Analysis on Turbulent Flows using Large-eddy Simulation on the Seaside Complex Terrain

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Abstract. The purpose of this study is the Large-eddy Simulation (LES) of the turbulent wind on the complex terrain, and the first results of the simulation are described. The authors tried to apply the LES code, which was developed as an atmospheric simulator in Japan Agency for the Marine-Earth Science and Technology (JAMSTEC), to the wind prediction for the wind energy. On the wind simulation, the highest problem would be the boundary conditions, and the case in this paper was simplified one. The case study in this paper is the west wind on a complex terrain site, which is the wind from sea for the site. The steady flow was employed for the inlet condition, because the wind on the sea is the low turbulent wind, and almost all the turbulence would be generated by the roughness of the ground surface. The wall function was employed as the surface condition on the ground surface. The computational domain size was about $8 \times 3 \times 2.5$ km^3, and the minimum cell size was about $10 \times 10 \times 3$ m^3. The computational results, the vertical profile of the averaged wind speed and the turbulence intensity, agreed with the measurement by the meteorological masts. Moreover, the authors tried the analysis of the turbulence characteristics. The power spectrum density model, and the cross spectrum analyses gave the knowledge of the turbulent characteristics on the complex terrain and the hints for the domain and grid of the numerical analysis.

1. Introduction

The purpose of this study is the Large-eddy Simulation (LES) of the turbulent wind to get the knowledge of the turbulence characteristics of the complex terrain. There had been many studies of the numerical simulations for the wind on the terrains, however there would be a lot of works to do, especially for the estimation of the turbulence on the complex terrain. On the wind prediction for the complex terrain, both of RANS and LES had got the excellent results[1][2]. The authors tried to apply LES code, which is called MSSG-A and developed in the Earth Simulator Center of Japan Agency for the Marine-Earth Science and Technology (JAMSTEC), to the wind analysis for the wind energy and tried the simulation of the high resolution. On the wind simulation, one of the important problems is the boundary conditions and it would be much more difficult to determine the boundary condition on the field than the wind tunnel simulation. There are many studies using mesoscale simulation results as inflow boundary conditions. One of the purpose of this study is a simplified prediction method without extra resources like mesoscale simulations. Therefore, the steady flow with no turbulence was employed as the inlet condition for a sea wind case in this study, because the wind on the sea would

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include less turbulences, and the turbulence generated by the roughness of the ground surface would be dominant around the measuring points. The wall function was employed as the surface condition of the ground. The minimum cell size was about 10 × 10 × 3 m^3. The computational results, the vertical profile of the averaged wind speed and the turbulence intensity, agreed with the measurement. Then, the authors tried the analysis of the turbulence characteristics. The power spectrum density model, and the cross spectrum analyses gave the knowledge of the turbulent characteristics on the complex terrain and the hints for the domain and grid of the numerical analysis.

2. Numerical Methods

In this chapter, the numerical methods are described. The simulation code type was LES. The target site was the complex site, which was next to the sea. This situation may be suitable for the basic study of the turbulent wind on the terrain for some reason.

2.1. Numerical code

The CFD code, which was employed in this paper, was the LES code for an atmospheric phenomenon which was developed in the Earth Simulator Center of Japan Agency for the Marine-Earth Science and Technology (JAMSTEC), and was optimized for the Earth Simulator, and it is called MSSG-A (Atmospheric part of Multi-Scale Simulator for Geo-environment)[3]. MSSG-A is LES code based on the compressive Navier-Stokes equation with Smagorinsky parameterization[4] (Smagorinsky Constant Cs = 0.2) and employs yin-yan grid, 5th finite differential method for the advection terms, 4th finite differential method for the non-advection terms and 3rd Runge-Kutta method for the time integration. The code had been optimized for the vector type supercomputer, and demonstrated the high performance on the Earth Simulator.

