Application of LES CFD for flow simulation of an escarpment site with complex terrain

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Abstract: One of the wind turbines at Duogu wind farm, an existing operating wind farm located in China's Yunnan province experienced vibration problems. The turbine is located on top of a very steep cliff and the topography in the turbine vicinity is of complex nature. Analysis of turbine operational data indicates the vibration problem occurred only from a particular wind direction. With RIAM-COMPACT®, a LES CFD code was used to simulate the wind flow for the identified wind direction. Simulation results predicted the presence of a small hill located upstream at the top of the cliff is causing flow separation and turbulent wind conditions characterized by a reverse flow region predicted to be present in the bottom part of the wind turbine rotor. This simulation result agrees well with the deductions made from the vibration and turbine operational data. The simulation was also carried out with RANS CFD commercial software METEODYN WT. Significant turbulence and a reverse flow pattern were not predicted and distinct differences in the shear profile at turbine location were identified between the flows simulated by the two CFD software packages.

1. Site Description& Background

Dougu windfarm is located in the city of Mengzi, Honghe prefecture, Yunnan province, China. The windfarm started operation in 2012 and it consists of 33 Mingyang wind turbines of rated capacity 1.5MW. The turbines have a hub height of 65m with rotor diameter of 82.6m. The turbines are located on top of a cliff and aligned in a north-south direction with elevation ranges from around 1850 to 2200 meters.The cliff has a height of around 600m with slopes exceeding 60 degrees in places. Aerial photos from Google Earth indicate vegetation is abundant at the bottom of the cliff but scarce along the cliff and in the vicinity of turbines.

Since the start of operations, one of the wind turbines, Turbine no.12 (T12) has experienced vibration problems. T12 has the following coordinates: latitude 23.497622 degrees and longitudes 103.442547 degrees. Wind farm operator Yunnan Huadian Dougu Wind Power Corporation (YUDWPC) suspected the vibration issue is related to wind conditions. In mid-2015, YUDWPC approached Dr. Takanori Uchida, Associate Professor of the Research Institute for Applied Mechanics, Kyushu University for simulating the wind flow around turbine T12.

2. Operation Problem

The vibration problem of turbine T12 was investigated by the operator YUDWPC and a report was issued in April 2014 [1]. Stated in the report was that high vibration datawas recorded only when the wind was blowing from the southwest. Wind direction on the ground level was observed to be in the reverse direction from that recorded by the nacelle anemometer. Analysis of the vibration dataindicates the vibration is in the Y-axis (vertical) direction. This suggests the vibration is associated with abnormal vertical wind shear across the wind turbine rotor. As shown in Fig.1, a figure extracted from the report, it was deduced that the presence of the small hill located about 150m upstream from turbine T12 was causing the onset of turbulence and reverse flow which led to the vibration recorded.

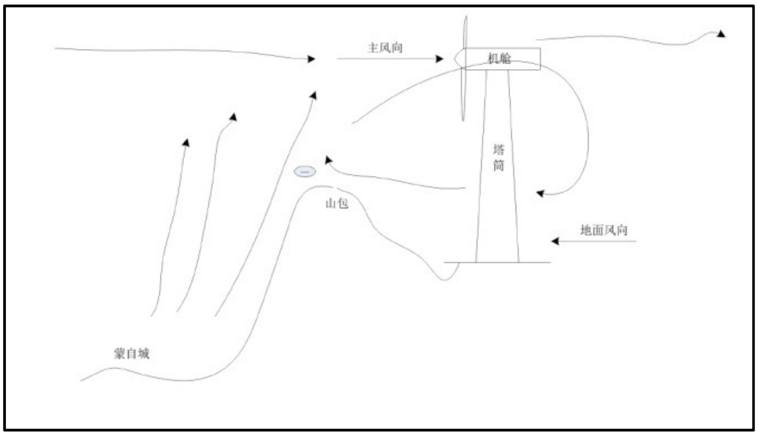

Fig.1 - Deduction made on the airflow upstream and in the vicinity of turbine T12

3. LES CFD Simulation by RIAM-COMPACT®

For LES CFD simulation, RIAM-COMPACT®, a software package developed by Kyushu University was employed. The software uses a standard Smagorinsky turbulence model and details of the code can be found in a number of published papers[2]. For the simulation, SRTM-90m data was used for elevation data. Wind direction is set to true north at 247 degreesand the CFD model constructed is shown in Fig. 2 with the following details:

