Application of LES CFD for transient wind flow simulation over complex terrain for a wind turbine suffering yaw-related damage

Graham Li[1] and Takanori Uchida[2]

[1]Tsubasa Windfarm Design, Sunagawa 4-62-8, Tachikawa, Tokyo, Japan

Phone: +81 80 2379 2899, Email: graham@twd-wind.com

[2]Research Institute for Applied Mechanics, Kyushu University, 6-1 Kasuga-koen, Kasuga, Fukuoka, Japan

Phone: +81 92 583 7701 ,Email: takanori@riam.kyushu-u.ac.jp

Abstract: One of the four wind turbines at Atsumi windfarm, an existing and operating windfarm in Japan's Aichi prefecture, has suffered frequent yaw-related damage. The turbine is located on relatively flat low-elevation terrain, but the topography immediately east of the turbine is highly complex. LES CFD code from software RIAM-COMPACT® is employed to simulate the wind flow for the easterly wind direction. Simulation results predicted that the presence of the complex topography upstream is causing the onset of turbulence, and that as a result, the turbine is experiencing turbulence characterized by extremely high vertical and horizontal wind speed differences (wind shear) across the rotor face. Transient time series output from the LES CFD simulation results was compared with IEC extreme wind conditions standards. It was found that the turbulent wind conditions exceed both the IEC Extreme Wind Shear (EWS) and the Extreme Direction Change (EDC) models. It can be deduced that such highly turbulent wind conditions translate into non-uniform loads which exceed the design loads of the yaw components and hence explain the occurrence of yaw-related damage.

1. Site Description & Background

Atsumi windfarm is located in the city of Tahara, Aichi prefecture, Japan. The windfarm started operation in December 2006 and consists of four Vestas V80 wind turbines with a rated capacity of 2.0MW. The turbines have a hub height of 78m and rotor diameter of 80m. Elevation of the turbine positions ranges roughly from 20m to 100m. Figure 1 shows the windfarm layout and the surrounding topography.

