turbine tower was also revealed. Barthelmie *et al*. (1996) examined the coastal meteorology at the world's first offshore wind farm in Vindeby,

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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 spectra of the three velocity components measured in a wind farm in the island of Andros, Greece. This analysis revealed that von Karman spectrum is suitable for the structure of the turbulence measured at some location in free stream condition. Vardar and Eker (2006) also developed a mathematical model of wind turbine blades through volumetric view to find out the effect of rotor blade volume on the performance. They observed that an increase in the volume of the rotor blade raised the speed of the start of motion, but reduced the rotor performance. However, intense topography effects like flow separation and wake effects were 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 siting 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 were in good agreement with the WAsP predictions. They, however, also found deviations in the directional wind speed predictions corresponding to 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 the 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. Tsang *et al*. (2009) conducted large-eddy simulation (LES) to examine the flow around a irregular complex terrain. The numerical results agreed well with the wind tunnel test; especially the mean velocity component within the boundary layer flow in the streamwise direction was predicted reasonably by the LES. Computational fluid dynamics (CFD) can be also used to investigate wind potential effectively. Morvan *et al*. (2007) proposed a general methodology for the automation of CFD applied to the computation of wind flow over the region of interest. 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-ε turbulence model and a tree canopy model were used for accurate prediction of local area wind energy distribution. The predicted results agreed better with the measured data than that by WAsP in a two-dimensional cliff (front-step), a hill model, and a practical size of domain (3000 m x 1800 m x 200 m) considering 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 mathematical models of the fluid flow equations. They showed that CFD techniques were useful and capable of identifying the separated flow region clearly unsuitable for installation of wind turbines.

However, few researches have been performed on the assessment of wind flow on the complex terrain of mountainous region to the authors' knowledge. 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.

2. Numerical methods

The mountainous terrain was discretized by a mesh generation program (Chin *et al*. 2004) which reads digitized map with contour lines of iso-heights 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 was then used to generate 3-D volume mesh above the surface. In the present study, an area of 10 km x 12 km was considered for simulation, and the upper boundary was set at 6 km above the sea level as shown in Fig. 1. This figure also shows a wind farm consisting of 49 wind turbines installed on the mountainous region. As seen from the figure, most wind turbines are located on ridges of mountains. The details of computational meshes are shown in Fig. 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 had three blades of 40 m radius, and the height of the turbine hub was 80 m above the ground level. Since many wind turbines adopt the tilted rotor axis in order to provide sufficient clearance between the rotor blades and the tower, a tilt angle of 7° was considered in the present analysis (Hau 2005).

At inlet boundary plane a logarithmic boundary layer profile with free stream velocity of 15 m/s

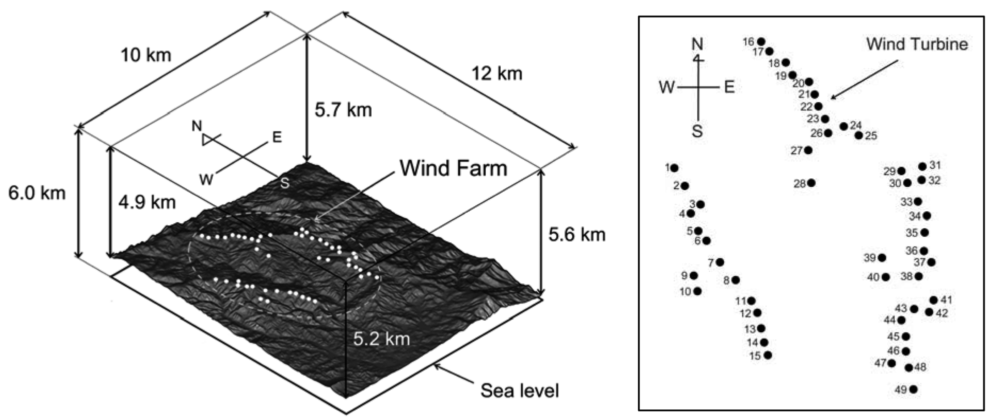


Fig. 1 Computational domain of a wind farm which consists of 49 wind turbines installed on mountainous terrain (left). Circles indicate the locations of the wind turbine installations (right)