2.2. Site

The Target site (called Site-K in this paper) was the complex terrain site near the sea, which is located in the south-west area of Japan (Figure 1.). At this site, 2 meteorological mast were installed and the wind speed at 3 height positions (30 m, 40 m, 50 m) and the wind direction at 1 height position (58 m) were measured. In this paper, the turbulent wind prediction of the west wind is described. For the west wind case, the computational domain size was 8 km for the east-west direction, 3km for the north-south direction (red box area in Figure 1), and 2.46 km for the vertical direction. This computational domain had the sea surface in west and that position was the inlet. The computational resolution for the complex terrain should be higher and, in the authors' opinion, the cell size should be smaller than 10 m. However, the computational resource would be too large when the calculation would be done with 10 m cell size for the computational domain. So, the resource saving was done with the 'Nesting' function of MSSG-A. By this function, 10 m cell size was applied for the area near around the masts (Domain-1) and 20 m cell size was for the other area (Domain-2).

2.3. Numerical Conditions

The boundary conditions were the steady wind with no turbulence for the inlet, the convectional condition for the outlet, the slip condition for the side and top, the wall function model for the bottom surface (Table 2). At the inlet condition, the steady wind was employed because the inlet was located in the sea surface. It may be general agreement that the wind on the sea would include less turbulence than the land. The mean wind speed was 12 m/s, the atmospheric boundary layer height was assumed as 1000 m, the vertical profile in the layer was given by $U / U_1 = (z / z_1)^{1/n}$ (Table 3). When using U_1 as a velocity scale and z_1 as a length scale, Reynolds number was about Re=8.0×10^8.

The bottom surface setups would need the information about the vegetation and, however, such information was difficult to achieve. So, in this paper, the bottom surface was divided into the 2 condition, the ground and the sea. For the ground (z>0.0 m), the roughness length z_0 was 0.2, assuming the low plants. For the sea, the roughness length z_0 was 0.001. Corresponding the roughness length setups, the wall function gives the wall condition.

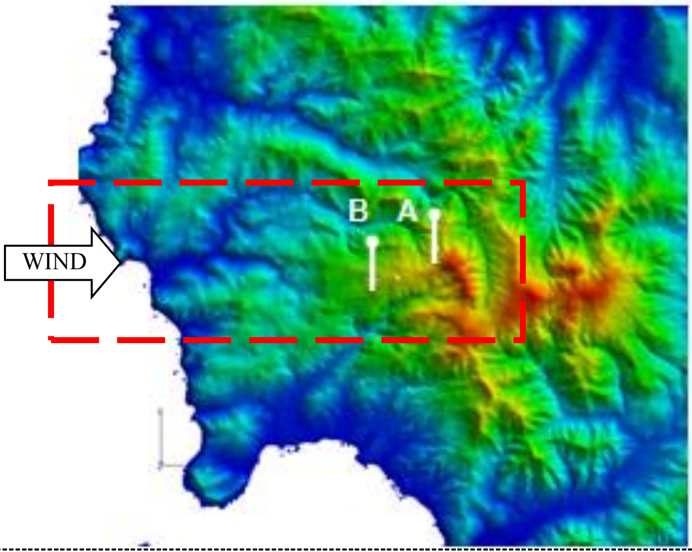


Figure 1. Site-K and the computational domain.

Table 1. Computational Domains and Grids.

Domain	Domain (x[m]×y[m]×z[m])	Grid size (dx[m]×dy[m]×dz[m])	Number of grids
1	8800 × 3200 × 2460	20.0 × 20.0 × 3.0~	440 × 160 × 64 (=4.5×10^6)
2	2400 × 2400 × 2460	10.0 × 10.0 × 3.0~	240 × 240 × 64 (=3.7×10^6)

Table 2. Boundary Conditions.

