HIGH RESOLUTION LES OF TURBULENT AIRFLOW OVER COMPLEX TERRAIN

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ABSTRACT

It is highly important in Japan to choose a good site for wind turbines, because the spatial distribution of wind speed is quite complicated over steep complex terrain. We are developing the unsteady numerical model called the RIAM-COMPACT (Research Institute for Applied Mechanics, Kyushu University, Computational Prediction of Airflow over Complex Terrain). The RIAM-COMPACT is based on the LES (Large-Eddy Simulation). The object domain of the RIAM-COMPACT is from several m to several km.

First, to test the accuracy of the RIAM-COMPACT we have performed the experimental and numerical simulation of a non-stratified airflow past a two-dimensional ridge and a three-dimensional hill in a uniform flow. Attention is focused on airflow characteristics in a wake region. For this purpose, the velocity components were measured with a SFP (Split-Film Probe) in the wind tunnel experiment. Through comparison of the experimental and numerical results, they showed a good agreement. The accuracy of both of the wind tunnel experiment by the SFP and also numerical simulation by the RIAM-COMPACT were confirmed.

Next, we have applied the RIAM-COMPACT to the airflow over real complex terrain. The numerical results obtained by RIAM-COMPACT demonstrated that the changes induced on the wind field by the topographic effect, such as the local wind acceleration and the flow separation, were successfully simulated. The amount of power generation was evaluated in consideration of the correlation with the observational data.

Finally, wind simulation of an actual wind farm was executed using the high resolution elevation data. As a result, an appropriate point and an inappropriate point for locating a wind turbine generator were shown based on the numerical results obtained. This cause was found to be a topographical irregularity in front of the wind turbine generator.

KEYWORDS: WIND POWER, MICRO-SITING TECHNIQUE, RISK MANAGEMENT, COMPLEX TERRAIN, LES

Introduction

There exists a great and urgent need to reduce CO2 emissions as a way to combat global warming. Therefore, attention has focused on the development of environmentally friendly wind energy (natural energy). In Japan, the number of wind power generation facilities has increased rapidly from several WTGs (Wind Turbine Generators) to a large-scale WF (Wind Farm). The output of the WTG is proportional to the cube of the wind speed. Therefore, it is important that the windy region in which the WTG is installed be chosen carefully. The terrain in Japan is remarkably different from that of Europe and America, and thus it is extremely important to consider Japan’s unique topographic effect on the wind, such as a local speed-up, separation, reattachment, and so on\(^{(3),(4)}\).

The social and technological requirements for wind power are strong. Concentrating on a space of several km or less, we are developing an unsteady, non-linear-type numerical simulator called the RIAM-COMPACT (Research Institute for Applied Mechanics, Kyushu University, Computational Prediction of Airflow over Complex Terrain)\(^{(3),(5)}\). The RIAM-COMPACT is a FORTRAN program
based on the FDM (Finite-Difference Method), and adopts an LES (Large-Eddy Simulation) technique as a turbulence model. We have been examining the practical use of the RIAM-COMPACT for several years. The RIAM-COMPACT has already been marketed by certain tie-up companies. Estimation of annual electrical power output is also possible now based on field observation data.

In the present study, first, to test the accuracy of the RIAM-COMPACT we have performed the experimental and numerical simulation of a non-stratified airflow past a two-dimensional ridge and a three-dimensional hill in a uniform flow. Attention is focused on airflow characteristics in a wake region. For this purpose, the streamwise velocity component was measured with a SFP (Split-Film Probe) in the wind tunnel experiment. Next, we have applied the RIAM-COMPACT to the airflow over real complex terrain.

**Numerical method**

We consider a three-dimensional airflow of incompressible and viscous fluid over complex terrain with characteristic length scales on the order of kilometers, so that the Coriolis force can be neglected. In an LES, the flow variables are divided into a GS (Grid-Scale) part and a SGS (SubGrid-Scale) part by the filtering operation. The filtered continuity and Navier-Stokes equations written in non-dimensional form are given by

\[
\frac{\partial \bar{u}_i}{\partial x_i} = 0, \quad \frac{\partial \bar{u}_i}{\partial x_i} + \bar{u}_i \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \frac{1}{Re} \frac{\partial^2 \bar{u}_i}{\partial x_i^2}.
\]

All the variables are non-dimensionalized by an appropriate velocity \(U_{in}\) and a length scale \(h\). In the above equations, the effect of the unresolved subgrid-scales appears in the SGS stress as follows:

\[
\tau_{ij} = \bar{u}_i \bar{u}_j - \bar{u}_i \bar{u}_j
\]

which must be modeled. In this study, \(\tau_{ij}\) is parameterized by an eddy viscosity assumption of Smagorinsky (6) through the following constitutive relations:

\[
\tau_{ij} = \left(\frac{\delta_{ij}}{3}\right) \tau_{kk} = -2 v_{SGS} \bar{S}_j, \quad v_{SGS} = (C_s f_s \Delta)^2 |\bar{S}|, \quad f_s = 1 - \exp(-z' / 25),
\]

\[
|\bar{S}| = (2 \bar{S}_j \bar{S}_j)^{1/2}, \quad \bar{S}_j = \frac{1}{2} \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right), \quad \Delta = \left(h_x h_y h_z\right)^{1/3}.
\]

The most important factor involved in a successfully accurate simulation of airflow over complex terrain is correctly determining how to specify the topography model as the boundary conditions in the computation. In the present study, we employ a generalized curvilinear collocated grid, where the Cartesian velocity components and pressure are defined at the center of a cell, while the volume flux components multiplied by the Jacobian are defined at the mid-point on their corresponding cell surfaces. The original governing equations in the physical space are transformed to the computational space through a coordinate transformation.