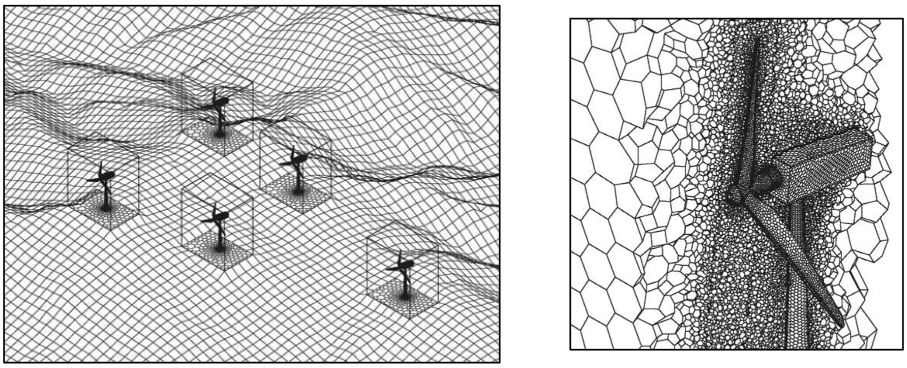
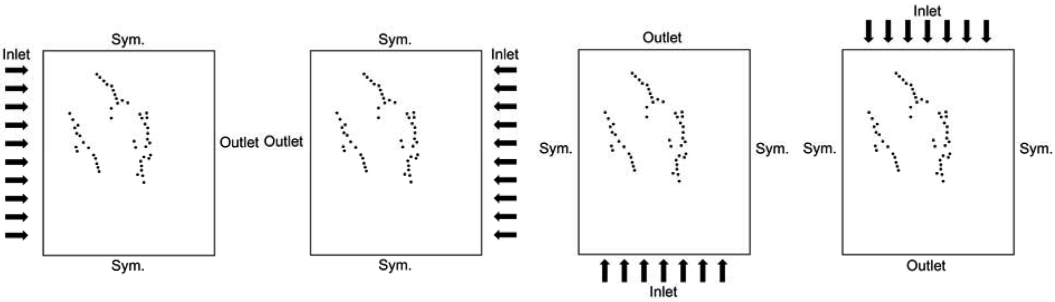


Fig. 2 Detailed view of the meshes for mountainous region in complex topography (left) and the embedded polyhedral cells for the wind turbine (right) to resolve the flow passing through the wind turbine



(a) West wind (b) East wind (c) South wind (d) North wind

Fig. 3 Computational cases with various wind directions and adopted boundary conditions

was imposed from the meteorological reports of the region 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 east wind of 12% frequency for the 9-years period. Simulations were performed for west and east winds as a matter of primary interest. There were total of four different cases of computation including additional south and north wind directions whose frequencies are of around 5%. Fig. 3 shows the computational cases with four different wind directions, where small dots indicate the locations of the wind turbines. In the present analysis, it is noted that all wind turbines have the same direction of the rotating axis paralleled to the incoming flow. Fig. 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 was imposed by assuming that the boundaries were located far away from the area of interest so that the flow structure at boundaries might have minimal effect on the flow field near wind turbines. Frozen rotor method is used by setting multiple reference frames in the present analysis to consider the rotational effect of the wind turbines by imposing a rotational speed in the regions swept by turbine blades. To evaluate the performance of wind turbine generators, the torque acting on the turbine blades was calculated from final solutions of each computational case.