Inlet boundary	Steady flow (See Table 3)
Outlet boundary	Convection
Side and top boundary	Slip
Bottom (surface) boundary	Wall function
Reynolds number Re	8.0×10^8

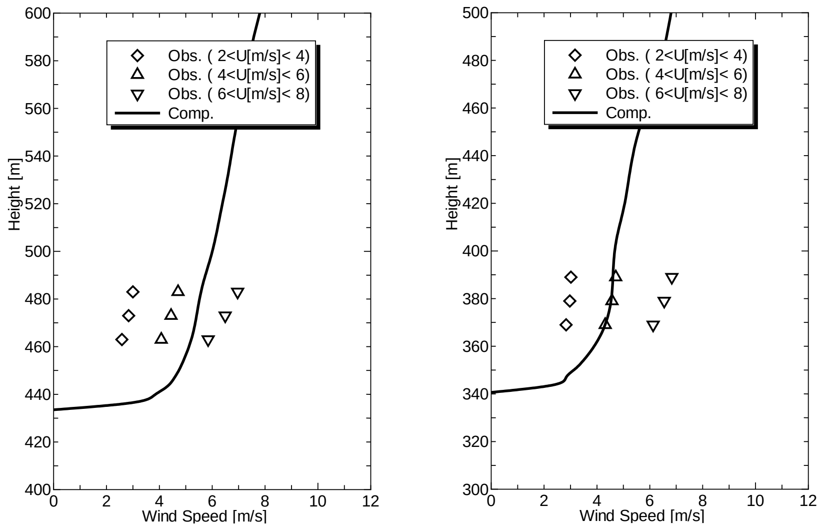
Table 3. Inflow Condition.

Mainstream wind speed U_1 [m/s]	12.0
Boundary layer height z_1 [m]	1000
Vertical wind speed profile parameter in boundary layer n	7
Turbulence component	No

3. Results - Mean wind speed and Turbulence Intensity

3.1. Mean wind speed
The inlet condition was the 12 m/s steady wind and, however, the wind speeds at the meteorological masts were different. When comparing the turbulence, the velocity value would be important and the velocity was evaluated before. Figure 3 shows the vertical profile of the wind speed at Mast-A and B. Figure 3 shows the numerical results and the observations at 30, 40, 50 m height. The vertical axis is

height above sea level (sum of the topographical height and mast height). The observation was arranged with the 2 m/s bin for the wind speed at the 50m height. The numerical results were near the averaged plots from 4 m/s to 6 m/s of the observation, so the average data from 4 m/s to 6m/s would be important.

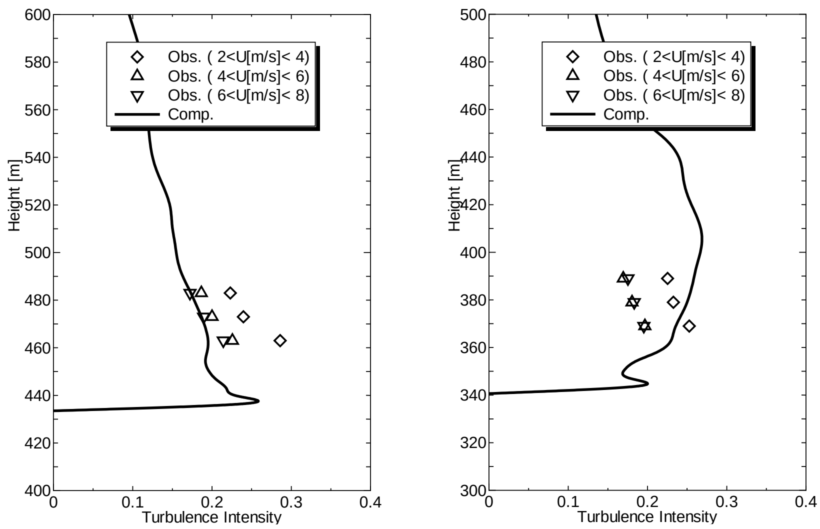


(a) Mast-A (b) Mast-B

Figure 3. The Mean wind speed at Mast-A and B of the observation and the computational result in this study.