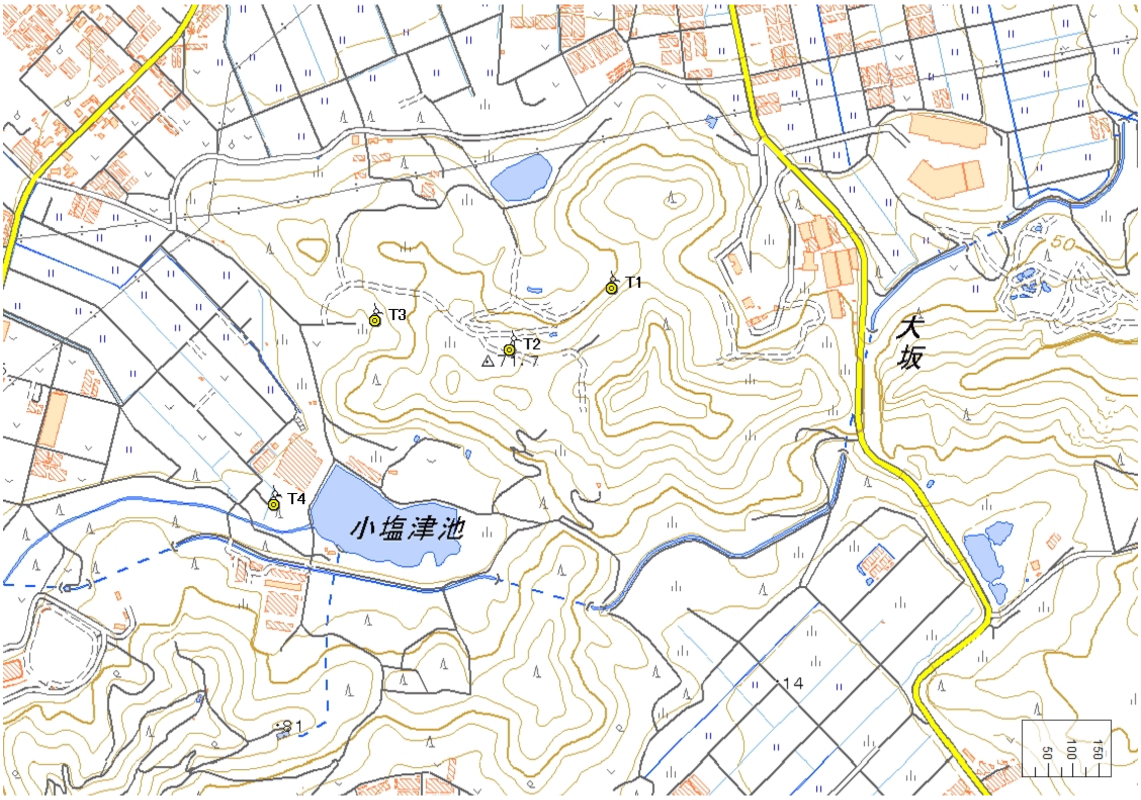

Fig.1 - Topography and turbine positions (T1 to T4) of Atsumi windfarm
(elevation contours in 10m, meter scale in the bottom right corner)

It can be seen from Figure 1 that there is a hill about 250m east of turbine T2. This hill is clearly visible in Figure 2, a photo taken from northwest of the site. There is about a 50m elevation difference between the top of the hill and the position of turbine T2.

Fig.2 - Photo of Atsumi windfarm

Turbine T2 has the following coordinates: latitude 34.608525 degrees and longitudes 137.100081 degrees. Since the start of operations, it has experienced a particularly high frequency of yaw gear and yaw motor damage compared with the other three wind turbines.

Wind farm operator Kyudenko suspected that this damage was linked to wind conditions. In 2011, Kyudenko approached Dr. Takanori Uchida, Associate Professor of the Research Institute for Applied Mechanics, Kyushu University to simulate the wind flow around turbine T2 [1].

2. Wind Direction

It was known that most yaw damage was happening in the autumn months of every year. The wind conditions in these months were investigated using GPV-MSM-S mesoscale data issued by the Japan Meteorological Agency. Figure 3 shows the wind rose in October 2010 for the grid point nearest to the site. The grid point has coordinates of latitude 34.6 degrees and longitudes 137.125 degrees.

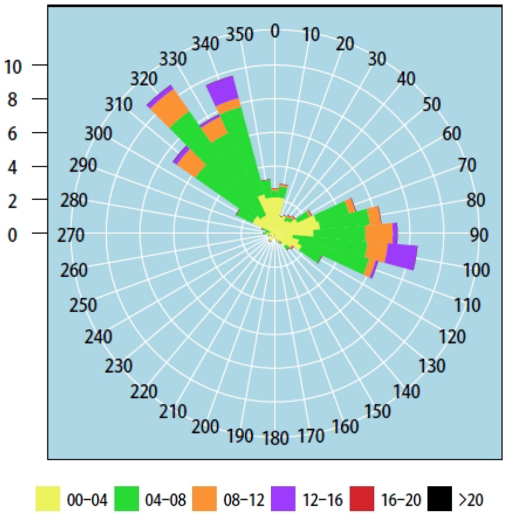

Fig.3 - Wind Rose of Year 2010 October based on GPV-MSM-S Mesoscale Data
(wind speed range in m/s is represented by the colour legend)

Referring to Figure 3, strong wind (12m/s to 16m/s) represented by the purple bar was blowing from the northwest (310 degrees to 340 degrees) and also from the east (90 degrees to 110 degrees). The topography northwest of turbine T2 is relatively non-complex with no presence of undulating terrain. In sharp contrast, the topography east of turbine T2 is hilly and highly complex. It could be deduced that terrain-induced turbulent wind conditions were likely related to wind blowing from the east and not from the northwest.

