Analysis of the Airflow Field around a Steep, Three-dimensional Isolated Hill with Commercially Available CFD Software

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Abstract

The present study compared the prediction accuracy of two CFD software packages for simulating a flow around a three-dimensional, isolated hill with a steep slope: 1) Meteodyn WT (turbulence model: k-L RANS), which is one of the leading commercially available CFD software packages in the wind power industry and 2) RIAM-COMPACT® (turbulence model: the standard Smagorinsky LES), which has been developed by the lead author of the present paper. Although the Reynolds number settings differed between the simulation with Meteodyn WT and that with RIAM-COMPACT®, distinct differences in the flow patterns were identified in the vicinity of the isolated hill (especially downstream of the isolated hill) between the flows simulated by the two CFD software packages.

Key words：Meteodyn WT, RIAM-COMPACT®, Isolated hill

1. Introduction

The lead author has developed the numerical wind diagnosis technique named RIAM- COMPACT®[1], which is based on an LES turbulence model. An exclusive license for RIAM-COMPACT® has been granted by Kyushu TLO Co., Ltd. to RIAM-COMPACT Co., Ltd. (http://www.riam-compact.com/), a venture corporation which originated at Kyushu University. Efforts have been made to promote this software mainly in the wind power industry (e.g., private wind power providers, local governments, and wind turbine manufacturers) in Japan.

At the same time, other original CFD software packages have been developed outside Japan and have been distributed in various countries. One such leading software package is Meteodyn WT[2], which has been developed by Meteodyn in France (http://meteodyn.com/). Meteodyn WT is a CFD software package which incorporates a RANS turbulence model and is specialized for wind power resource assessment. On January 20, 2014, "WT4.5", the latest version of the software, was released.

In the present paper, numerical simulations are conducted for airflow around a three-dimensional, isolated hill with a steep slope angle using RIAM-COMPACT®, which is based on an LES turbulence model, and Meteodyn WT, which is based on a RANS turbulence model. The computational results from these simulations are compared.

2. Overview of the two software packages and the computational parameters

For the present study, numerical simulations are conducted for high Reynolds number flow around a three-dimensional, isolated hill with a steep slope angle using RIAM-COMPACT®, which is based on an LES turbulence model, and Meteodyn WT, which is based on a RANS turbulence model (see Table 1). Fig. 1 shows the computational domain and grid used for the simulation with Meteodyn WT. An enlarged view of the computational grid in the vicinity of the isolated hill from the simulation with Meteodyn WT is shown in Fig. 2. Fig. 3 shows the method used to set the inflow profile in Meteodyn WT and the inflow profile generated for the present study. Fig. 4 illustrates the characteristic scales used in RIAM-COMPACT®; for the present study, h is the height of the isolated hill, U_{in} is the wind velocity at the inflow boundary at height h, and ν is the coefficient of dynamic viscosity.

The computational techniques and parameters used for the simulations with the two software packages are

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CFD model	RIAM-COMPACT®	METEODYN WT
Turbulence model	The standard Smagorinsky LES model	k-L RANS model (A single equation model)
Atmospheric stratification (Atmospheric stability)	Neutral	
Coriolis force	Not included	
Surface roughness	Not included (Smooth surface)	Roughness length: 0.05 (For the ground surface not on the isolated hill: 0.001)
Surface boundary condition	No-slip boundary condition (The three components of the wind velocity are set to zero.)	
Shape function of the isolated hill	$0.5h \times \{1+\cos(\pi r/a)\}$, where $r = (x^2+y^2)^{1/2}$, a = 2h	
Height of the isolated hill h	100 (m)	
Reynolds number Re $(= U_{in}h/\nu)$	10^6	10^7
Time step Δt	$10^{-5}h/U_{in}$ (s)	-
Dimension of the computational domain	19h (i) × 18h (j) × 8h (k)	
Number of computational grid points	436 (i) × 325 (j) × 101 (k) (Approx. 14.3 million)	436 (i) × 325 (j) × 37 (k) (Approx. 5.2 million)
Streamwise (x) grid spacing ($\triangle$x)	(0.035 - 0.5) h	
Spanwise (y) grid spacing ($\triangle$y)		
Vertical (z) grid spacing ($\triangle$z)	(0.0001 - 0.6) h	(0.005 - 1.2) h

