

Micro-siting technique for wind turbine generators by using large-eddy simulation

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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 Research Institute for Applied Mechanics, Kyushu University, COMputational Prediction of Airflow over Complex Terrain (RIAM-COMPACT). The RIAM-COMPACT is based on the large-eddy simulation (LES). 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 an experimental and a 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 split-film probe (SFP) 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 the 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. Furthermore, the forecast accuracy of an actual wind speed is examined.

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1. Introduction

There exists a great and urgent need to reduce CO₂ emissions as a way to combat global warming. Therefore, attention has been focused on the development of environmentally friendly wind energy. In Japan, the number of wind power generation facilities has increased rapidly from several wind turbine generators (WTGs) to a large-scale wind farm (WF). The wind energy 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 wind speed-up, separation, reattachment, and so on (Murakami et al., 2003; Ishihara, 2003).

The social and technological requirements for wind power are highly demanding. Concentrating on a space of several km or less, we are developing an unsteady, non-linear-type numerical simulator called the Research Institute for Applied Mechanics, Kyushu University, COMputational Prediction of Airflow over Complex Terrain (RIAM-COMPACT) (Uchida and Ohya, 1999, 2003a, b). The RIAM-COMPACT is a FORTRAN program based on the finite-difference method (FDM), and adopts an large eddy simulation (LES) technique as a turbulence model. In an LES, comparatively large-eddy structures are calculated directly, and only eddy structures that are smaller than the calculation mesh are modeled. We have been examining the practical use of the RIAM-COMPACT for several years. As a result, the RIAM-COMPACT has already been marketed by certain tie-up companies and can be operated by one desktop PC and one mobile PC running Windows. An estimation of the annual electrical power output is also now possible based on the observed field data.

In general, as a first step in the development of the calculation code of an unsteady wind simulation such as LES, the forecast accuracy is verified with the influence of the surface roughness and inflow turbulence omitted, and then calculations are made for a real-life situation. Accordingly, there is a strong need for a wind tunnel experiment conducted under simplified and idealized conditions to verify the calculation code. However, very little experimental data of this type has been reported.

A wind tunnel experiment that omits the influence of the surface roughness and inflow turbulence, etc., is conducted in the present study. The goal of this wind tunnel experiment is to acquire data to verify the forecast accuracy of the RIAM-COMPACT. In addition, properties of the flow phenomena around a simple terrain in a uniform flow are clarified. In the present study, a two-dimensional ridge model and a three-dimensional isolated hill model with a steep slope are targeted as simple terrains. The Noma cape wind power plant in the Kagoshima prefecture is targeted as a complex terrain. Finally, the forecast accuracy of an actual wind speed is examined.

2. Wind tunnel experiment using the SFP

The wind tunnel experiment of the present study was conducted using the thermally stratified wind tunnel of the RIAM, Kyushu University. The stability condition of the air was assumed to be neutral. This wind tunnel has measurements of 13.5 m in length $\times$ 1.5 m in width $\times$ 1.2 m in height. The range of the wind speed is 0.5–2.0 m/s. When the wind speed is set to 1.0 m/s, the distribution of turbulence intensity in the stream wise direction is

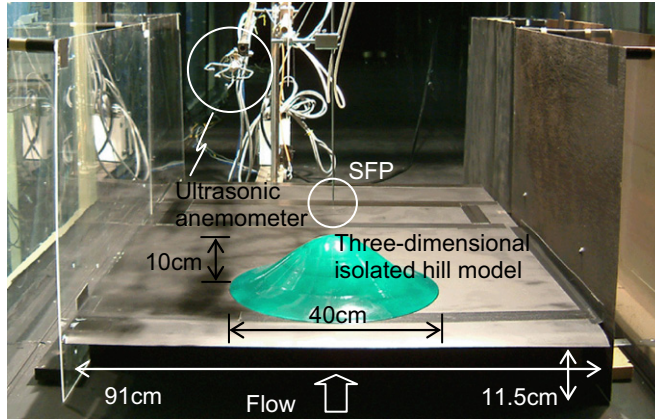


Fig. 1. Arrangement of the wind tunnel experiment.

about 0.4%. The uniform flow was imposed as an inflow condition in the present study, as shown Fig. 1. The shape of a cross section of the two-dimensional ridge model and the three-dimensional isolated hill model are the same, and can be described by the following expressions:

$$z(r) = 0.5h \times \{1 + \cos(\pi r/a)\}, \quad r = (x^2 + y^2)^{1/2} \quad (1)$$

The shape parameter a in the above expression assumes $2h$ ($= 20$ cm). Here, h is the height of the model. This model has a steep angle of gradient ($\alpha = 40^\circ$). The x -axis is set to the stream wise direction, the y -axis to the span wise direction, and the z -axis to the vertical direction. The ratio of the model height $h = 10$ cm and the height $H = 1.2$ m of the wind tunnel is $H/h = 12$. The corresponding blockage ratio ($= h/H \times 100$) is 8.3%. To measure the flow phenomenon, a split film probe (SFP) (Kanomax Japan Inc., Osaka, Japan) was used. In the present study, the SFP was inserted from the upper side of the model so that the split side might become parallel to the vertical axis (z -axis). Only the velocity component (u) in the stream wise direction (x) was measured while traversing the SFP in the perpendicular z -direction. After the low-pass filter of the offset voltage 2.5 V, 1 gain time, and the cutoff frequency 200 Hz is processed, the time series data of the voltage value are input to the desk-top PC at a sampling frequency of 500 Hz through the analog-to-digital conversion board. The number of data points at each measurement is 50,000. That is, the sampling duration is 100 s. The uniform wind speed is assumed to be $U = 1.5$ m/s. The angle of the wind to the model is 0° . The Reynolds number, Re ($= Uh/\nu$) based on the height $h = 10$ cm of the model is about 10^4 .