3. LES CFD Simulation by RIAM-COMPACT®

For the LES CFD simulation, RIAM-COMPACT®, a software developed by Dr. Takanori Uchida of Kyushu University, was employed. The LES CFD code is based on a standard Smagorinsky turbulence model. Details of the code and other validation simulation results can be found in a number of published papers [2-7].

For the topography data, 10m mesh DEM data issued by the Geospatial Information Authority of Japan (GSI) was used. CFD wind direction was set to true north at 100 degrees, the highest-occurrence frequency from the easterly direction. The CFD model constructed is shown in Figure 4 with the following details:

- Domain Size: 12.5km(x), 6.0km(y), 3.2km(z)
- Elevation: 0m(min) - 328m(max)
- Calculation Grid Points: 620(x), 300(y), 50(z)
- Total Number of Grid Points: 9.3 million
- Grid Spacing: 5m-120m(x), 5m-76m(y), 1m-211m(z)

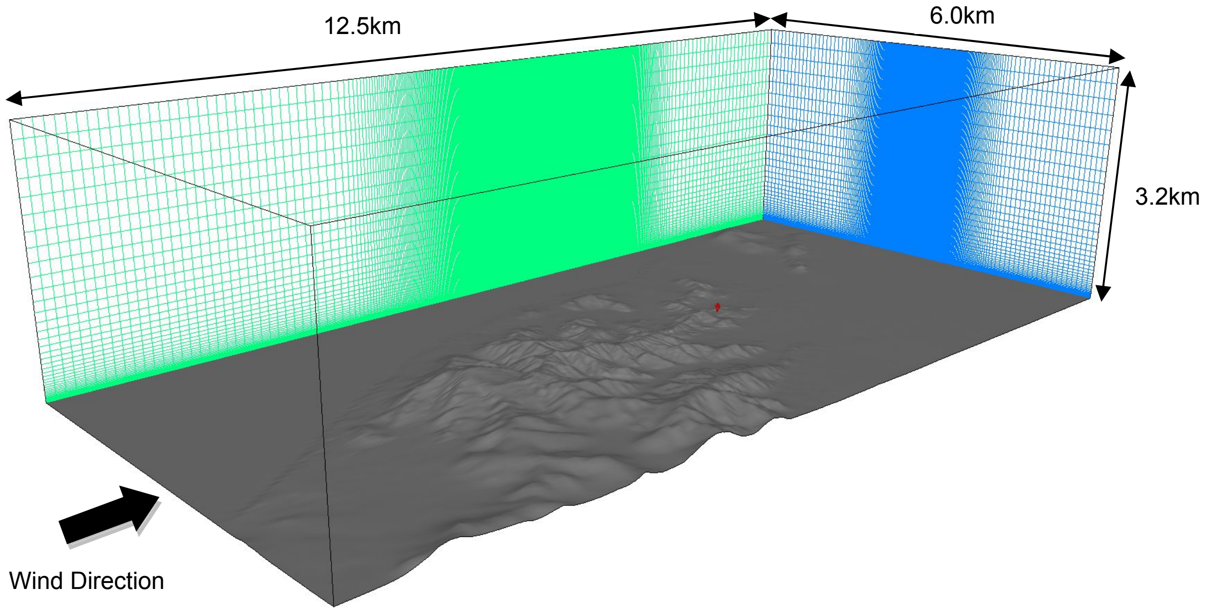

Fig.4 - LES CFD model domain and calculation mesh (Turbine T2 is shown in red colour)

To increase calculation accuracy, mesh concentration is applied around turbine T2 to a minimum of 5m in both x and y direction as shown in Fig.4. No roughness consideration is given in constructing the CFD calculation model. Atmospheric stability is set at neutral stability. After the calculation was stabilized, numerical results in the calculation domain were output for a real time of ten minutes with an interval of one second.

4. LES CFD Simulation Results

Fig.5 shows an instantaneous wind speed contour plot upstream of turbine T2, cutting vertically across the wind turbine rotor. The topography upstream approaching turbine T2 is highly undulating and as a result a number of flow separations were predicted. The largest vortex formation was predicted at a hill of elevation 328m located 4.4km upstream as indicated in Fig.5.