Table 1   Comparison of computational techniques and parameters
used for the simulations with RIAM-COMPACT® and Meteodyn WT
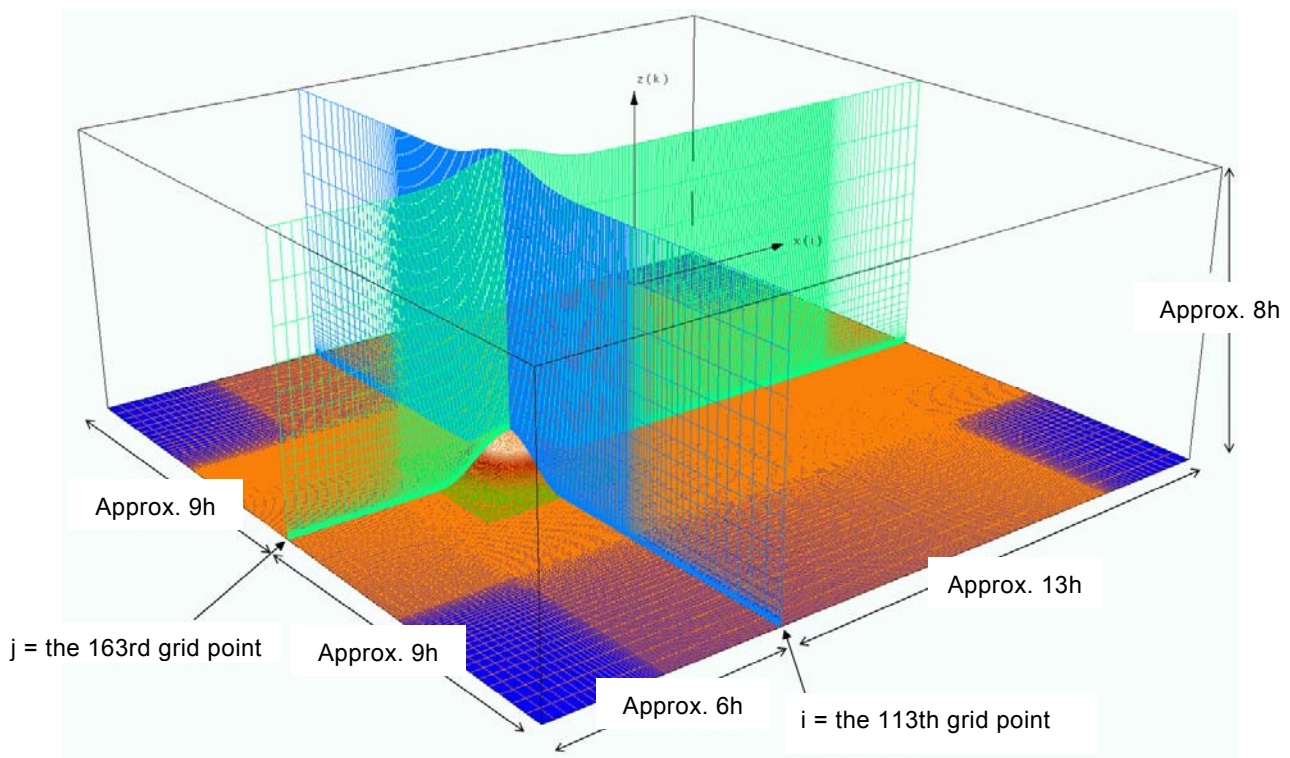