3. Numerical simulation using the RIAM-COMPACT

In the present study, a numerical simulation of flow past a two-dimensional ridge model and a three-dimensional isolated hill model was conducted under the same conditions as used in the wind tunnel experiment. In an LES, the governing equations consist of the filtered continuity and Navier–Stokes equations. We employ a generalized curvilinear

collocated grid, and then 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 (Kim and Moin, 1985) 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 successive over relaxation (SOR) 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 is used (Kajishima, 1994). The weight of the numerical viscosity term is sufficiently small ($\alpha = 0.5$), compared with the Kawamura–Kuwahara scheme ($\alpha = 3$) (Kawamura et al., 1986). A conventional standard Smagorinsky model (Smagorinsky, 1963) was used as the SGS model, together with a wall-damping function. The calculation domain and the coordinate system are shown in Fig. 2, for an example of a three-dimensional isolated hill model. The calculation domain is $40h(\pm 20h) \times 9h \times 10h$ in the x -, y -, and z -directions, respectively. It is almost the same as that in the wind tunnel experiment. Here, h is the height of the model. The number of grids is $260 \times 121 \times 71$ in the x -, y -, and z -directions. Fig. 3 shows the calculation mesh near the model. The grid spacing in the x -, y -, and z -directions is $(0.04\text{--}1) \times h$, $(0.05\text{--}0.5) \times h$, and $(0.0035\text{--}0.5) \times h$, respectively. The boundary conditions for the velocity field in the computational domain are as follows: uniform flow (inflow), free-slip condition (top and side boundary), and convective outflow condition (outflow), as shown in Fig. 2. For the boundary condition of the ground, to impose the same conditions as in the wind tunnel experiment, the free-slip condition was imposed from the inflow boundary to $17h$. The non-slip condition was imposed from the downstream direction. The Reynolds number was assumed to be $Re (= Uh/\nu) = 10^4$ as in the wind tunnel experiment.

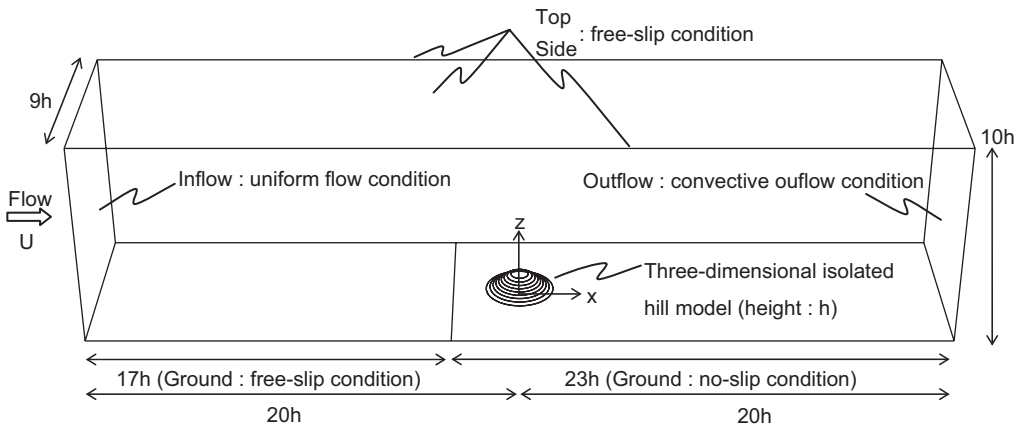


Fig. 2. Computational domain and coordinate system.

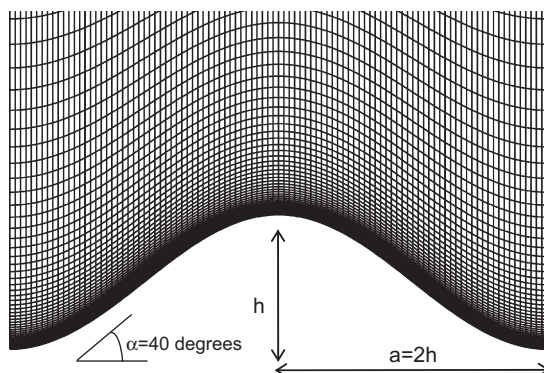


Fig. 3. Computational mesh near a three-dimensional isolated hill model, side view ($y = 0$).

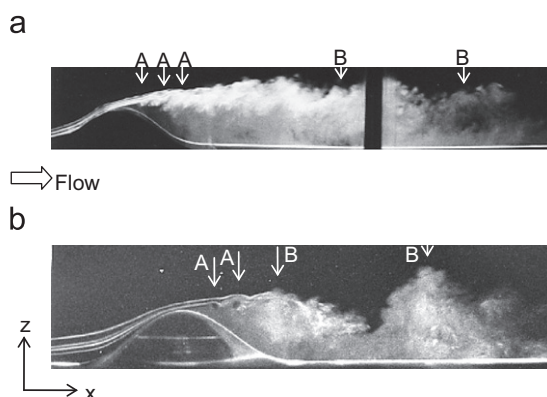


Fig. 4. Comparison of the visualization in the wind tunnel experiment by using the smoke-wire technique, side view ($y = 0$): (a) two-dimensional ridge model and (b) three-dimensional isolated hill model.

4. The case of simple terrain

4.1. Flow visualization of the instantaneous flow field

The comparison of the instantaneous flow field between a two-dimensional ridge model and a three-dimensional isolated hill model is shown in Fig. 4, as for the wind tunnel experiment. In the wind tunnel experiment, the flow field was visualized by the smoke wire technique. The wind speed was set to 1.5 m/s. This is the same condition as for the flow measurement using the SFP. The height of the wire was adjusted so that smoke could flow in the vicinity of the surface of the model in order to focus on the behavior of the shear layer separated from the hilltop. On the other hand, the flow field was visualized by the passive particle tracking method in the numerical simulation. Fig. 5 shows the results for the span central side ($y = 0$). The release interval of a passive particle is $\Delta t = 0.1$ and the results shown are for a total of 100 scenes. The qualitative flow patterns of the numerical simulation and the wind tunnel experiment are very similar. Airflows around the model include the unsteady vortex shedding in both models. That is, the flow separates in the

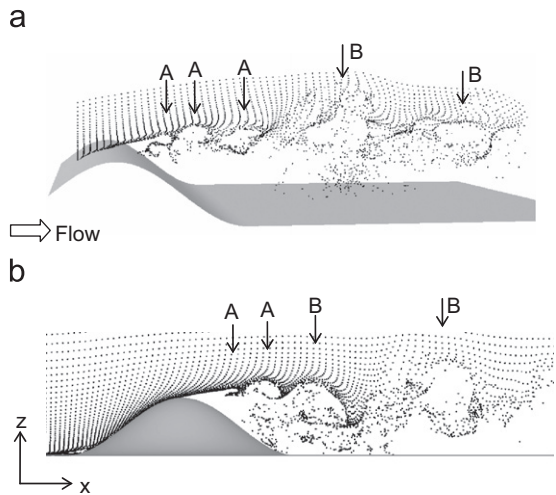


Fig. 5. Comparison of the visualization in the numerical simulation (RIAM-COMPACT) by using the passive particle tracking method, side view ($y = 0$): (a) two-dimensional ridge model and (b) three-dimensional isolated hill model.