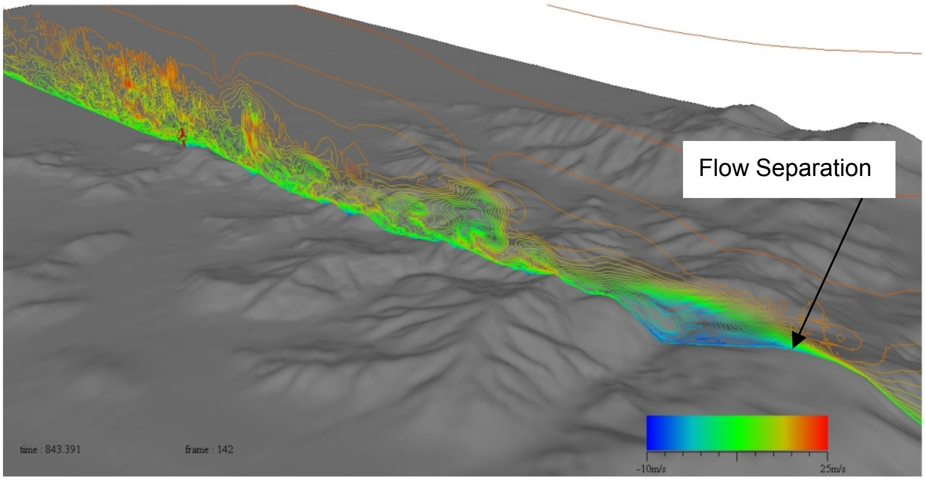

Fig.5 - Instantaneous Wind Speed Contour of 1m/s interval (turbine T2 is shown in red colour)

(click here to see animation)

The series of flow separations and onset of turbulence will affect the flow conditions approaching turbine T2. The last of the flow separations was predicted to occur at the hill located immediately east of the turbine as shown in Figure 6.

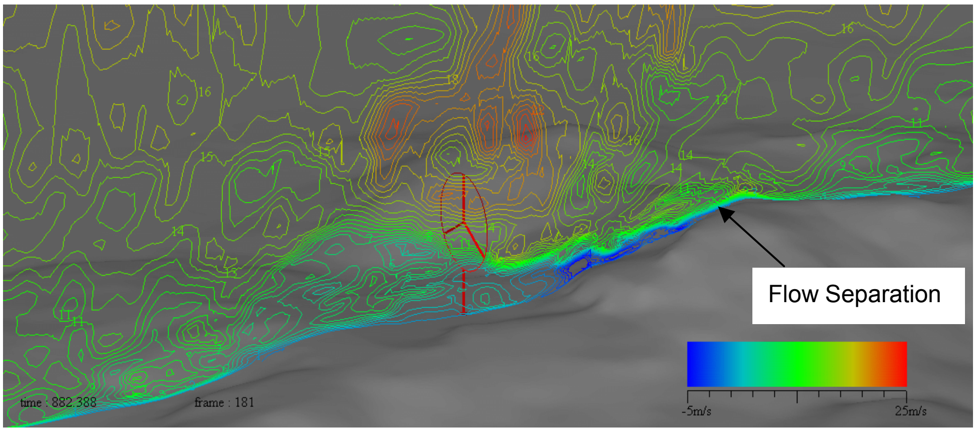

Fig.6 - Instantaneous Wind Speed Contour of 1m/s interval at turbine T2

(wind speed in m/s are given next to contour lines)

(click here to see animation)

The very high density of the wind speed contour lines in Figure 6 means a highly non-uniform flow with high shear across the rotor face. At this instantaneous moment, the wind speed difference between the top and bottom of the rotor is around 16m/s or an equivalent wind shear exponent of 1.94.

The time series of the wind speed difference vertically and horizontally across the turbine rotor is shown in Figure 7.