The coupling algorithm of the velocity and pressure fields is based on a fractional step method (7) with the Euler explicit scheme. Therefore, the velocity and pressure fields are integrated by the following procedure. In the first step, the intermediate velocity field is calculated from the momentum equations without the contribution of the pressure gradient. In the next step, the pressure field is computed iteratively by solving the Poisson equation with the SOR (Successive Over Relaxation) method. Finally, the divergence-free velocity at the \((n+1)\) time-step is then obtained by correcting the intermediate velocity field with the computed pressure gradient. As for the spatial discretization in the governing equations, a second-order accurate central difference approximation is used, except for the convective terms. For the convective terms written in non-conservation form, a modified third-order upwind biased scheme (8) is used. The weight of the numerical viscosity term is sufficiently small (\(\alpha = 0.5\)), compared to the Kawamura-Kuwahara scheme (\(\alpha = 3\)) (9).
Numerical results and discussion

First, to test the accuracy of the RIAM-COMPACT, we have performed the experimental and numerical simulation of a non-stratified airflow past a two-dimensional ridge and a three-dimensional hill in a uniform flow. The Reynolds number, based on the uniform flow and the height of the model, is about $10^4$. Fig.1 shows the comparison of the smoke photograph in the wind tunnel experiment. Here, it is a result of span central side ($y=0$). Airflows around the model include the unsteady vortex shedding in both of a two-dimensional ridge and a three-dimensional hill. Fig.2 shows the comparison of the visualization results in the numerical simulation (RIAM-COMPACT). These results were visualized by the passive particle tracking method. The numerical results were compared with the wind tunnel experiment, and an excellent agreement was obtained qualitatively. Fig.3 shows the streamlines for the time-averaged flow field in the span central side ($y=0$). The eddy region is formed behind both models. A clear difference can be perceived in the streamwise direction. The eddy size of a three-dimensional hill is smaller than that of a two-dimensional ridge. Attention is focused on airflow characteristics in a wake region. For this purpose, the velocity component in the streamwise direction was measured with a SFP in the wind tunnel experiment. Fig.4 shows the comparison of the mean-velocity profiles. Through comparison of the experimental and numerical results, they showed a good agreement. The accuracy of both of the wind tunnel experiment by the SFP and also numerical simulation by the RIAM-COMPACT were confirmed as the result.

We have applied the RIAM-COMPACT to the airflow over real complex terrain. First of all, 1/2500 model of Noma cape wind power plant in the Kagoshima prefecture were made, and the wind tunnel experiment and the numerical simulation were calculated. In the numerical simulation, 10m DEM (Digital Elevation Model) data of Hokkaido-chizu co., ltd. was used. Those results are omitted. Furthermore, 5m resolution elevation data was constructed based on the paper map. The calculation intended for 16 wind directions was done by using it. The result obtained was compared with the observation data. A part of the result is shown to Fig.5, Fig.6 and Fig.7. The wind speed was evaluated in consideration of the correlation with the observational data. The relative error to the observation value of both of an annual average wind speed and an annual electric power output was within 1%.

Finally, wind simulation of an actual wind farm was executed using the high resolution elevation data. Only the calculation for the prevailing wind direction was done in this research. Fig.8 shows the geographical features around the WTGs and numerical conditions. In the present study, the surroundings of the WTGs sites were constructed from CAD data of the DXF form with 5m resolution. The surroundings were constructed with 50m elevation data provided by the Geographical Survey Institute. Thus, the high resolution elevation data originally constructed based on the paper map and the DXF file were merged with existing elevation data by using the GIS (Geographical Information System) technique. The elevation data measured using a laser profiler, and free space shuttle elevation data (SRTM: Shuttle Radar Topography Mission data) is also used. The WTG in the present study has a rotor diameter of 52m, and a hub height of 44m. To clarify the topographic effect on the wind field near the ground, the surface roughness, such as a forest canopy, is not considered. The boundary conditions for the velocity field in the computational domain are as follows: 1/7 power law profile (inflow), free-slip condition (top and side boundary), convective outflow condition (outflow), non-slip condition (ground).

Fig.9 shows the velocity vectors and the corresponding contour lines of turbulence intensities for a time-averaged field in the vertical plane of each WTG. In the case of WTG-A, it is understood that all rotor heights share almost the same speed distribution. In addition, a local speed-up due to geographical effects is confirmed. On the other hand, the separated flow is confirmed under the rotor center in the case of WTG-B. This is due to the turbulent flow mechanically generated from the topographical irregularity in front of WTG-B. That is, WTG-B is influenced by the turbulent flow generated by geographical features: this tower is located in a low point that shifts slightly from the hilltop. The flow phenomenon shown here cannot be reproduced if high resolution elevation data of 5m resolution is not used. As a result, an appropriate point and an inappropriate point for locating a wind turbine generator were shown. This cause was found to be a topographical irregularity in front of the wind turbine generator.
Conclusion

An unsteady, non-linear-type numerical simulator called the RIAM-COMPACT that we are developing was introduced. The prediction accuracy intended for simple terrain was clarified, and the application example to the real complex terrain was shown. Furthermore, a numerical simulation for the WF during operation was executed by using elevation data of 5m resolution. An appropriate point and an inappropriate point for locating a WTG were shown based on the numerical results obtained.

References

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Fig. 4 Comparison of the mean-velocity profiles, line: calculation by RIAM-COMPACT, symbol: experiment by SFP

Fig. 5 Velocity vector in the vertical plane

Fig. 6 Comparison of time series data of observation value and prediction value, No. 1

Fig. 7 Comparison of monthly mean wind speed, No. 1

Fig. 8 Geographical features around the WTGs and numerical conditions

Fig. 9 Time-averaged field in the vertical plane