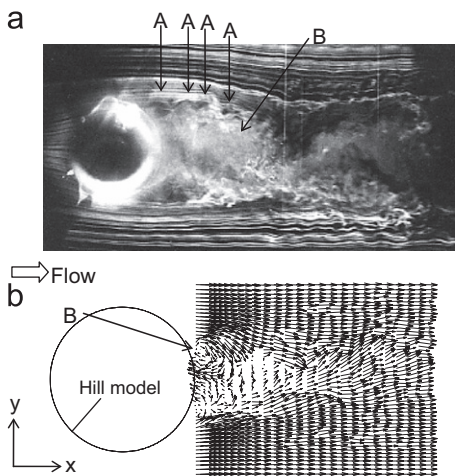


Fig. 6. Instantaneous flow pattern past a three-dimensional isolated hill model, top view ($z^* = 0.5h$): (a) wind tunnel experiment (smoke-wire technique) and (b) numerical simulation by the RIAM-COMPACT (velocity vectors).

vicinity of the hilltop, and the separated shearing layer rolls up and forms isolated eddies (arrow A in the figure). These small eddies then merge together. As a result, large vortices are formed, and are shed away to the downstream area of the model (arrow B in the figure).

As for the flow field past a three-dimensional isolated hill model, the comparison between the numerical simulation and the wind tunnel experiment in the horizontal plane is shown in Fig. 6. A small eddy structure in which the separated shear layer is formed is

observed behind the model (arrow A in the figure). A large eddy structure formed by the merging of the small numerous small eddies (arrow B in the figure) is also clearly observed.

The streamline was drawn from various positions based on the numerical results to investigate the behavior of the eddy region formed behind the model. Fig. 7 shows these

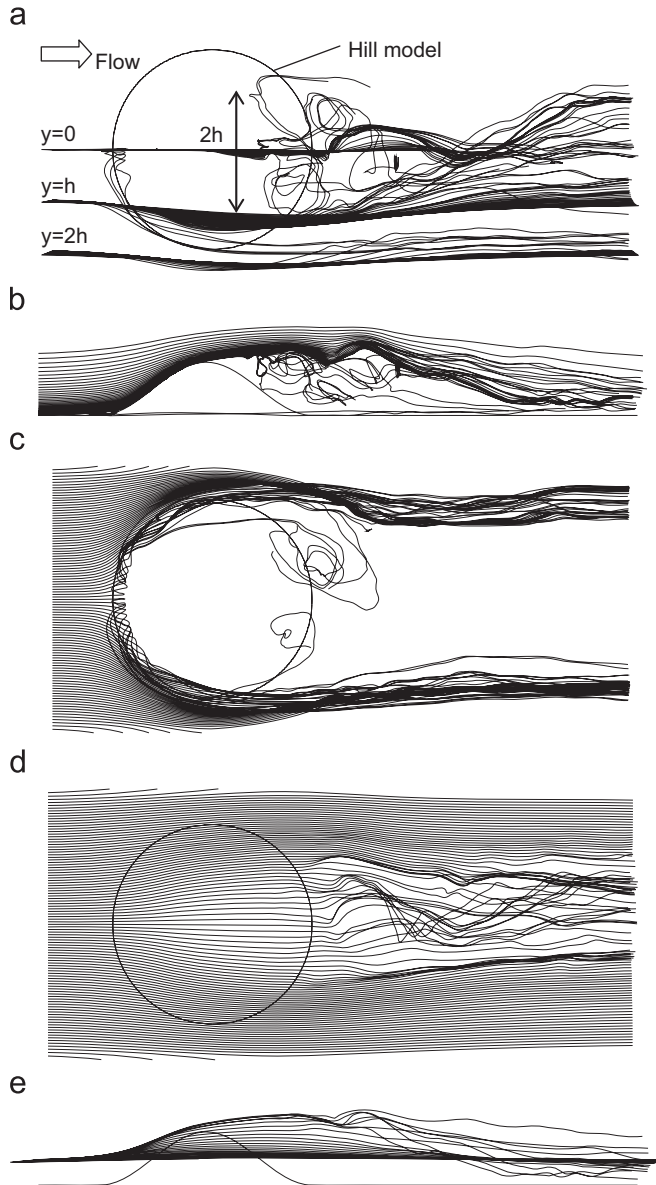


Fig. 7. Instantaneous streamlines around a three-dimensional isolated hill model: (a) top view of result of drawing from $y = 0, h, 2h$; (b) side view of result of drawing from $y = 0$; (c) top view of result of drawing from $z^* = 0.0035h$; (d) top view of result of drawing from $z^* = 0.5h$ and (e) side view of result of drawing from $z^* = 0.5h$. Here, h shows the height of the hill.

results. First, we will focus our attention on Fig. 7(a, b). The streamlines of $y = 0$ are entrained in the eddy region formed behind the model, and show three-dimensional behavior. On the other hand, in $y = h, 2h$ shown in Fig. 7(a), the streamlines are not almost displayed in the eddy region behind the model. As for the size of the eddy region behind the model in the y -direction, it is suggested that it is about $2h$ from these results. A horseshoe vortex appears near the ground to surround the model in Fig. 7(c). The flow going over the model is clearly observed in Fig. 7(d, e). However, streamlines are not entrained in the eddy region behind the model.

4.2. Flow visualization of the time-averaged flow field

The numerical simulations for the time-averaged flow field between a two-dimensional ridge model and a three-dimensional isolated hill model are compared in Fig. 8. In the case of the two-dimensional ridge model, a space average of the y -direction was made. The interval of the non-dimensional time average was 100 for both models. The eddy region was formed behind both models. We first focused our attention on the size of the eddy formed behind the model. The size in the z -direction is almost same for both cases. However, a clear difference can be seen in the x -direction. The eddy size of a three-dimensional hill is smaller than that of a two-dimensional ridge. The size from the top part of the model is about $8h$ for a two-dimensional ridge model. On the other hand, it is about $3.5h$ for a three-dimensional isolated hill model. Thus the size for the three-dimensional model is about half that for the two-dimensional model. The center of the eddy region is