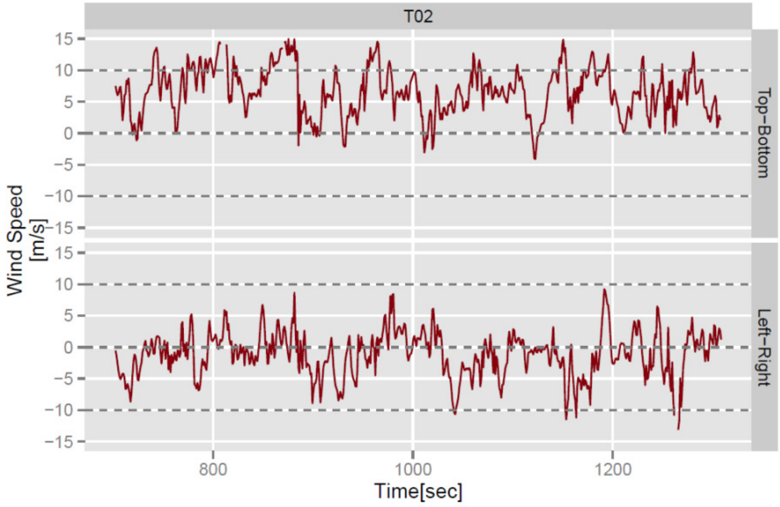

Fig.7 - Vertical (Top-Bottom) and Horizontal (Left-Right)
Wind Speed Differences across turbine rotor face

Both time series are highly fluctuating. The vertical wind speed difference lies mostly in the range of 0m/s to 15m/s, whereas the horizontal wind speed differences fluctuates around 0m/s with a minimum and maximum around -10m/s to +10m/s. The resulting vertical wind shear exponent time series is shown in Figure 8.

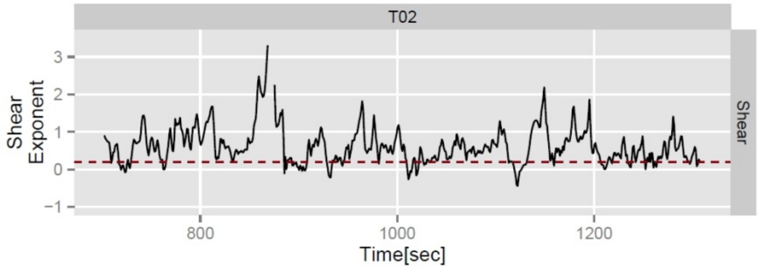

Fig.8 - Time series of vertical wind shear exponent
(red dotted line is IEC Standard average shear value of 0.2)

The maximum calculated wind shear exponent exceeds 3.0 with an average value of 0.67, far exceeding the IEC standard average shear value of 0.2. The calculated ten-minute average turbulence intensity (TI) is 0.27, which also exceeds the IEC TI by a large margin of 0.07. The mean values are summarized in Table 1.

	Average	Exceeding IEC Standard
Wind Speed [m/s]	11.88	-
Wind Shear Exponent	0.67	YES
Turbulence Intensity	0.27	YES
Inflow Angle [degrees]	-5.6	-

Table 1 - Average values of Wind Speed, Wind Shear Exponent, Turbulence Intensity and Inflow Angle

Wind direction across the rotor face was also suggested to highly fluctuate as shown in Figure 9. Wind direction at hub level centre ranges from 29.3 degrees to 148.5 degrees, translating to a deviation of -70.7 degrees to +48.5 degrees.