Fig.1   Computational domain and grid used for the simulation with Meteodyn WT, Re = 10^7
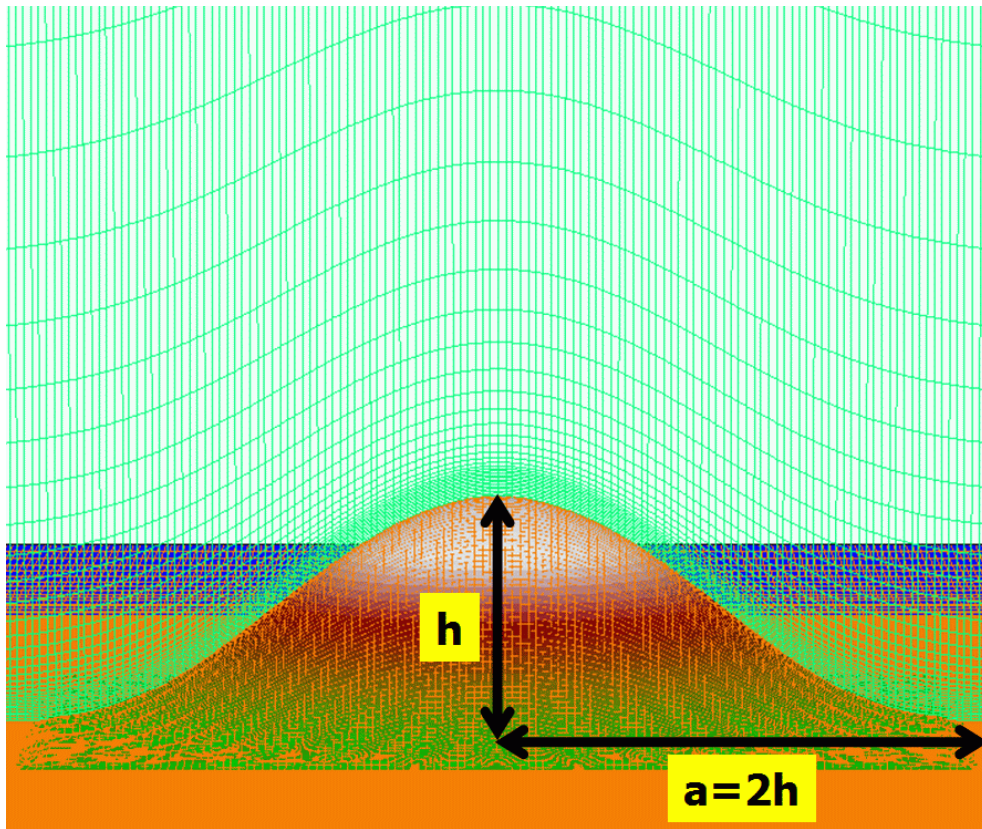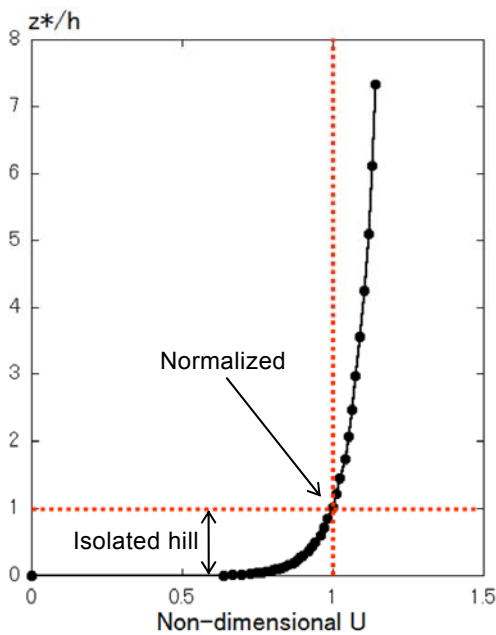
Fig.2   Enlarged view of the computational grid used for the simulation with Meteodyn WT, Re=10^7

In Meteodyn WT, the inflow wind is not a uniform flow. The inflow wind velocity changes with height in order to represent actual atmospheric flow. Specifically, the inflow wind can be classified into the following three layers.

• Surface layer: 0 < z < hs
→The profile is determined by the logarithmic law.

• The Ekman layer: hs < z < hbl
→Transition from the upper-surface-layer wind to the geostrophic wind in the free atmosphere

• Free atmosphere: hbl < z < Zskv
→The geostrophic wind is applied throughout this layer including as the top boundary condition.

The inflow profile is calculated based on the following reference values:

• Vref = 10.0 m/s: the reference wind velocity
• Href = 10.0 m: the reference height
• Zoref = 0.05 m: the reference roughness length

In the surface layer, the inflow profile is calculated based on the atmospheric stability, surface roughness data from the vicinity of the inflow boundary, and an assumption that turbulence kinetic energy is constant across the layer.

In the Ekman layer, turbulence kinetic energy is assumed to decrease linearly with height.

Fig.3   Method adopted in Meteodyn WT for setting the inflow profile and
the inflow profile generated for the present study

listed in Table 1. The present study uses the RIAM-COMPACT® natural terrain version software package, which is based on a collocated grid in a general curvilinear coordinate system, in order to numerically predict local wind flow over complex terrain with high accuracy while avoiding numerical instability. In this collocated grid, the velocity components and pressure are defined at the grid cell centers, and variables that result from multiplying the contravariant velocity components by the Jacobian are defined at the cell faces. For the numerical technique, the finite-difference method (FDM) is adopted, and a large-eddy simulation (LES) model is used for the turbulence model. In the LES model, a spatial filter is applied to the flow field to separate eddies of various scales into grid-scale (GS) components, which are larger than the computational grid cells, and sub-grid scale (SGS) components, which are smaller than the computational grid cells. Large-scale eddies, i.e., the GS components of turbulence eddies, are directly numerically simulated without the use of a physically simplified model. In contrast, dissipation of energy, which is the main effect of small-scale eddies, i.e., the SGS components, is modeled according to a physics-based analysis of the SGS stress.