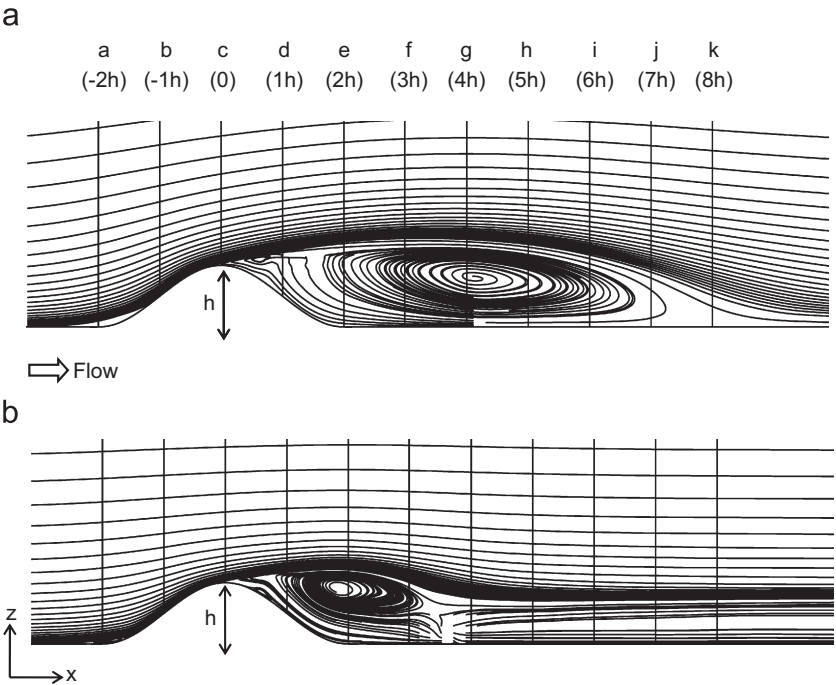


Fig. 8. Streamlines for the time-averaged flow field, $t = 200\text{--}300$, side view ($y = 0$): (a) two-dimensional ridge model and (b) three-dimensional isolated hill model.

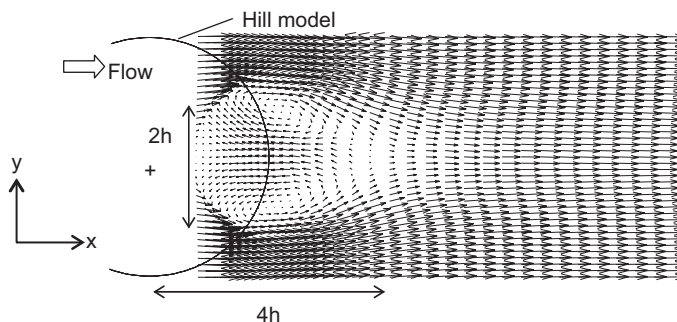


Fig. 9. Velocity vectors for the time-averaged flow field past a three-dimensional isolated hill model, $t = 200\text{--}300$, top view ($z^* = 0.5h$). Here, h shows the height of the hill.

located about $4h$ downstream of the hilltop for a two-dimensional ridge model. On the other hand, it is about $2h$ downstream of the hilltop for a three-dimensional isolated hill model. In the case of a three-dimensional isolated hill model, the flow going over the hilltop and the flow going around the side of the model interfere with each other, and this interference is thought to be one of the main causes of small eddy region. Consequently, the shear layer separated from the hilltop reattaches on the downstream ground for the two-dimensional ridge model. This phenomenon was not observed in the three-dimensional isolated hill model (see Fig. 8).

The velocity vectors in the horizontal section above $z^* = 0.5h$ are shown in Fig. 9 for a three-dimensional isolated hill model. A symmetrical eddy region is formed behind the model. The size of the y -direction is approximately twice the model height of h as previously mentioned. The size of the x -direction is about $4h$.

4.3. Vertical distribution of turbulence quantities in the time-averaged flow field

The mean-velocity profiles ($U = \langle u \rangle$) and standard deviations ($\sigma_u = \langle u'^2 \rangle^{1/2}$) in the x -direction were evaluated at 11 points, as shown in Fig. 8. Figs. 10 and 11 show these results. Here, the solid line is a numerical simulation, and the symbol is a wind tunnel experiment. The sign of $\langle \rangle$ shows the time average in the wind tunnel experiment intended for a two-dimensional ridge model. On the other hand, this sign indicates the time average and the space average of the y -direction in the numerical simulation. For the case of a three-dimensional isolated hill model, this sign indicates only the time average in both of the wind tunnel experiment and the numerical simulation. The fluctuation from the mean value is defined by $u' = u - \langle u \rangle$. The various turbulence quantities described above were calculated from the resolved part during a non-dimensional time 100 in the numerical simulation. In the cases of both the wind tunnel experiment and the numerical simulation, a horizontal axis is normalized by the wind speed aloft (U_{ref}) in each place point, and a vertical axis is normalized by the model height h . Here, z^* indicates the height from the surface of the model.

We will consider the mean-velocity profiles shown in Fig. 10. The results of the numerical simulation by the RIAM-COMPACT and the wind tunnel experiment by the SFP show an excellent agreement in both models. In both cases, there is almost no significant difference between point a ($x = -2h$) and point d ($x = 1h$). A remarkable