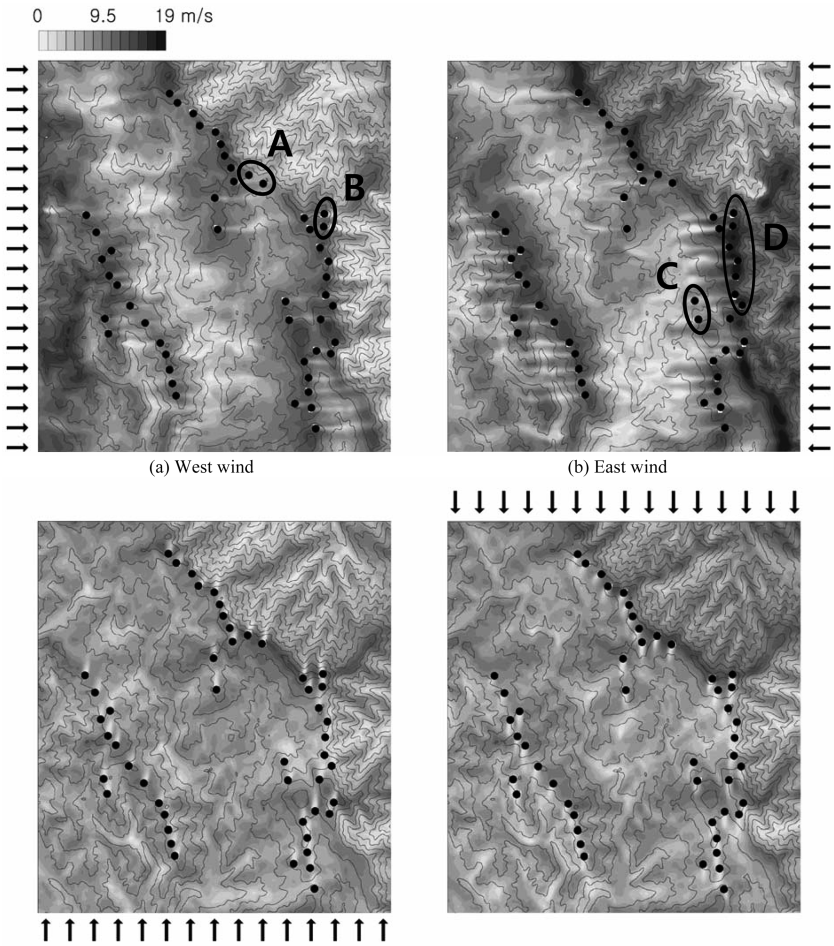
Total 22,000,000 computational cells were used in the domain possessing the wind farm consisting of 49 wind turbines. STAR-CD V4.08 (Computational Dynamics Ltd. 2008) was employed to simulate the flow field in the wind farm. A steady incompressible full 3-D Navier-Stokes equation was solved with standard k-ε model for turbulence. For the simulation, a 20-CPU Linux cluster with Intel Xeon Quad-Core 2.5 GHz 64-bit processor was used to perform the parallel computation. The typical computation time was around 2 days to achieve converged solution over 1,000 iterations.

3. 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. The performances of the wind turbines are then evaluated from the estimated flow fields for different wind directions.

A global view of the computed flow pattern for four different wind directions is presented in Fig. 4. This figure shows the spatial distribution of the resultant wind speed at the hub height of the wind turbine above the ground level, which gives useful information for estimating wind potential at the locations of the wind turbine installations. 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 were installed. The wind speed increases in the uphill on the mountainous region, and decreases in the downhill. Mountain chain modeled in the present study is 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, most wind turbines were installed along ridges in south-north direction to achieve higher speed of incoming flow. With a view of relation between the topographical configuration and the wind speed, the south and north wind conditions induce less flow acceleration due to small changes in elevation along these flow directions. For the above reason, average wind speeds at the ridges of the mountain chain in south and north wind conditions are quite lower than those in west and east wind cases. In the results of west and east wind simulations the wind turbines located at ridges where the predicted wind speed is relatively high, are expected to generate sufficient power output. It is, however, noted that the wind turbines as indicated with ‘A’ and ‘B’ may suffer incoming flow defect since they are in the wake region induced by the upstream turbines. It can be also observed that the area with flow deficit as depicted by ‘C’ in the figure. This low speed of incoming flow may lead to a poor performance of the wind turbine.