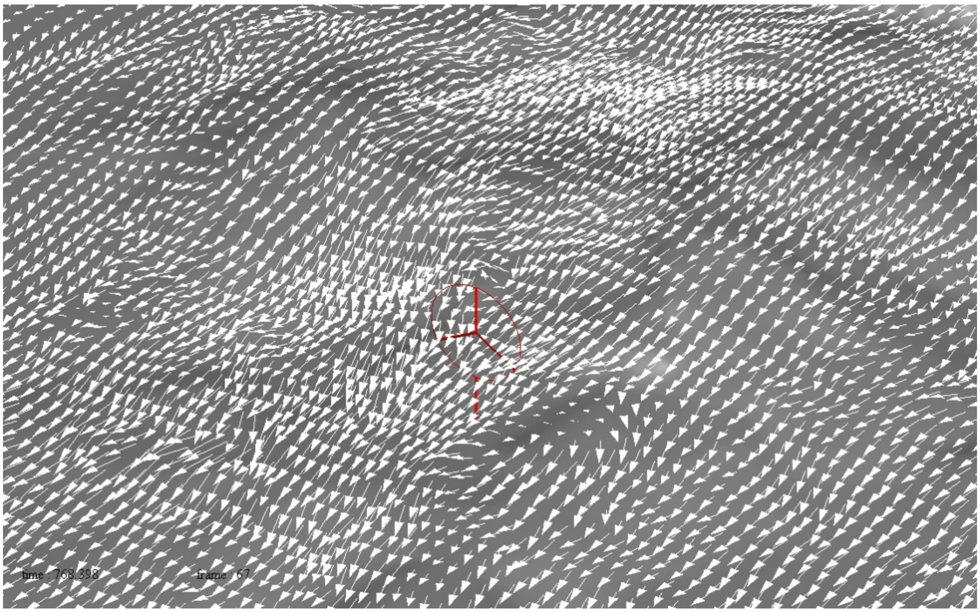

Fig.9 - Instantaneous Vector Plot - Wind Direction fluctuation at hub height level at turbine T2

(click here to see animation)

5. Comparison with IEC Extreme Wind Models

A number of extreme wind models are defined in IEC Standard 61400-1. These extreme models are related to wind turbine design, and turbine components like yaw gears or yaw motors are required to satisfy these extreme conditions. The LES CFD simulation provides transient time series data which enables comparison with extreme wind models.

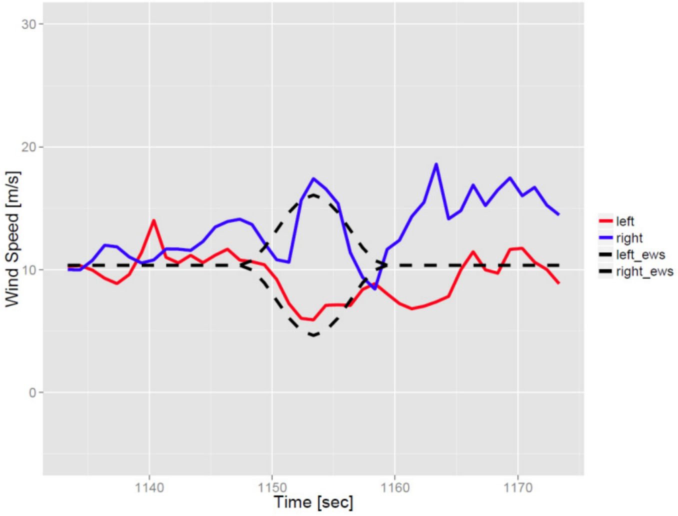

Fig.10 - Comparison with Horizontal Extreme Wind Shear (EWS)

Wind speed time series at rotor right and left positions hub at height level are compared with the IEC Extreme Wind Shear (EWS) model. As shown in Figure 10, the wind speed amplitude and rate of change exceed the EWS model.