For the governing equations of the flow, a filtered continuity equation for incompressible fluid and a filtered Navier-Stokes equation are used. Because high wind conditions with mean wind speeds of 6 m/s or higher are considered in the present study, the effect of vertical thermal stratification, which is generally present in the atmosphere, is neglected (neutral atmosphere). The effect of the surface roughness is not taken into consideration, and the surfaces of the ground and the isolated hill are treated as smooth surfaces.

For the computational algorithm, a fractional step (FS) method is used, and a time marching method based on the Euler explicit method is adopted. The Poisson's equation for pressure is solved by the successive over relaxation (SOR) method. For discretization of all the spatial terms except for the convective term in the Navier-Stokes equation, a second-order central difference scheme is applied. For the convective term, a third-order upwind difference scheme is applied. An interpolation technique based on four-point differencing and four-point interpolation by Kajishima is used for the fourth-order central differencing that appears in the discretized form of the convective term. For the weighting of the numerical diffusion term in the convective term discretized by third-order upwind differencing, $\alpha = 3.0$ is commonly applied in the

Kawamura-Kuwahara scheme. However, $\alpha = 0.5$ is used in the present study to minimize the influence of numerical diffusion. For LES subgrid-scale modeling, the standard Smagorinsky model is adopted with a model coefficient of 0.1 in conjunction with a wall-damping function. Refer to Uchida[1] for details of the computational techniques.

Since simulations for a flow with Re ($= U_{in}h/\nu$) = 10^7 were not feasible with the RIAM-COMPACT® natural terrain version software because of the time step, a numerical wind simulation is performed at Re = 10^6, which is an order of magnitude smaller than the flow simulated with Meteodyn WT. For this simulation, the number of grid points in the vertical direction is set to 101 (37 for the simulation with Meteodyn WT), and the minimum vertical spacing is set to $\Delta z_{min}/h = 10^{-4}$ based on the equation below ($\Delta z_{min}/h = 5.0 \times 10^{-3}$ for the simulation with Meteodyn WT, see Table 1):

$$\Delta z_{min}/h = \frac{0.1}{\sqrt{Re}}$$

At the inflow boundary, an inflow profile which is almost identical to the inflow profile used for the simulation with Meteodyn (Fig. 3) is used. Free-slip conditions are applied at the lateral and upper boundaries, and convective outflow conditions are applied at the outflow boundary. At the surfaces of the ground and the isolated hill, no-slip conditions are imposed. The time step is set to $\Delta t = 10^{-5} h/U_{in}$ (refer to Table 1).

In contrast to RIAM-COMPACT®, Meteodyn WT adopts the RANS equation with a one-equation closure scheme (k-L turbulence model; here, k and L refer to turbulence energy and the turbulence length scale, respectively.) Details of the computational techniques used in Meteodyn WT are explained in http://meteodyn.com.
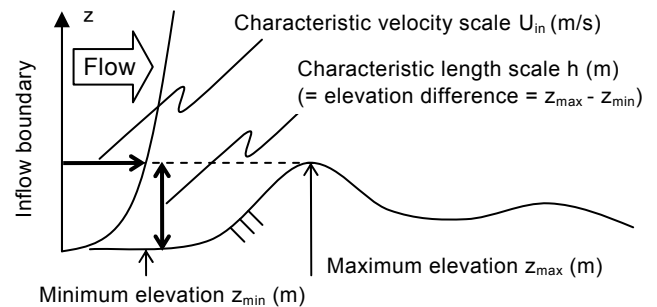