Fig. 5 shows the local areas with flow deficit due to the topography and the wake of upstream turbines under west wind condition. In left-side of the figure, wind turbine (hereinafter referred to as WT) 25 is located in the downhill, where wind decelerates, so that lower performance of the WT 25 is expected. The effect of the wake induced by the presence of the upstream turbines is also obvious as shown in right-side of the figure. WT 31 and 32 are in the wake region of the upstream turbines 29 and 30, respectively. These turbines also suffer deficiencies in incoming flow to generate power. The vertical profiles of the streamwise velocity components are shown in Fig. 6 for WT 25, 31 and 32 at axial planes of the rotation of the turbines. Non-dimensional velocity component is used in the figure by using the free stream velocity, and the color level in the figures denotes the level of the



(a) West wind

(b) East wind

(c) South wind

(d) North wind

Fig. 4 Contour plots of horizontal wind speed at hub height (80 m) above the ground level. Circles show the locations of wind turbines shown in Fig. 1

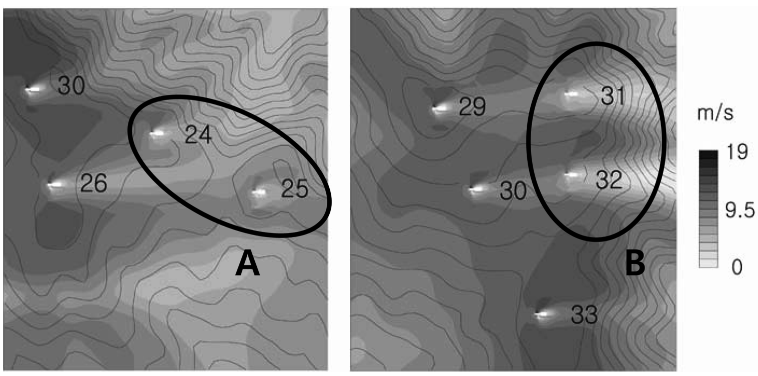
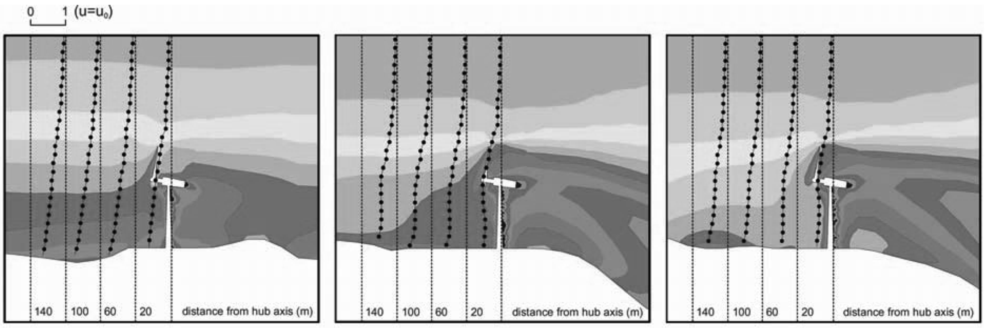


Fig. 5 Local flow deficit induced by topography (left) and by wake of upstream turbines (right)



(a) WT 25 (b) WT 31 (c) WT 32

Fig. 6 Comparison of vertical profiles of streamwise velocity at various upstream positions of hub axis in west wind simulation