3.2. Turbulence Intensity

As stated above, the average data from 4 m/s to 6m/s would be important. Comparing the numerical result and the observation of the averaged from 4 m/s to 6 m/s, the plots were very similar at Mast-A, but it was overestimated at Mast-B. This is because Mast-B isn't on a ridge, and the location information includes the inaccuracy, which causes the difficulty to predict. The errors of the velocity and the turbulence intensity were described in Table 4.



(a) Mast-A (b) Mast-B

Figure 4. The Turbulence Intensity at Mast-A and B of the observation and the computational result in this study.

Table 4. U_{err} [%] and T_{err} [%].

	U_{err}	T_{err}
Mast A	19%	7.5%
Mast B	2%	53.1%
Average	10%	30.3%

3.3. The power spectrum and the vorticity

Figure 5 shows the power spectrum of the turbulent wind at Mast-A. This shows the numerical result was along by the $f^{-5/3}$ line (f is frequency) and it meant the flow was well developed turbulent. Figure 6 shows the iso-surface visualization of the vorticity (vorticity=0.04). The development of the turbulence by the topography

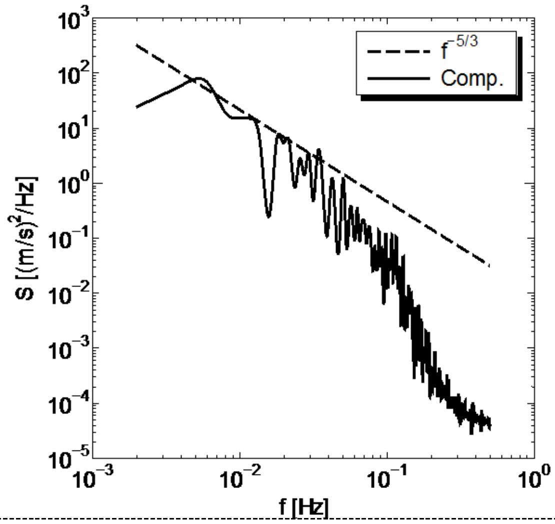


Figure 6. The power spectrum of the turbulence.

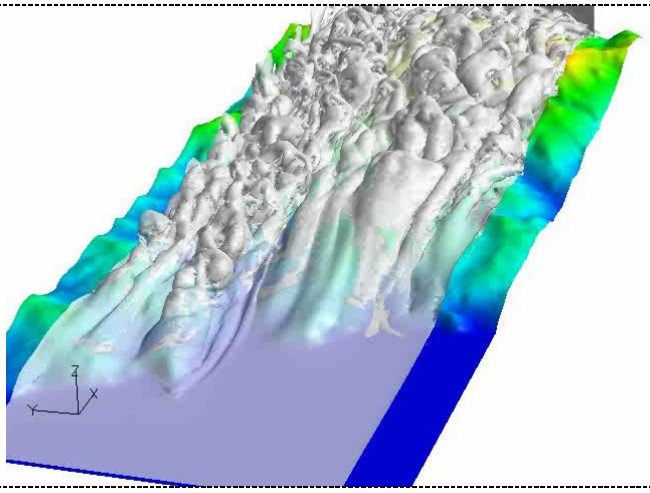


Figure 7. Iso-surface of vorticity.