Fig.4   Characteristic scales used in RIAM-COMPACT®

Flow

A flow separation region (vortex region) characterized by negative wind velocities does not form.
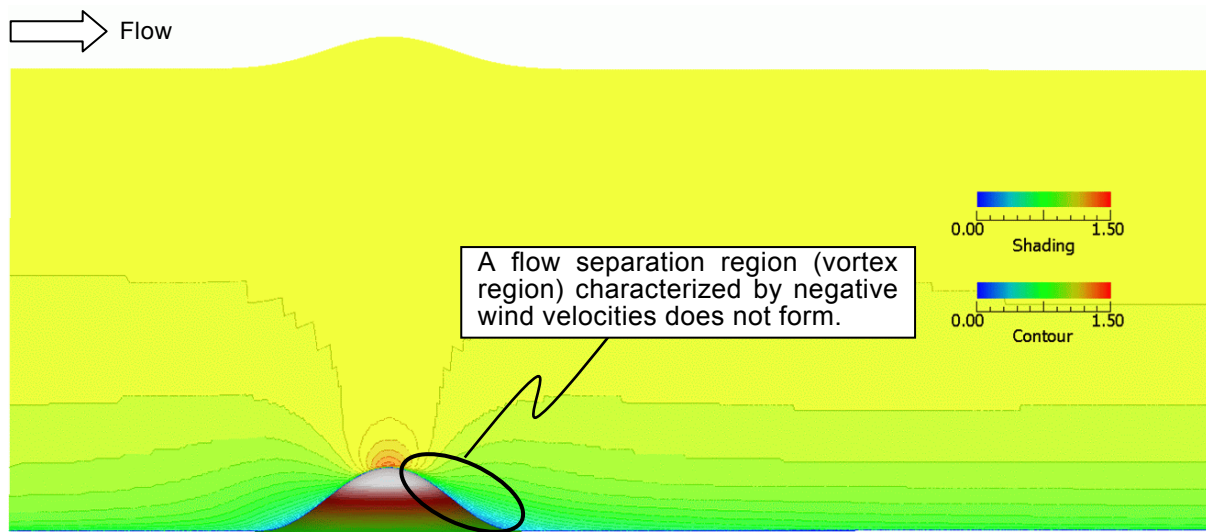
0.00   1.50
Shading

0.00   1.50
Contour

Fig.5   Streamwise (x) wind velocity distribution at the center of the span (y = 0),
Meteodyn WT, k-L RANS model, Re = 10^7

Flow

0.00   1.00
Shading

0.00   1.00
Contour

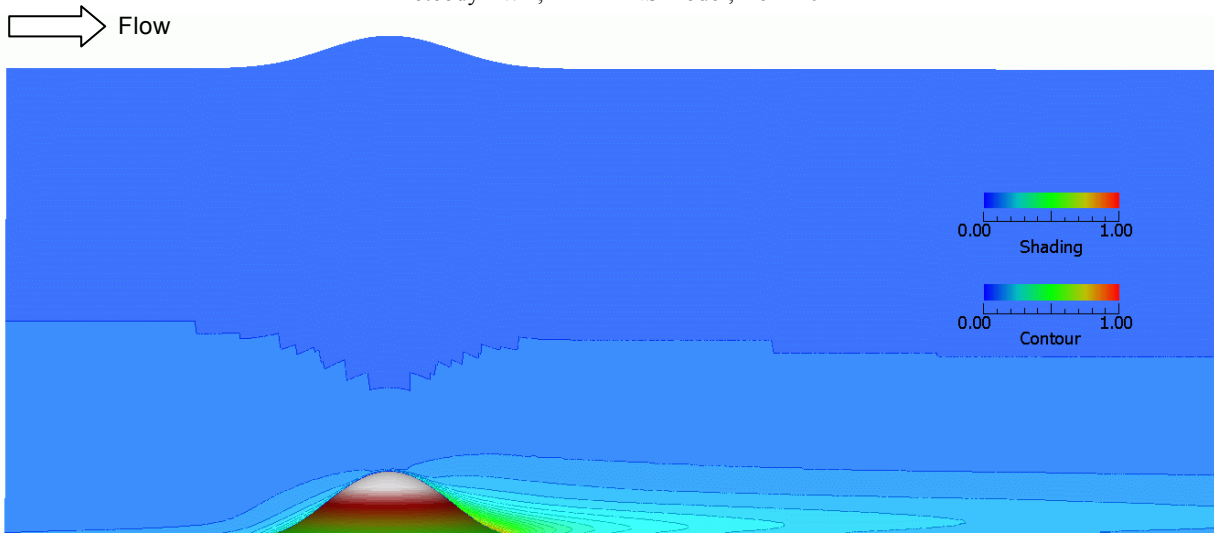Fig.6   Streamwise (x) turbulence intensity distribution at the center of the span (y = 0),
Meteodyn WT, k-L RANS model, Re = 10^7