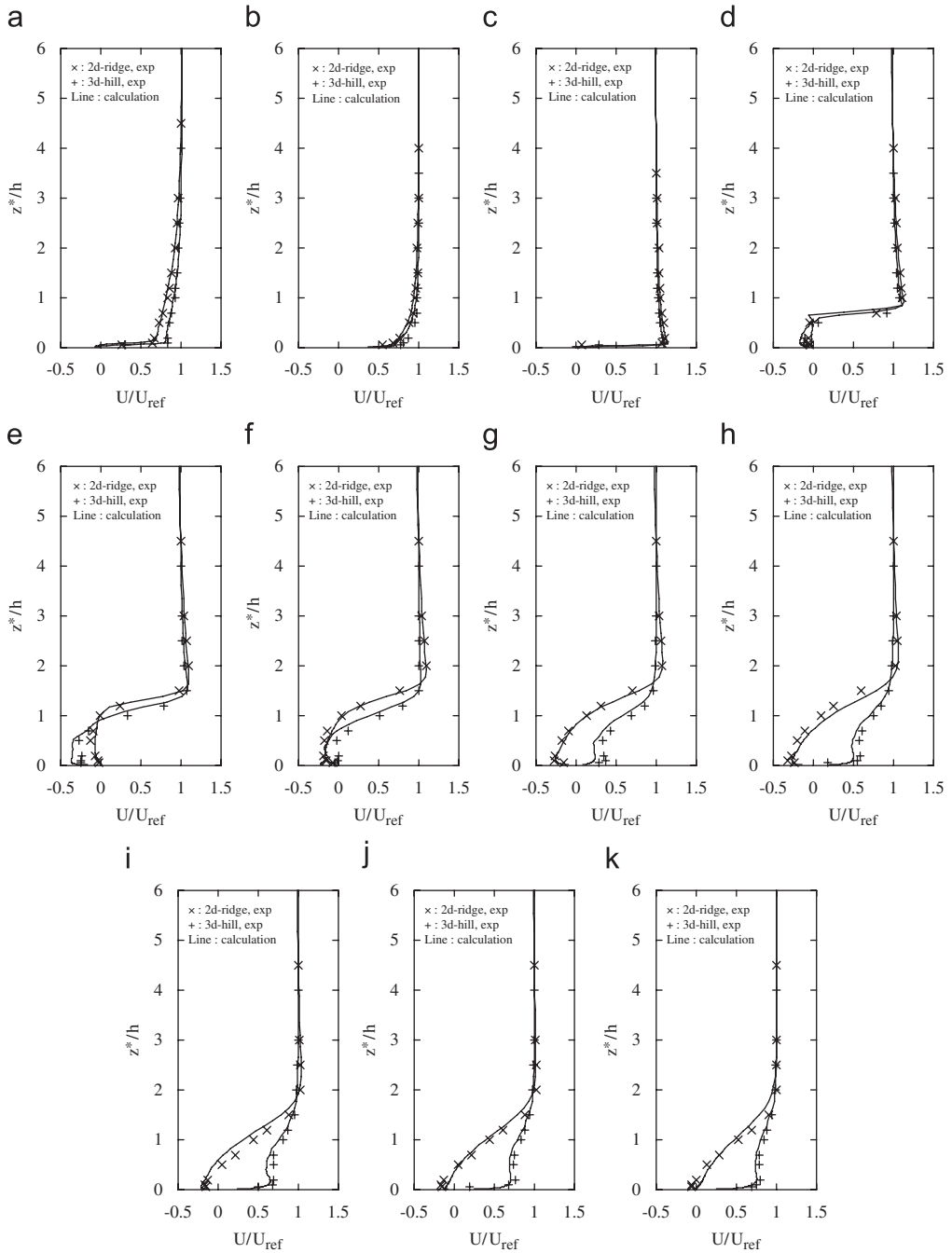


Fig. 10. Comparison of the mean-velocity profiles, line: numerical simulation by the RIAM-COMPACT, symbol: wind tunnel experiment by the SFP; (a) $x = -2h$; (b) $x = -1h$; (c) $x = 0$; (d) $x = 1h$; (e) $x = 2h$; (f) $x = 3h$; (g) $x = 4h$; (h) $x = 5h$; (i) $x = 6h$; (j) $x = 7h$ and (k) $x = 8h$. The h shows the height of the hill.

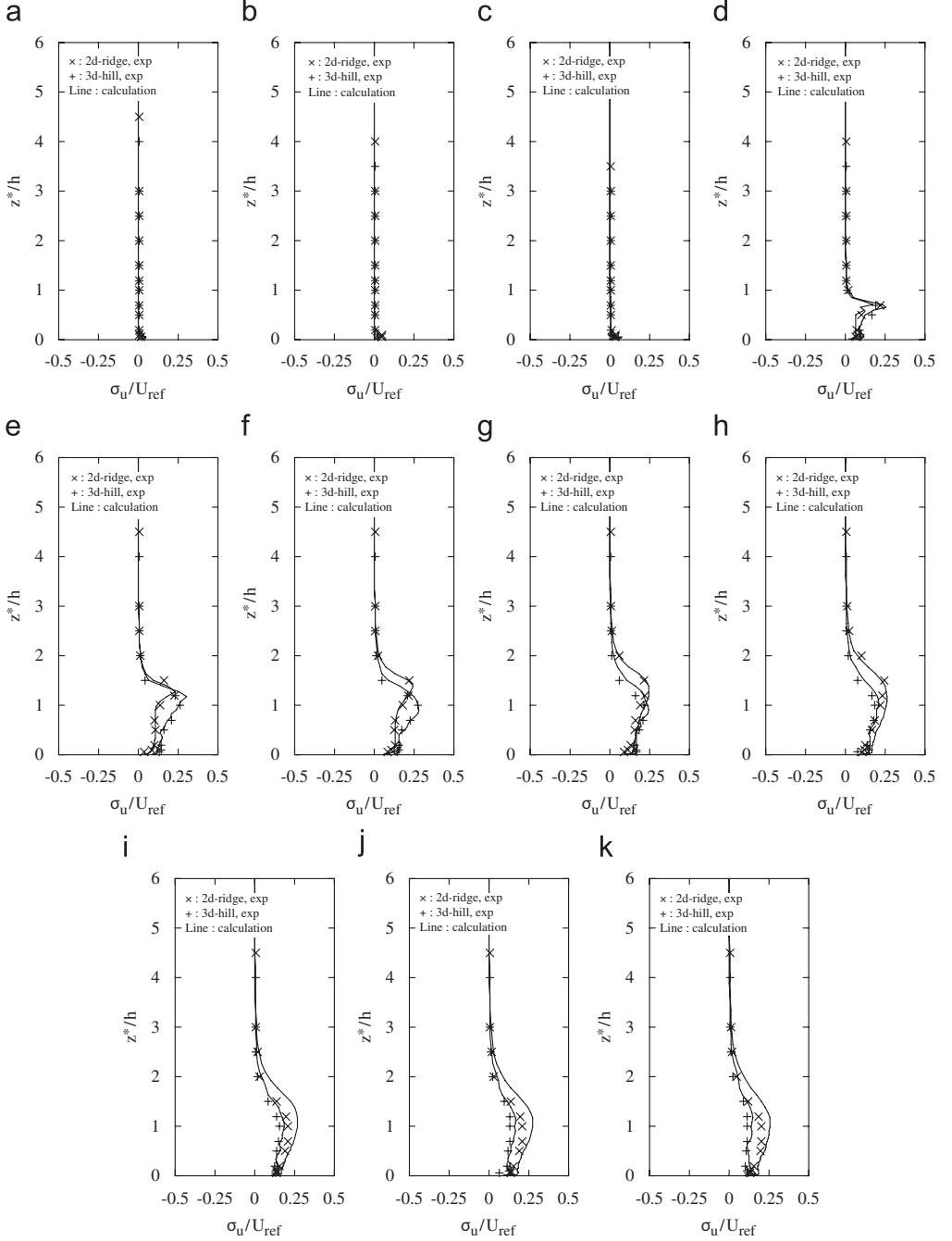


Fig. 11. Comparison of the standard deviations, line: numerical simulation by the RIAM-COMPACT, symbol: wind tunnel experiment by the SFP: (a) $x = -2h$; (b) $x = -1h$; (c) $x = 0$; (d) $x = 1h$; (e) $x = 2h$; (f) $x = 3h$; (g) $x = 4h$; (h) $x = 5h$; (i) $x = 6h$; (j) $x = 7h$ and (k) $x = 8h$. The h shows the height of the hill.

difference is seen from point e ($x = 2h$) with $z^*/h < 2$, corresponding to the eddy region shown in Fig. 8. For the three-dimensional isolated hill model, it is interesting that the profile shows an approximately uniform distribution in the z -direction in $z^*/h < 1$ of the downstream from point g ($x = 4h$).