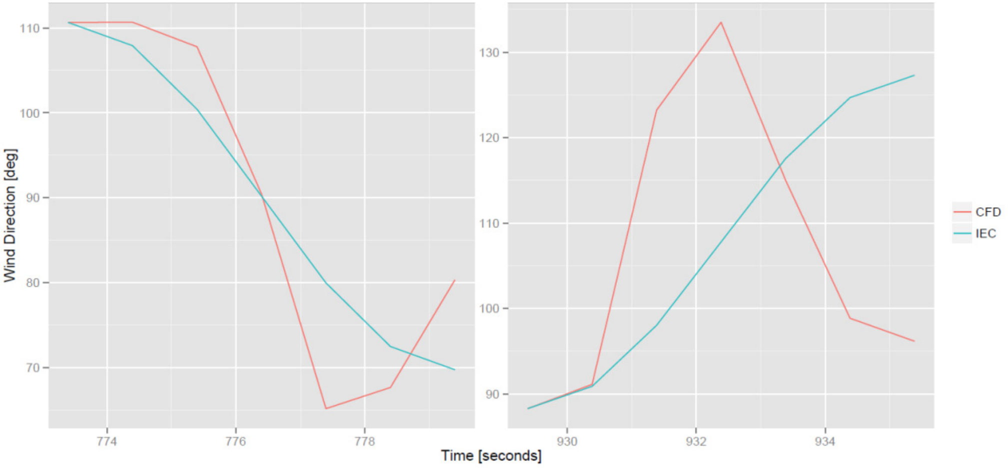

Fig.11 - Comparison with Extreme Direction Change (EDC)

The wind direction time series at centre hub height level position is compared with the IEC Extreme Direction Change (EDC) model. Both events in Figure 11 show a change in direction exceeding 40 degrees occurs in less than 3 seconds, exceeding the EDC model.

6. Conclusions

In the present paper, flow simulation was carried out for a turbine which has experienced high-frequency yaw-related component failures. LES CFD codes from software RIAM-COMPACT® were employed. The simulation suggested a series of flow separations and onset of turbulence upstream, and as a result significant turbulence is seen at the turbine position. The calculated ten-minute average shear and turbulence intensity exceeds the IEC standard values. Transient time series data was compared with two IEC extreme wind models (Extreme Wind Shear and Extreme Direction Change). It was found that the transient wind speed and direction fluctuations also exceeds the wind conditions of the extreme models. It can be concluded that the cause of yaw component failure is closely related to the terrain-induced turbulence as predicted by the LES CFD simulation results.

References

[1] T.Uchida, Y.Ohya, Diagnois of Airflow Characteristic in Wind Farm - Case of the Atsumi Wind Farm - (in Japanese with English Abstract), Technical Report of JWEA 2011, Vol.35, No.3, pp.14, 2011

[2] T.Uchida, Y.Ohya, Large-eddy simulation of turbulent airflow over complex terrain, J. Wind Eng. Ind. Aerodyn. 91, pp.219–229, 2003

[3] T.Uchida, Reproducibility of Complex Turbulent Flow Using Commercially-Available CFD Software- Report 1: For the Case of a Three-Dimensional Isolated-Hill With Steep Slopes - Reports of Research Institute for Applied Mechanics, Kyushu University, No.150, pp.47-59, 2016

[4] T.Uchida, Reproducibility of Complex Turbulent Flow Using Commercially-Available CFD Software - Report 2: For the Case of a Two-Dimensional Ridge With Steep Slopes - Reports of Research Institute for Applied Mechanics, Kyushu University, No.150, pp.60-70, 2016

[5] T.Uchida, Reproducibility of Complex Turbulent Flow Using Commercially-Available CFD Software- Report 3: For the Case of a Three-dimensional Cube - Reports of Research Institute for Applied Mechanics, Kyushu University, No.150,pp.71-83,2016

[6] T.Uchida, F.Watanabe, S.Mikami, Analysis of the Airflow Field around a Steep, Three-dimensional Isolated Hill with Commercially Available CFD Software (2nd report in Japanese), Reports of Research Institute for Applied Mechanics, Kyushu University, No.149, pp.72-77, 2015

[7] T.Uchida, F.Watanabe, S.Mikami, Analysis of the Airflow Field around a Steep, Three-dimensional Isolated Hill with Commercially Available CFD Software, Reports of Research Institute for Applied Mechanics, Kyushu University, No.149, pp.91-98,2015