- Domain Size: 14km x 13.3km x 8.3km
- Elevation: 1275m(min) - 2232m(max)
- Calculation Grid Points: 300 x 400 x 60
- Total Number of Grid Points: 7.2 million
- Grid Spacing: 8m-957m(x), 13m-72m(y), 1m-470m(z)

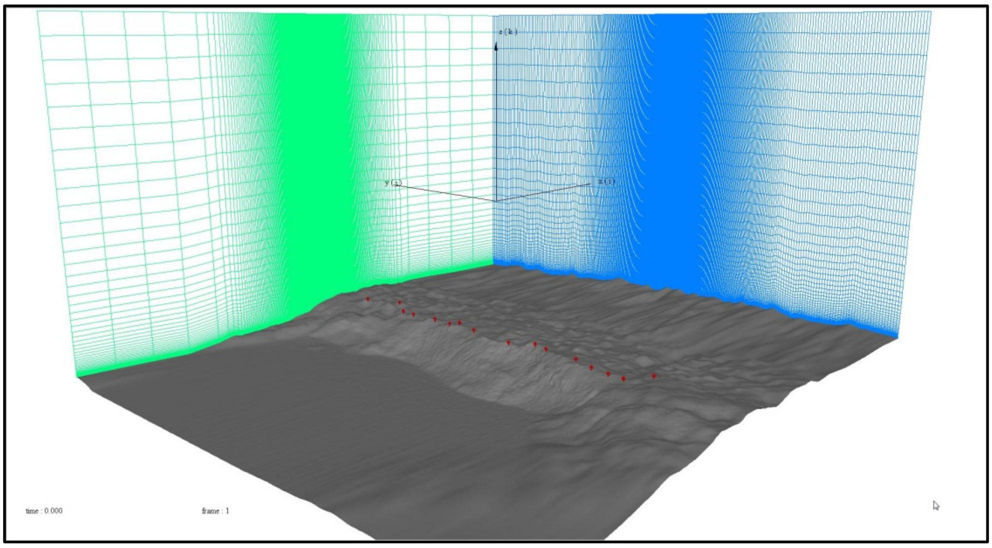

Fig.2 - LES CFD domain and calculation mesh constructed by RIAM-COMPACT®

To increase calculation accuracy, the mesh is concentrated around the turbine positions in both the x and y direction as shown in Fig.2. No roughness consideration is given in constructing the CFD calculation model. Atmospheric stability is set at neutral stability. After the calculation has been stabilized, numerical results in the calculation domain are output for a real time of ten minutes with an interval of one second.

4. LES CFD (RIAM-COMPACT) Simulation Results

Fig.3 shows an instantaneous vector plot across turbine T12. This picture clearly shows flow separation occurred at the small hill located 140m upstream from the turbine,and the onset of the formation of the recirculating vortex behind the hill. The turbulent flow extends downstream forming a reverse flow region characterized by negative values of wind speed covering the lower part of the wind turbine rotor.

The simulation results also indicate that the wind flow is relatively undisturbed above hub height level. The U component wind speed time series during the ten-minute simulation at rotor top, hub, rotor bottom and surface level (10m) positions are plotted in Fig.4.