Next, we will consider the standard deviations shown in Fig. 11. The result of the numerical simulation by the RIAM-COMPACT and the wind tunnel experiment by the SFP show a good agreement in all points for both cases. The value of the standard deviation is almost zero at all the heights for points a ($x = -2h$), b ($x = -1h$), and c ($x = 0$). A significant value is obtained for $z^*/h < 2$ at points d–k. This is mainly due to the separated flow from the model. We will focus on the peak value in $z^*/h < 2$ for the points d–g. The magnitude of values is almost the same for both models. The points d and e are almost the same for the peak position. The differences are clearly apparent at both points f and g. In the case of the three-dimensional isolated hill model, the position is located below that of the two-dimensional ridge model.

4.4. Spectral analysis using the FFT

We compared the period of a vortex shedding of isolated eddies and that of large vortices based on the results of the wind tunnel experiment. To clarify the time behavior of isolated eddies and large-scale vortices, a part (10–15 s) of the time series data of gap $u' (= u - \langle u \rangle)$ from the mean value is shown in Figs. 12 and 13. Moreover, the positions

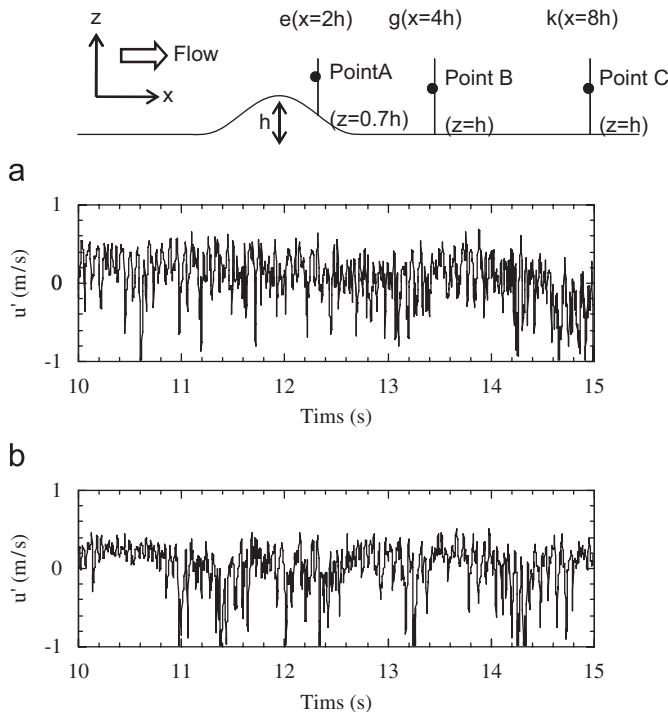


Fig. 12. Comparison of the time series data at position A, wind tunnel experiment by the SFP: (a) two-dimensional ridge model and (b) three-dimensional isolated hill model.

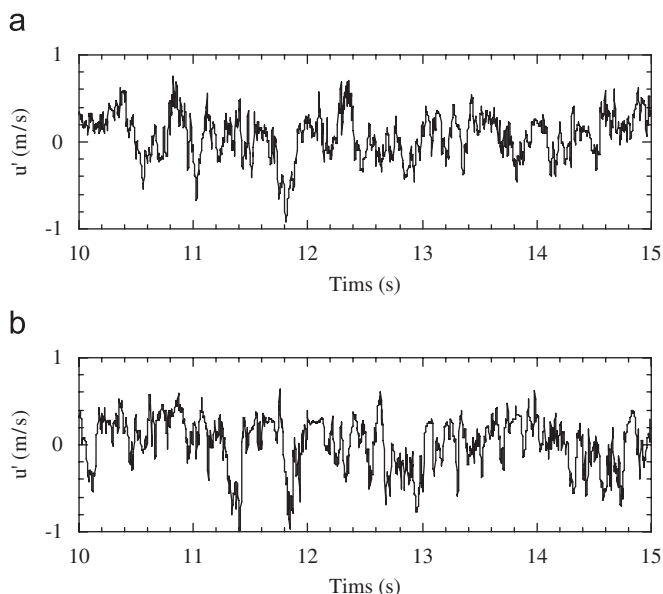


Fig. 13. Comparison of the time series data at position B and C, wind tunnel experiments by the SFP: (a) two-dimensional ridge model (position C) and (b) three-dimensional isolated hill model (position B).

(points A–C) in which the time series data was acquired are also shown. The position of the y -direction where the time series data was acquired is the same and central side ($y = 0$) in both models.

We will consider the results of Fig. 12. The shape of the waves is similar for both models. The sharp peak with a short cycle is clearly observed; corresponding to the shedding of isolated eddies. The wave shows a similar tendency in Fig. 13. It is understood that there is a significant difference between the shedding cycle of isolated eddies and large-scale vortices. To do a detailed examination, a spectral analysis was performed based on the time series data ($t = 0\text{--}100$ s, 50,000 pieces) shown in Figs. 12 and 13. Fig. 14 shows these results. The fast Fourier transform (FFT) was used for the calculation of the power spectrum. The power spectrum was obtained by dividing each of the 1024 data points ($= 210$ pieces) by 48. Finally, the ensemble average was executed. The vertical axis shows the power spectrum made dimensionless by the frequency f (Hz) and the standard deviation σ_u (m/s). The horizontal axis shows the dimensionless frequency St ($= fh/U$). Here, h is the height of the model, and U is the uniform flow speed. In Fig. 14(a), a sharp peak corresponding to the shedding of isolated eddies is clearly seen (arrow in the figure). The position is almost the same in both models, and $St = 0.87$. This becomes $f = 13$ Hz (cycle about 0.08 s). In other words, about 13 isolated eddies pass measurement point A during 1 s. In Fig. 14(b), the peak that shows the shedding of large-scale vortices is seen. The shedding cycle of the isolated eddies is almost same for both the models. However, the significant difference is seen at the shedding cycle of large-scale vortices (arrow in the figure). As for the case of a two-dimensional ridge model, St is smaller than that of a three-dimensional isolated hill model. It is $St = 0.067$ for a two-dimensional ridge model, and $St = 0.27$ for a three-dimensional isolated hill model. In the former case, this becomes $f = 1$ Hz (a cycle of about 1 s). In the latter case, this becomes $f = 4$ Hz (a cycle of about