4. Results - The power spectrum

4.1. The power spectrum density model

The power spectrum density (PSD) model gives the information about the turbulence characteristics of the wind of the field. PSD model described as the formula (1). The *a*, *b* and *c* are model's parameters, n is non-dimensional frequency defined as $n = f H / U$. For the length scale *H*, the measurement height is generally used and *H* is 50 m in this case. The peak non-dimensional frequency n_p is given by $n_p=1/b(c\text{-}1)$. Kaimal had suggested the PSD parameters for the flat terrain[5]. Hasegawa had investigated the parameters for the complex terrain by the measurement[6].

$$f S(f) / \sigma^2 = an / (a+bn)^2 \quad (1)$$

In the section above, the numerical data indicated the similar result to the observation. The PSD parameters were calculated from the data and the detailed turbulence characteristics of the wind should be discussed. When calculating the parameters, two type length scale *H* were used. In the first type, *H* was 50 m, which was the measurement height. In the second type, *H* was not constant and it was calculated from the data in same way as *a*, *b* and *c*. The parameters were calculated with the least square method and the parameters were calculated for each velocity component *u* and *v* (*u* is the longitudinal direction for the mainstream, *v* is the lateral direction).

4.2. Result

The calculated parameters are shown in Table 5 (constant *H* case) and Table 6 (not constant *H* case). Figure 7, 8, 9 and 10 shows the plots of the numerical data and the fitted PSD curve. In Table 6, the length scale *H* in *v* component were about 45 m and those were similar to 50 m, but *H* in *u* component were much smaller. The grid sizes of the calculation were 10 m in horizontal and 3 m in vertical, and those were similar to *H* in *u*. So, the grid sizes would be near the lower limit of this case. Ideally, the length scale should be estimation before the numerical simulation, for example using a measurement.

Comparing the numerical results with Kaimal's parameters, the parameters were quite different and this might indicate the difference between the wind on the flat terrains and the complex terrains. These were just the numerical results and it should be discussed comparing the measurements, so the preparations for it were making.

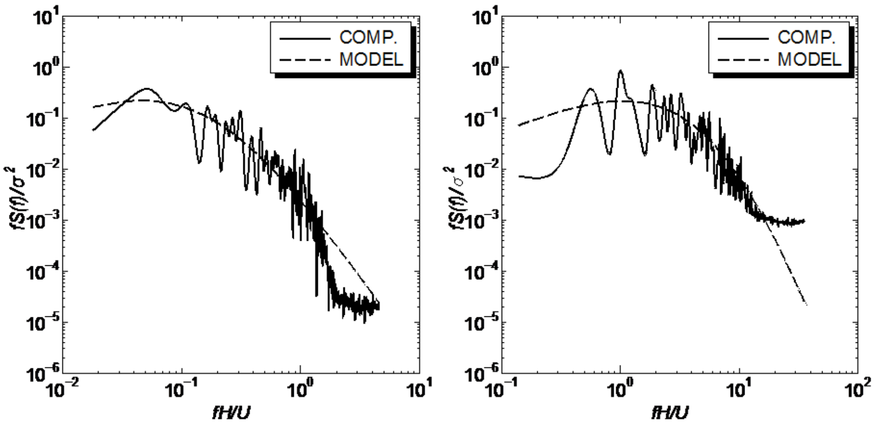
Table 5. PSD Parameters From Numerical Result (*H* =50 m).

Mast	Component	*H* [m]	a	b	c	n_p
A	*u*	50	14.9	6.45	4.35	0.05
	v	50	0.606	0.15	7.47	1.05
B	*u*	50	9.57	7.50	3.14	0.06
	v	50	0.246	0.0020	176	2.88

Table 6. PSD Parameters From Numerical Result.