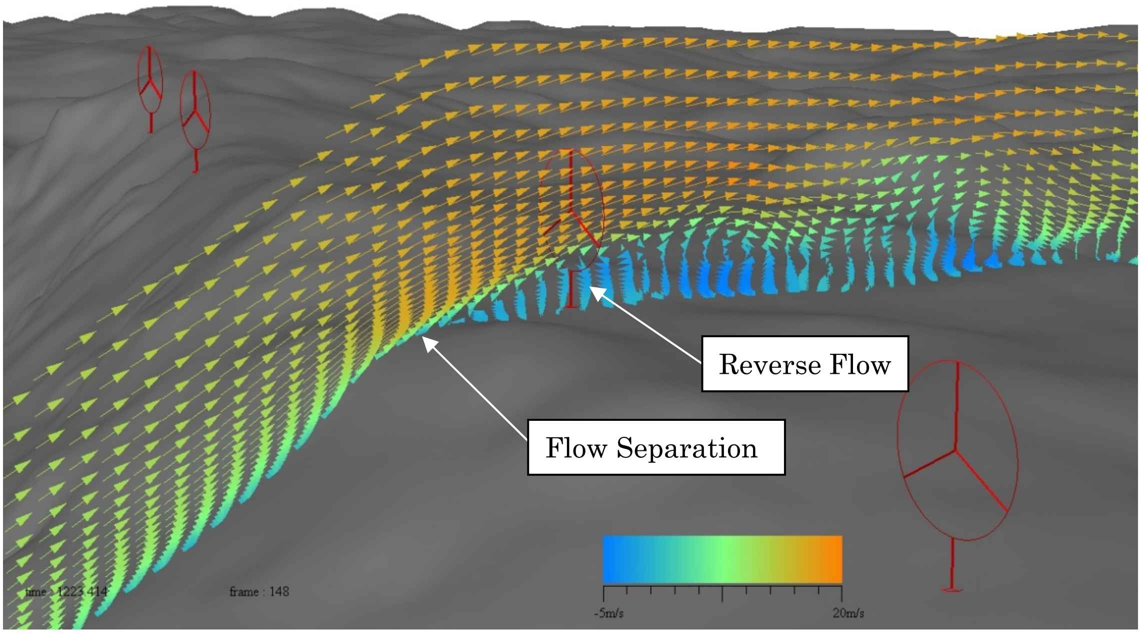

Fig.3 - Instantaneous vector plot at turbine T12

(Full animation URL link: http://www.twd-wind.com/RC/Dougu_Vector_T12.gif)

Referring to Fig.4, it is obvious that the wind speed at surface (10m) and rotor bottom is significantly lower and showing more fluctuations than the wind speed at the hub and top part of the rotor.

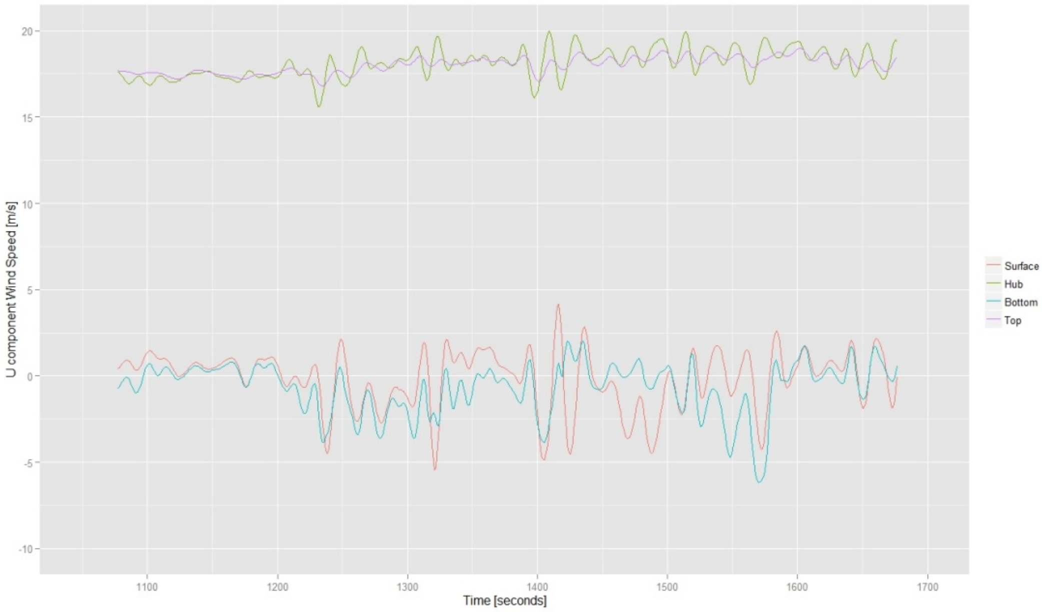

Fig.4 - Time Series of U componentwind speed at rotor top, hub, rotor bottom and ground surface level at turbine T12

Wind speed varies between 15 to 20m/s at hub height and rotor top whereas for rotor bottom wind speed fluctuates between minus 6.2m/s to 2m/s. Minus wind speed indicates the wind is flowing in reverse direction. During the ten-minute simulation, minus values account for 62% of the total data at rotor bottom.

When the rotor bottom wind speed is at its minimum of minus 6.2m/s the wind speed at rotor top is at 18.1m/s, hence a very large absolute wind speed difference of 24.3m/s. Excluding the minus wind speed data, the wind speed difference across the rotor face (between rotor top and rotor bottom) has a maximum value of 18.7m/s and an average of 17.4m/s. The maximum wind shear exponent is calculated to be 5.8 with an average value of 2.5, far exceeding the IEC standard average shear value of 0.2.