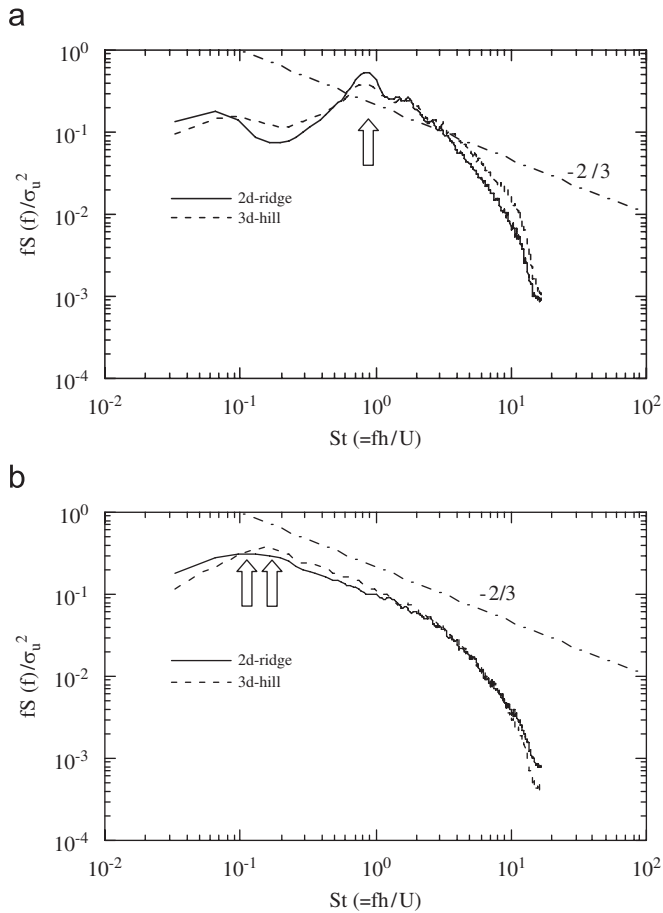


Fig. 14. Comparison of the power spectra, wind tunnel experiment by the SFP: (a) result of isolated eddies (position A, as shown in Fig. 12) and (b) result of large vortices (position B and C, as shown in Fig. 12).

0.25 s). Even if both the two-dimensional ridge model and the three-dimensional isolated hill model have the same section shape, it can be seen that the shedding cycle of large-scale vortices for a three-dimensional isolated hill model is shorter than that of a two-dimensional ridge model. This is mainly due to the mutual interference of the flow going over the model and the flow going around the side of the model in the case of the three-dimensional isolated hill model. The vortex shedding is promoted as a result. In Fig. 14(b), the Kolmogorov's $-2/3$ law is observed to be clearly reproduced.

5. The case of complex terrain

5.1. Results of the wind tunnel experiment and discussion

We have applied the RIAM-COMPACT to the airflow over real complex terrain. First, a 1/2500-scale model of the Noma cape wind power plant in the Kagoshima prefecture was



Fig. 15. Actual wind turbine installation positions of the Noma cape wind power plant in the Kagoshima prefecture.

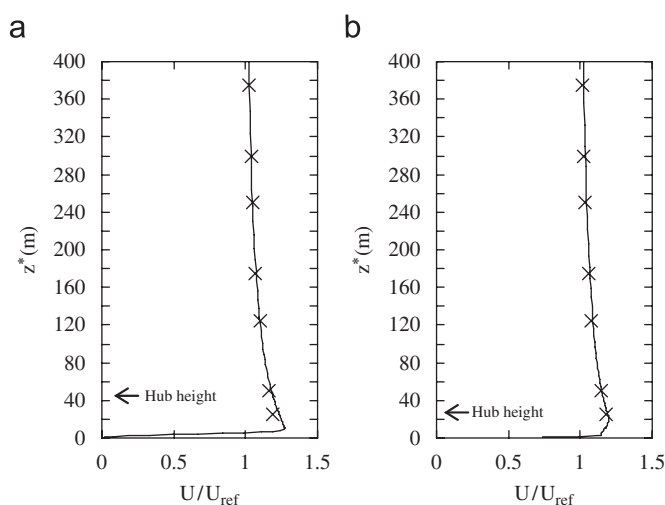


Fig. 16. Comparison of the vertical mean-velocity profiles of sites No. 4 and No. 5, line: numerical simulation by the RIAM-COMPACT, symbol: wind tunnel experiment by the SFP; (a) No. 4 site and (b) No. 5 site.

produced by hand, and the wind tunnel experiment and the numerical simulation were performed under the same conditions. In the numerical simulation, the shape of complex terrain was created based on 10 m digital elevation model (DEM) data provided by the Hokkaido-chizu Co., Ltd. The number of grid points is $251 \times 271 \times 81$ in the x -, y -, and z -directions, respectively. Other conditions are the same as for simple terrains, such as a two-dimensional ridge model and a three-dimensional isolated hill model. Flow measurement was performed using the SFP in the actual wind turbine installation positions shown in Fig. 15 for the north wind.

Fig. 16 compares the vertical mean-velocity profiles of sites No. 4 and No. 5 between the numerical simulation and the wind tunnel experiment. The horizontal axis is normalized by the wind speed aloft (U_{ref}) in each place point, and the vertical axis shows the height from the surface of the model. The numerical simulation by the RIAM-COMPACT and the wind tunnel experiment by the SFP show very good coincidence on the total height level. In particular, the local speed up is clearly seen in the vicinity of the center height of the hub.