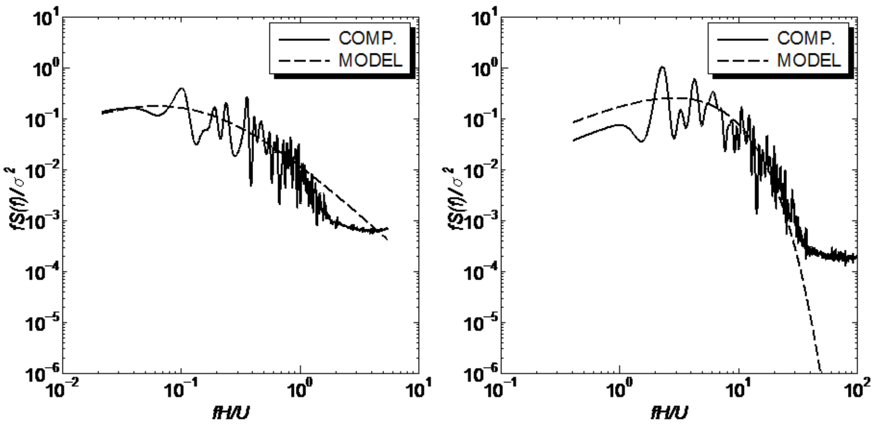
Mast	Component	H [m]	a	b	c	n_p
A	*u*	7.94	93.6	40.6	4.35	0.0073
	v	42.5	0.713	0.173	7.47	0.890
B	*u*	6.01	79.6	62.3	3.14	0.0075
	v	16.6	0.742	0.0048	218	0.955

Journal of Physics: Conference Series **555** (2014) 012058 doi:10.1088/1742-6596/555/1/012058



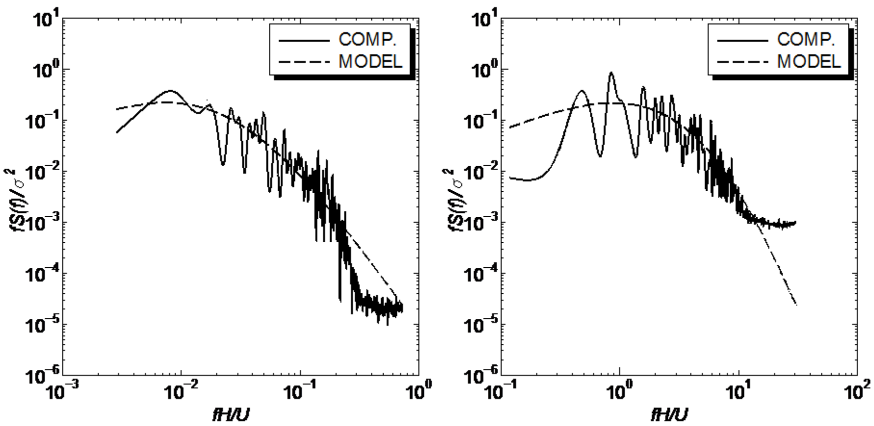
(a) *u* component (b) *v* component

Figure 7. PSD at MAST-A (H=50).



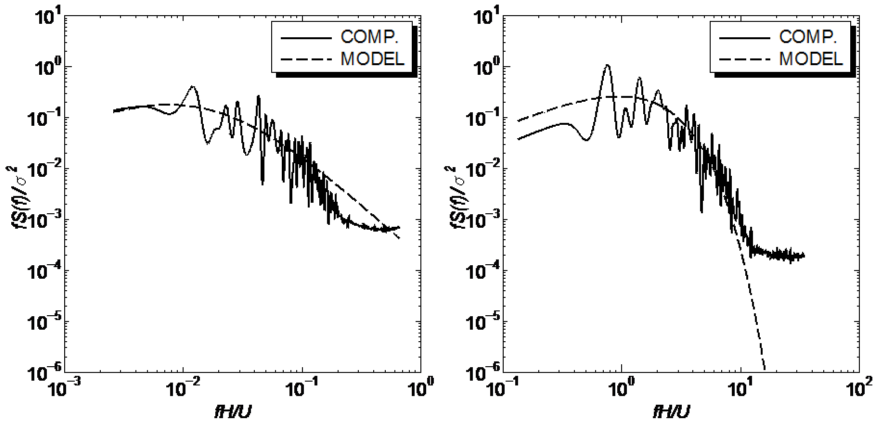
(a) *u* component (b) *v* component

Figure 8. PSD at MAST-B (H=50).



(a) *u* component (b) *v* component

Figure 9. PSD at MAST-A.