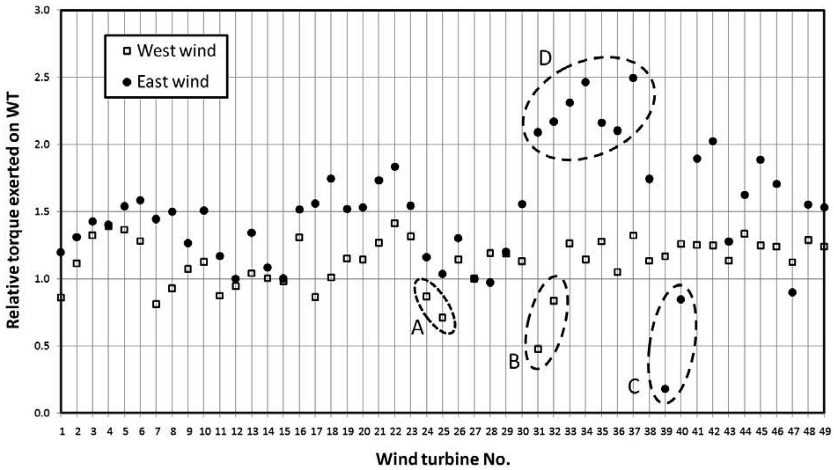


Fig. 7 Performance variations of the wind turbines in the wind farm for west and east wind cases

wind speed. Since the incoming wind speed of WT 31 is relatively low compared to those of WT 25 and 32, the performance of WT 31 is expected to be poorest among these turbines.

By integrating the force acting on the turbine blades the power output can be evaluated in order to examine the performance of each wind turbine as shown in Fig. 7. This technique enables us to estimate and compare the relative performances of all the installed wind turbines. In the graph, the torque exerted on each wind turbine was non-dimensionalized by the torque exerted on WT 27 where the topographical effect is minimal for east and west wind cases since it is located in the relatively level area for both west and east wind cases, and the effect of adjacent wind turbines are also minimal. The performance of the wind turbine is affected mainly by the topography and the wind condition of the area, and the wake of the upstream wind turbine. As noted by ‘A’ in the graph, WT 24 and 25 exhibit poor performances in west wind case since the turbines are located in the downhill where the flow decelerates as explained in Fig. 5. WT 31 and 32 noted by ‘B’ in the graph also show poor performance in the west wind case, which is due to the wake effect induced by upstream wind turbines; this result exactly corresponds with the predicted wind potential map shown in Figs. 4 and 5. In the east wind case, the turbines WT 39 and 40 marked by ‘C’ in the graph exhibit poor performances, since they are located on the down slope where the east wind decelerates. On the other hand, WT 31-37 show very high performance compared to other turbines in the east wind condition since they are located on the ridge of mountain and have very high wind potential as clearly shown by 'D' in the Fig. 4(b). In the graph, the results of south and north wind conditions are not shown because the wind potentials in these cases were much lower than cut-in speed which the wind 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 through simulations 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 wind turbines in the wind farm site, and alternative location for turbines, which are otherwise affected by poor wind potential due to topography and by wakes of upstream turbines, could be chosen for better overall performance of the wind farm.

4. Conclusions

A three-dimensional flow simulation was performed in the present study to assess the wind environment in a wind farm on mountainous area of complex terrain. To model the actual complex terrain, a digital map of the mountainous wind farm area was used, and total 49 wind turbine generators were also modeled in the computational domain with detailed geometry of tower, nacelle and blades of wind turbines. The rotating turbine blades were modeled by using a frozen rotor method, and the meteorological data of the region were used as an inlet boundary condition of the computation. From the results, wind potential maps for various wind directions were obtained to assess the wind environment of the wind farm. It was clearly seen from the results that the wind turbines installed at the ridges of the mountain, where the wind accelerates most, exhibited better performance. The wind turbines, however, installed at the downhill locations where the flow decelerates, and the turbines at the wake region of the upstream turbines due to the tandem installation were shown to suffer poor oncoming wind, and hence exhibited poor performances of the power generation. The computational method illustrated in the present study can be used to assess the wind environment of the potential wind farm site and to suggest optimum arrangements of the wind turbines in the site to generate maximum power.

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