Flow

A flow separation region (vortex region) characterized by negative wind velocities does not form.
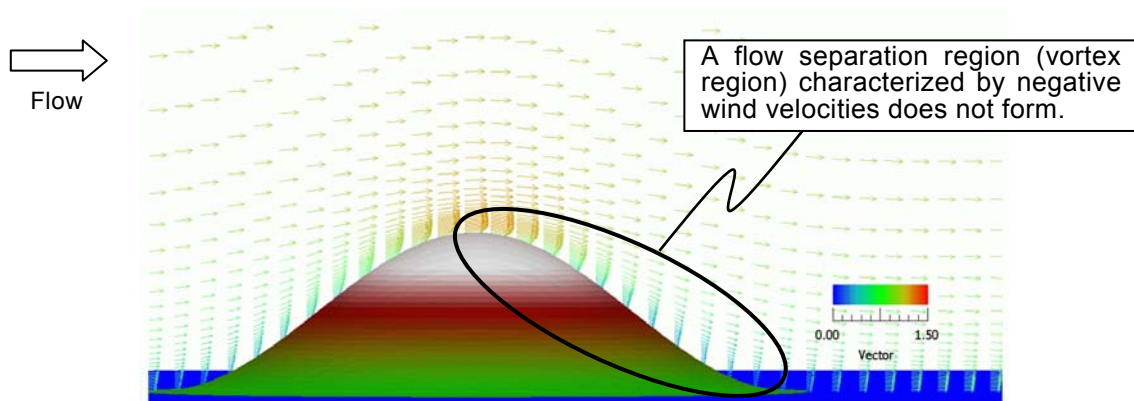
0.00   1.50
Vector

Fig.7   Velocity vectors at the center of the span (y = 0) in the vicinity of the isolated hill,
Meteodyn WT, k-L RANS model, Re = 10^7

Flow

(a) Instantaneous field

A flow separation region (vortex region) characterized by negative wind velocities forms.

Time : 190.10

Instantaneous flow field

Computed using RIAM-COMPACT(R) LES model

(b) Time-averaged field
Note: evaluated for t =100 − 200 h/U$_{in}$

A flow separation region (vortex region) characterized by negative wind velocities forms.