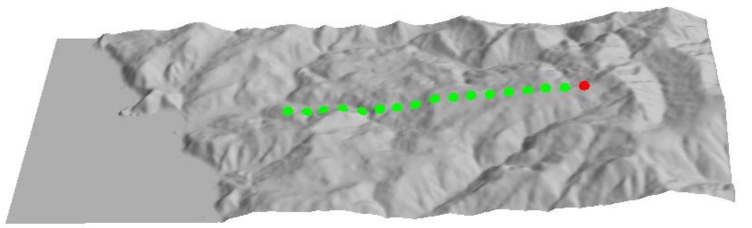
(a) *u* component (b) *v* component

Figure 10. PSD at MAST-B.

5. Results - The cross spectrum analysis

5.1. The cross spectrum analysis

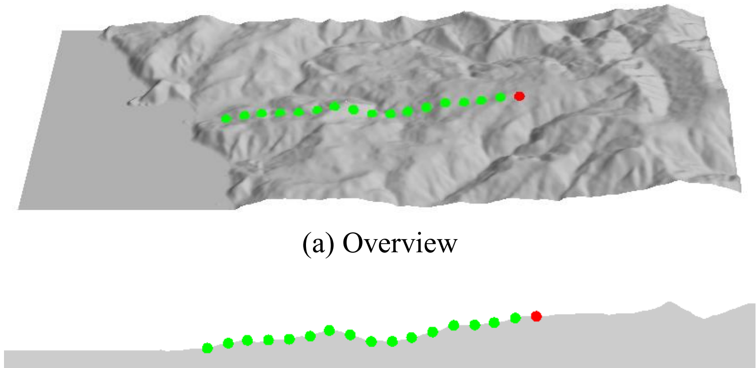
The turbulence's effect, how far the turbulence effects, is important. In this study, the cross spectrum analysis was used for the analysis of the effect. The cross spectrum analyses were done for the data of the mast and 16 upstream points, where the intervals were 200 m, and totally about 3 km area was analyzed. When the cross spectrum are described as $S_{i,j}$ (i and j are points, i,j =0,2,...,16, mast is 0), the correlation parameter between a mast (i =0) and a point j is defined as $S_{0,j}$ / $S_{0,0}$. Figure 11 and Figure 12 shows the analyzed positions for the Mast-A and B.



(a) Overview

(b) Sideview

Figure11. Sampling Points for Mast A (Red: Mast, Green: Upwind).



(a) Overview

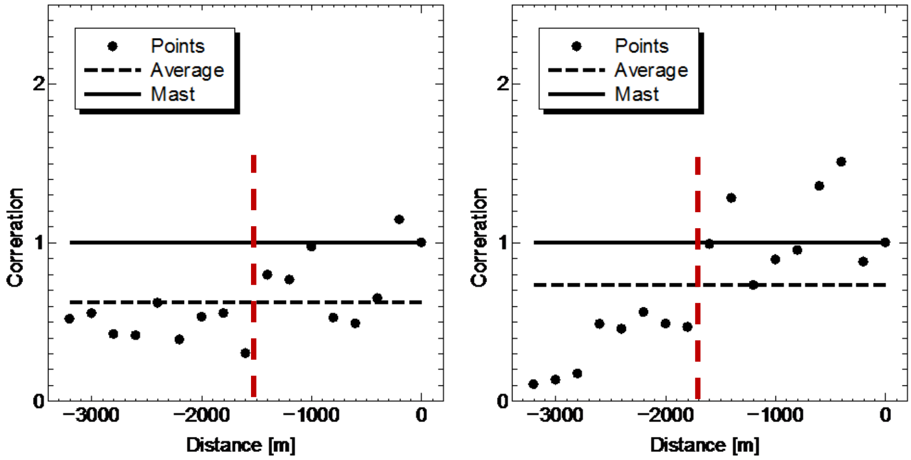
(b) Sideview

Figure 12. Sampling Points for Mast B (Red: Mast, Green: Upwind).