The average, minimum and maximum values of the U component wind speed at turbine T12 are shown in Fig.5. The average values represent the average shear profile seen at turbine T12. Referring to that, the reverse flow region results in a negative or very low wind speed from ground surface level to the rotor bottom of around 25m. Wind speed increases gradually from 25m and starts leveling off at around 50m.

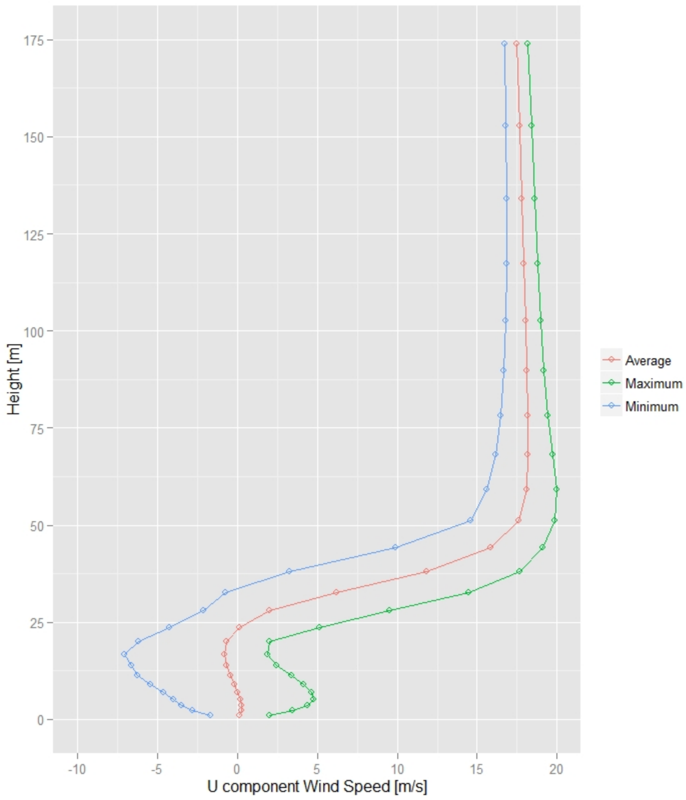

Fig.5 - Vertical Shear Profile predicted by RIAM-COMAPCT®

Average, minimum and maximum of U component wind speed variation with height

5. RANS CFD Simulation by METEODYN WT

A number of comparison studies have been published between the RIAM-COMPACT® and other RANS and LES-based software [3,4,5,6,7]. In general, these comparison studies show that LES-based software performs better than RANS based in terms of flow reproducibility[6,7]. In this study, commercial software METEODYN WT (turbulence model: k-L RANS) was employed and its results were compared with the results calculated by the RIAM-COMAPCT®.

The calculation parameters are shown in Table 1. The calculation domain is a radius of 10km for the x-y direction with turbine T12 as center; z direction has a maximum of 200m.

Wind Direction is set at 247 degrees with minimum vertical and horizontal resolution set to 5m and 2m respectively. Atmospheric stability is set to neutral. The calculation was completed smoothly with computation convergence recoded at 99.3%.

Direction	247 degrees
Thermal stability class	2
Smoothing - Whole domain	1
Forest model	Robust model
Minimum horizontal resolution	5m
Minimum vertical resolution	2m
Horizontal expansion coefficient	1.1
Vertical expansion coefficient	1.2
Mesh	2,346,300 points (225 x 237 x 44)
Maximum iteration number	25
Convergence	99.3%

Table 1 - Calculation parameters for METEODYN's calculation

6. RANS CFD (METEODYN WT) Simulation Results

METEODYN's calculation output includes the speed-up factor from height 20m to 200m at an interval of 20m at turbine T12. These values are shown in Table 2. The speed-up factor is the wind speed ratio at the given height referencing the wind speed at height 10m. The speed-up factor therefore resembles the vertical shear profile. Assuming a wind speed of 9.5m/s at 10m height, wind speed at different heights can be calculated based on the speed-up factor and the results are shown in Table 2.