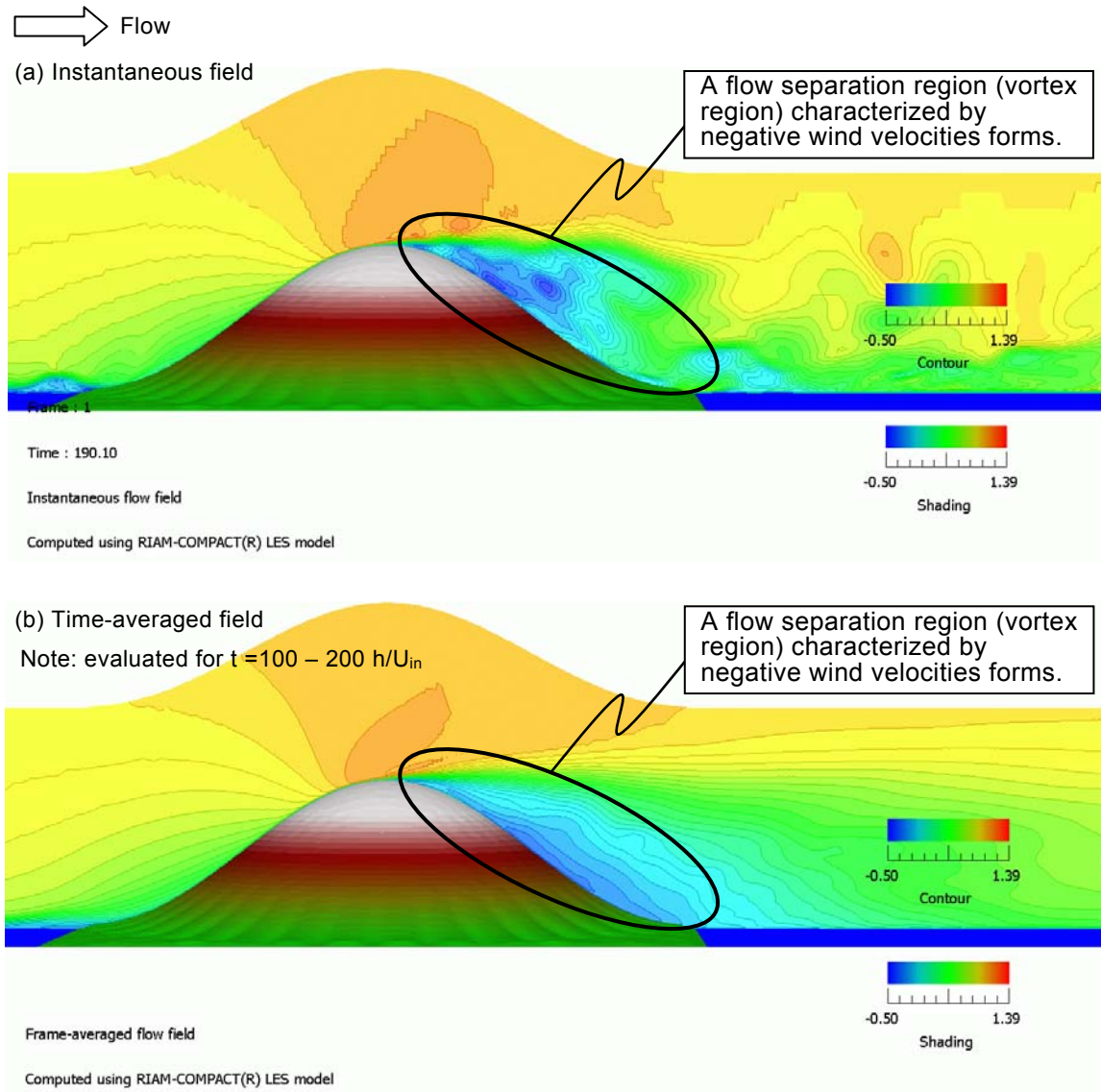Frame-averaged flow field

Computed using RIAM-COMPACT(R) LES model

Fig.8　Streamwise (x) wind velocity distribution at the center of the span (y = 0) in the vicinity of the isolated hill, RIAM-COMPACT®, the standard Smagorinsky LES model, Re = 10^6

3. Simulation results from the two software packages

Figs. 5 - 7 show results from the simulation with the Meteodyn WT software package (turbulence model: k-L RANS). These results (for a flow at Re = 10^7) indicate that a reverse flow region (vortex region) characterized by negative values of wind velocity does not form downstream of the isolated hill, and a pattern resembling potential flow is present there. Fig. 8 shows the results from the simulation with the RIAM-COMPACT® natural terrain version software package (turbulence model: the standard Smagorinsky LES). Examinations of the results reveal that a reverse flow region (vortex region) characterized by negative values of wind

velocities clearly exists downstream of the isolated hill in the simulated flow at Re (=U$_{in}$h/ν) = 10^6.

4. Summary

The present study compared the prediction accuracy of two CFD software packages for simulating a flow around a three-dimensional, isolated hill with a steep slope: 1) Meteodyn WT (turbulence model: k-L RANS), which is one of the leading commercially available CFD software packages in the wind power industry and 2) RIAM-COMPACT® (turbulence model: the standard Smagorinsky LES), which has been developed by the lead author of the present paper. Although the Reynolds number settings differed between the simulation with

Meteodyn WT and that with RIAM-COMPACT®, distinct differences in the flow patterns were identified in the vicinity of the isolated hill (especially downstream of the isolated hill) between the flows simulated by the two CFD software packages.

Acknowledgements

References

1) Takanori UCHIDA, Validation Testing of the Prediction Accuracy of the Numerical Wind Synopsis Prediction Technique RIAM-COMPACT for the Case of the Bolund Experiment –Comparison against a Wind-Tunnel Experiment–, Reports of RIAM, Kyushu University, No.147, pp.7-14, 2014

2) http://meteodyn.com/

Addendum

As discussed in the main text of the present paper, no reverse flow region (vortex region) characterized by negative wind velocities was identified downstream of the isolated hill in the result from the simulation with Meteodyn WT (k-L RANS model), in which the Reynolds number was set to Re = 10^7 (the default value for Meteodyn WT). Accordingly, in order to investigate if a flow pattern similar to that simulated with Meteodyn WT (k-L RANS model) can also be formed with the use of RIAM-COMPACT® (the standard Smagorinsky LES model), a simulation is conducted with RIAM-COMPACT® in which the method for setting the surface boundary conditions is modified.

Specifically, the values of the three components of the wind velocity from k = 2 on the computational grid of Meteodyn WT (k-L RANS model) (k = 1 corresponds to the surface of the ground or the isolated hill in Meteodyn WT) are assigned as the values for the surface boundary conditions (k = 1) for the simulation with RIAM-COMPACT® (the standard Smagorinsky LES model) (Fig. 9). That is, this simulation is one in which non-zero values are assigned for the wind velocity at the surfaces of the ground and the isolated hill at all computational steps (Dirichlet boundary condition). The Reynolds number, based on the height of the isolated hill, is set to Re (= $U_{in}h / \nu$) = 10^4, and the computational grids shown in Figs. 1 and 2 are used. For the inflow profile, a uniform flow profile is adopted in which the

wind velocity does not change in the vertical direction. The other boundary conditions are set using the same methods as those discussed in the main text of the present paper. The time step is set to $\triangle t = 2\times10^{-3}\, h/U_{in}$. The results obtained from this simulation are compared to those from a simulation which is identical to the simulation described in this addendum, except that no-slip conditions are applied at the surfaces of the ground and the isolated hill, that is, the three components of the wind velocity are all set to zero as Dirichlet boundary conditions. For convenience, the simulation in which non-zero wind velocities are applied as a Dirichlet boundary condition is denoted as Case 1, and the simulation in which all three components of the wind velocity are set to zero is denoted as Case 2. A comparison of the simulation results is shown in Fig. 10.