5.2. Result

Figure 13(a) and (b) shows the correlation parameters for Mast-A and B and those shows the tendency that the correlation would become smaller as the distance from the masts. In the figures, the $S_{0,0}$ / $S_{0,0}$ =1 lines and averaged $S_{0,j}$ / $S_{0,0}$ lines were added and the effects of the turbulence should be discussed with the lines. In both case of Mast-A and B, the correlation parameters fell down around the 2 km upstream position from the masts. This might mean the turbulence which is measured at the mast would be strongly affected from the 2 km area and weakly affected from the more far area.

This results gave the hints for the computational domain of the simulation. The results shows the 2 km area from the mast would be important and the computational domain should include the area and maybe the enough resolution should be arranged.



(a) Mast-A (b) Mast-B

Figure 13. Correlation Distribution.

6. Conclusion

In this study, the numerical analysis of the turbulent wind on the seaside complex terrain was done with the LES code and the simplified inflow setup. The LES code, which is the compressive atmosphere model called as MSSG developed by JAMSTEC, will be more useful for the prediction of the turbulent wind than RANS codes. The simplified inflow setup, in which the steady flow with no turbulence is employed, is available without extra resources of mesoscale simulations. However, this would be available for the limited cases like the sea wind case in this study. As the results, the turbulence characteristics, the PSD parameters and the cross spectrum analysis were shown. The simulation gave the fine result in the averaged wind speed and the turbulence intensity. The PSD parameters gave the knowledge about the turbulence characteristics and the grid sizes for the simulation. The cross spectrum analysis gave the knowledge about the turbulence's effects and some hints on the computational domain size. From the results of this study, the requirements of the grid size and domain size are 10 m or smaller for the grid size, 2 km or larger for the upstream area from the masts. However, these requirements will be required before the numerical simulation, so a method should be discussed to guess those from the observation or topographical feature, etc.

Acknowledgement
The CFD code MSSG was developed in the Earth Simulator Center of Japan Agency for the Marine-Earth Science and Technology (JAMSTEC) and they had also assisted the simulations for the computational resources. Some part of this study were supported by the New Energy and Industrial Technology Development Organization (NEDO) project "The new technology development for the wind and other renewable (Basic and application)".

References

[1] Bechmann A., Sørensen N.N., "Hybrid RANS/LES Applied to Complex Terrain", Wind Energy 13: 36-50, 2010.
[2] Takanori Uchida, Yuji Ohya, "Large-eddy simulation of turbulent airflow over complex terrain", Journal of Wind Engineering and Industrial Aerodynamics, 91, pp.219-229, 2003.
[3] Keiko Takahashi, Xindong Peng, Ryo Onishi, Takeshi Sugimura, Mitsuru Ohdaira, Koji. Goto, Hiromitsu Fuchigami, Multi-Scale Weather/Climate Simulations with Multi-Scale Simulator for the Geoenvironment (MSSG) on the Earth Simulator, Annual Report of the Earth Simulator Center, April 2007-March 2008, 27-33, 2008.
[4] Smagorinsky, J., “General Circulation Experiments With The Primitive Equations, I. The Basic Experiment”, Monthly Weather Review, 91, 3 (1963), pp.99–164.
[5] J. C. Kaimal, J. C. Wyngaard, Y. Izumi, O. R. Cote, "Spectral characteristics of surface-layer turbulence ", Q. J. R, Meteorol., 98, pp.563-589, 1972.
[6] Yutaka Hasegawa, Hitoshi Suzuki, Hiroshi Imamura, Koji Kikuyama, Kunihiko Hatabara, Yusuke Majima, " Analysis of Turbulence Characteristics for Surface Layer Over Complex Terrain : Evaluation of Power Spectrum and Coherency", Transactions of the Japan Society of Mechanical Engineering (B), Vol. 71, No. 711, pp.105-112, 2005.