Height [m]	Speed-up factor	Wind Speed [m/s]
20	1.850	17.58
40	1.952	18.54
60	2.002	19.02
80	2.013	19.12
100	2.008	19.08
120	1.998	18.98
140	1.987	18.88
160	1.977	18.78
180	1.968	18.70
200	1.959	18.61

Table 2 - Speed-up factor at turbine T12 and calculated wind speed

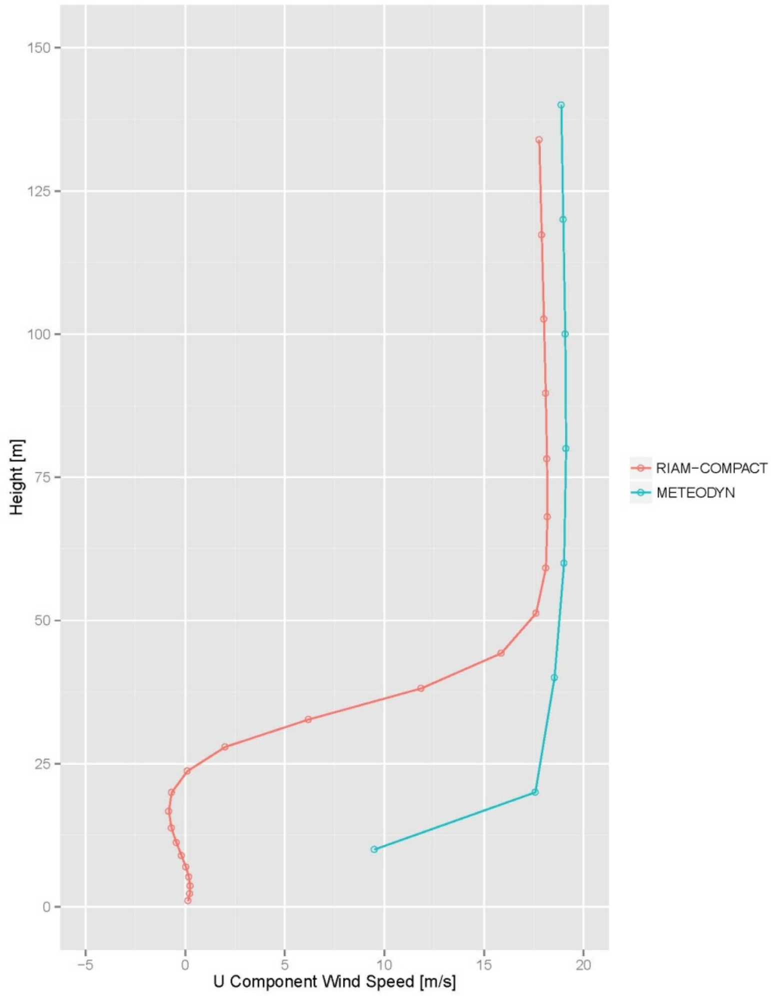

Fig.6 - Comparison of vertical shear profile between the wind flows simulated by RIAM-COMPACT® and METEODYN

The wind speed figures in Table 2 are plotted in Fig.6 and the resulting wind shear profile is compared with the shear profile (average values) predicted by RIAM-COMPACT®. It can be seen from Fig.6 that the shapes of the two profiles are similar from 50m upwards but distinctively different below 50m. METEODYN does not seem to predict any flow separation and reverse flow region and therefore there is no significant wind speed reduction between 25m and 50m, and also no negative wind speed values below 25m as predicted by RIAM-COMPACT®. Numerical comparison results are shown in Table 3.

	RIAM-COMPACT	METEODYN
Wind Speed near rotor bottom [m/s at height]	0.11 [23.7m]	17.58 [20m]
Wind Speed near rotor top [m/s at height]	18.0 [102.6m]	19.08 [100m]
Wind Speed Difference [m/s]	17.9	1.5
Average Shear Exponent	3.5	0.025
Average Shear Exponent exceeding IEC Standard	YES	NO

Table 3 -Numerical comparison of vertical shear profile between RIAM-COMPACT® and METEODYN

Referring to Table 3, across the wind turbine rotor face, RIAM-COMPACT predicted a large wind speed difference with a shear exponent exceeding the IEC standard value of 0.2 by a large margin. In sharp contrast, METEODYN predicted a small wind speed difference with a shear exponent of 0.025 which is significantly below the IEC standard.

7. Conclusions

In the present paper, a turbine which has vibration problems was simulated using the commercial software METEODYN WT as well as RIAM-COMPACT®. It was deduced from the vibration and turbine operation data that a possible reverse flow region near the rotor bottom was the direct cause of the vibration. Simulation results from LES-based code RIAM-COMPACT® predicts a flow separation upstream and a reverse flow region at the rotor bottom. Simulation results from RANS-based software METEODYN produced a very different shear profile which suggests the reverse flow and the associated flow separation were not predicted.

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