An examination of Fig. 10 reveals that no flow separation region (vortex region) characterized by negative wind velocities forms downstream of the isolated hill in Case 1, in which non-zero wind velocities are applied as a Dirichlet boundary condition. In this case, a flow pattern resembling potential flow exists downstream of the isolated hill instead. In contrast, in Case 2, in which all three components of the wind velocity are set to zero as a Dirichlet boundary condition, a distinct flow separation region (vortex region) forms downstream of the isolated hill. Thus, the flow pattern which forms in the vicinity of the isolated hill varies significantly according to the velocity boundary conditions applied for the surfaces of the ground and the isolated hill.
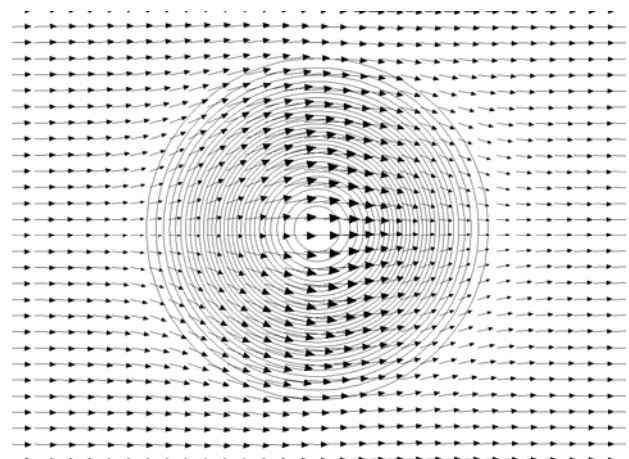

Fig.9　Velocity vectors at the surfaces of the ground and the isolated hill (k = 1), simulation for which the wind velocity from k = 2 in Meteodyn WT is used as a Dirichlet boundary condition, Case 1

A flow separation region (vortex region) characterized by negative wind velocities does not form.

A flow separation region (vortex region) characterized by negative wind velocities forms.

Uniform flow

(a) Case 1: Simulation result from the case
in which non-zero wind velocities are applied
as a Dirichlet boundary condition

(b) Case 2: Simulation result from the case
in which all three wind-velocity components are
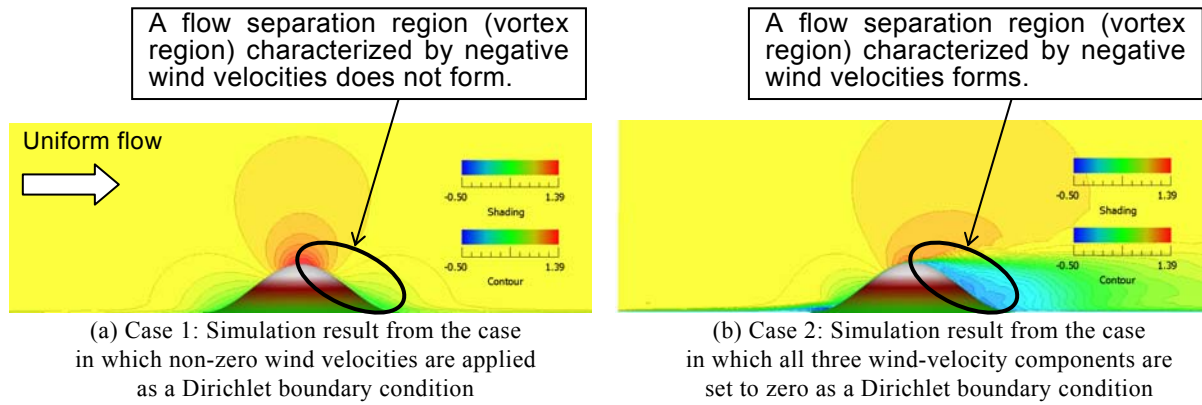set to zero as a Dirichlet boundary condition

Fig.10   Streamwise (x) wind velocity distribution in the vicinity of the isolated hill at the center of the span (y = 0),
RIAM-COMPACT®, the standard Smagorinsky LES model, Re = 10^4