5.2. Reproducibility and accuracy of the real wind speed

The main problem regarding the current WF is its low power output. It is thought that the main cause of this inefficiency is the small geographical rises and depressions in the WTG site. It is assumed that these irregularities mechanically generate wind turbulence. Therefore, a regular evaluation of flow characteristics is necessary in the WF during operation. We thus propose the use of the RIAM-COMPACT to diagnose the WF site's airflow characteristics (Uchida and Ohya, 2006). The high-resolution elevation data of 10 m or less that reflects the current state of land use is indispensable for this. We developed a technique for constructing high-resolution elevation data of 10 m or less based on a paper map and the computer-aided design (CAD) data in DXF form by using the geographical information system (GIS) technique (Uchida et al., 2005). In the present study, the high-resolution elevation data with 5 m resolution were constructed from a paper map.

The reproducibility and accuracy of the real wind speed was performed by using the high-resolution elevation data with 5 m resolution for the Noma cape wind power plant in Kagoshima prefecture. Concretely, the No. 4 site was set to a reference point and the No. 1 site was set to an evaluation point. The No. 1 site and the No. 4 site are about 600 m away by a straight-line distance. The wind speed at the height of the hub of the No. 1 site was predicted in consideration of the correlation with the observed data. The actual conversion procedure to get the real wind speed is as follows. First, the wind simulation is carried out for 16 wind directions, and the fully developed time-averaged flow fields are obtained. Next, the ratio of the hub height wind speed of the No. 1 site and the No. 4 site is computed, and is summarized for every wind direction. Here, the wind speed of the No. 4 site as a reference point is normalized as one. Finally, according to the wind direction of the No. 4 site as a reference value for each time point, the wind speed ratio calculated beforehand is multiplied by the time series data of the wind speed of the No. 4 site. If this operation is applied to each of the values observed over one year (June 2002–May 2003), and the statistical analysis is performed, then the monthly averaged wind speed and the annual average wind speed can be acquired in the No. 1 site as an evaluation point.

The numerical results obtained are shown in Figs. 17–19. Fig. 17 shows the velocity vectors in the vertical plane in the case of the north wind direction. The numerical results

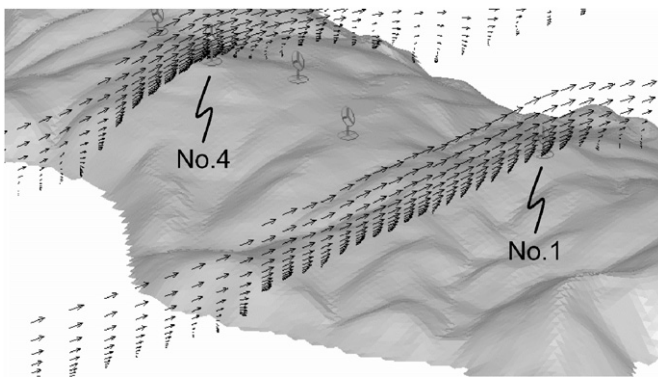


Fig. 17. Velocity vector in the vertical plane in the case of the north wind direction.

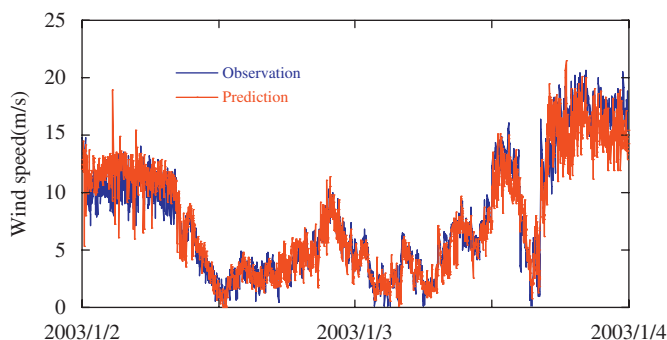


Fig. 18. Comparison of the time series data obtained on two different days of the No. 1 site.

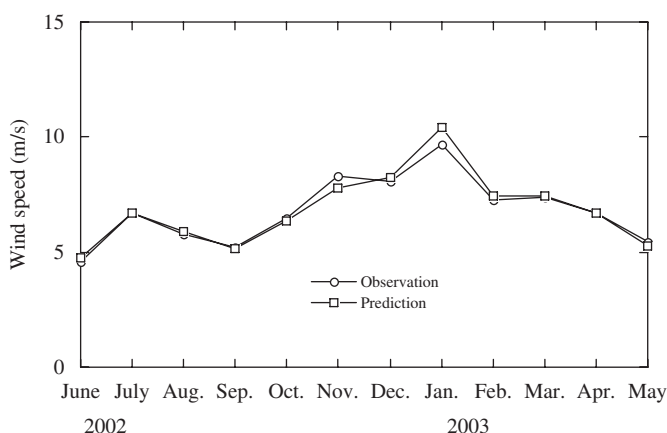


Fig. 19. Comparison of the monthly average wind speed of the No. 1 site.

obtained by the RIAM-COMPACT demonstrated that the changes induced on the wind field by topographic effects such as the local wind speed-up were successfully simulated. Fig. 18 compares the time series data obtained on two different days of the No. 1 site. The values predicted by the RIAM-COMPACT excellently reproduce the observed values. Fig. 19 shows the comparison of the monthly average wind speed of the No. 1 site. The wind speed is reproduced qualitatively and quantitatively through one year. As for the monthly average wind speed, the error relative to the observed value was within 10%. For the annual wind speed, the observed value became 6.81 m/s, and the predicted value became 6.84 m/s. The relative error was less than 1%.

6. Concluding remarks

We introduced an unsteady, non-linear-type numerical simulator called the RIAM-COMPACT that is under development by our research group. First, to test the accuracy of the RIAM-COMPACT, we performed an experimental and a numerical simulation of a non-stratified airflow past two simple terrains, a two-dimensional ridge model and a

three-dimensional hill model, in a uniform flow. Attention was focused on the airflow characteristics in the wake region. For this purpose, the streamwise velocity component was measured with the SFP in the wind tunnel experiment. The experimental and numerical results were found to be in a good agreement. The accuracy of both the wind tunnel experiment by the SFP and the numerical simulation by the RIAM-COMPACT were confirmed. Next, we applied the RIAM-COMPACT to a case of airflow over an actual complex terrain. The numerical results obtained by the RIAM-COMPACT demonstrated that the changes induced on the wind field by the topographic effect, such as the local wind speed-up and the flow separation, were successfully simulated. The wind speed was evaluated in consideration of the correlation with the observed data. As for the monthly average wind speed, the error relative to the observed value was less than 10%. For the annual wind speed, the observed value became 6.81 m/s, and the predicted value became 6.84 m/s. The relative error was less than 1%. Based on these results, we conclude that the Noma wind power plant, with its ocean surround, is in a relatively ideal location. Verification in a more complex mountainous district remains a goal for future study.

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