Application of CFD for Turbulence Related Operational Risks Assessment of Wind Turbines in Complex Terrain

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Abstract: As the amount of relatively flat area available for wind power reduces, the ability to predict turbulence risks for complex terrain sites is becoming an important issue. Here the cause of the repeated failure of yaw systems for an existing operational turbine was investigated with a combination of SCADA data analysis and LES-based CFD. The total number of yaw gear and yaw motor failures for the affected turbine (T7) reached over thirty for the past seven years, significantly higher than the rest of the turbines at the same site. SCADA data shows that T7 records a significantly high data count of turbulence intensity (TI) exceeding the IEC Class A. TI vs wind speed graphs in 10 degrees wind direction sector bin reveal the highest turbulence intensity falls in the W to NW wind direction sector. Upon close inspection of the terrain, highly complex undulating terrain is present in the WNW direction from T7. The effect of this terrain was investigated by applying LES-based CFD. The computational grid was set at 401(x)×631(y)×61(z), a total of 15,434,891 grid points. The flow direction was set at 290 degrees with inflow wind speed at 7m/s. The CFD results show vortex generation and flow separation occurred in the upstream, which translates into highly fluctuating wind speed at hub level and also large vertical and horizontal wind shear across the rotor face of T7. These highly fluctuating wind conditions explain qualitatively the high TI data and also the frequent yaw system failures.

1. Introduction

In recent years, rapid growths have been seen in the introduction of wind energy across the world. And in Japan, the government has recently passed a fixed tariff law for supporting the further spread of renewable energies. However, a number of pressing technical problems are facing the industry, namely, noise, lightning and turbulence. Along with lightning, turbulence is particularly an issued because gusty wind cause damage to wind turbines, resulting in lower availability and high repair costs. Therefore turbulence can have a major adverse impact on the project's economic performance. To be more specific, the turbulence referred to here is terrain-induced turbulence, caused by the highly complex terrain found abundantly in the mountainous areas of Japan. Of course not all turbines located in such terrain suffer from severe damage. The presence of the mountainous terrain also helps to bring a higher wind speed and hence a better wind resource. As the amount of relatively flat area available for wind power reduces, the capability to deal with or to maximize the potential of these highly complex terrain sites is becoming an important issue for the sustainable growth of wind energy not just in Japan but also worldwide.

A comprehensive wind measurement campaign will be the best way to confirm and quantify the level of turbulence. However, for highly complex terrain sites, the wind condition across the site can be extremely variable. Completely different wind conditions can exist between locations separated by a relatively short distance, say in less than a few hundred meters. Installing met masts at all turbine positions may be feasible but is a costly uneconomical option. In order to minimize the risk of unforeseeable turbine damage, reliable prediction of the wind flow becomes absolutely crucial and essential when considering wind turbine positions and suitable turbine models for any new complex terrain sites.

In this study, Computation Fluid Dynamics or CFD, based on the LES (Large Eddy Simulation) turbulence model is utilized to reproduce the complex flow pattern and to examine the risk associated with turbulent wind conditions. The wind power industry has now accepted that linear models such as WAsP fail to predict wind speed accurately for complex terrain sites. And in many studies, not just in the field of wind power, the unsteady and non-linear LES turbulence model is shown to be able to predict the dynamics of the turbulent structure with high accuracy. With recent rapid advances in high performance computing, turbulent flow simulation based on the LES turbulence model is now a reality. A number of technical papers describing the application of the LES model in wind power have been published. RIAM-COMPACT®, a LES based commercial CFD code, is selected for wind flow simulation at a highly complex terrain site where one of the turbines has suffered from frequent damage of yaw gear and yaw motor. Turbine operational data (SCADA Data) is analyzed for turbulence quantification. Finally, a comparison of the CFD simulation result between the frequently damaged turbine and another turbine will be made.

2. Wind Farm and Yaw Failures

The wind farm in consideration is Kihoku wind farm located in Kyushu, Japan. The wind farm consists of 16 wind turbines roughly aligned on a north-south ridge with highly complex terrain in the surroundings. Figure 1 shows the turbine locations and the terrain. Operation began on February 2004. All 16 wind turbines are of IEC Class 1A. Turbine model is Siemens 1.3MW with rotor diameter of 62m and hub height of 60m.

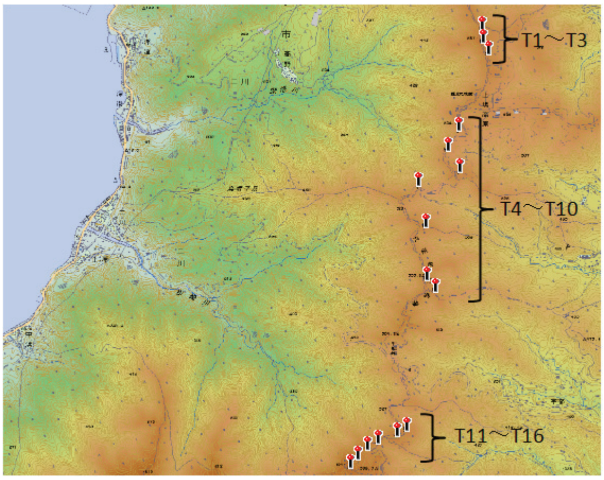

Figure 1 - Wind farm Layout
Locations of Turbine 1 (T1) to Turbine 16 (T16)

The total number of yaw gear and yaw motor failures since the start of operation is shown in Figure 2 for each of the turbines. The high frequency for Turbine T7 clearly stands out. Figure 3 shows photos of the typical damage conditions – large cracks and broken shaft. The locations of these damages are shown in the engineering drawing of the yaw gear/motor next to the photos. It is highly likely that these damages are due to excessive loads acting on the yaw system. As the loads or the force exerted on the wind turbine comes from the wind, this suggests the terrain surrounding turbine position T7 is creating excessive turbulence which leads to these failures.

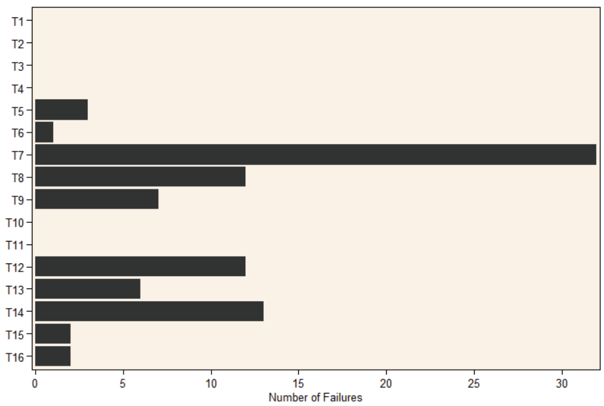

Figure 2 - Total Number of Yaw Gear and Yaw Motor Failures

3. SCADA Data Analysis

To investigate the level of turbulence at turbine T7 position, turbulence intensity (TI) calculated from SCADA data is plotted against wind speed and is shown in Figure 4 for both turbine T7 and also for turbine T5, which is located roughly 500m from T7. It can be clearly seen from Figure 4 that the level of turbulence is higher for T7 than that of T5. For T7, the average plus one standard deviation line crosses the red IEC standard class A line at 7m/s or above, whereas for T5 it stays below the IEC standard line until about 15m/s.

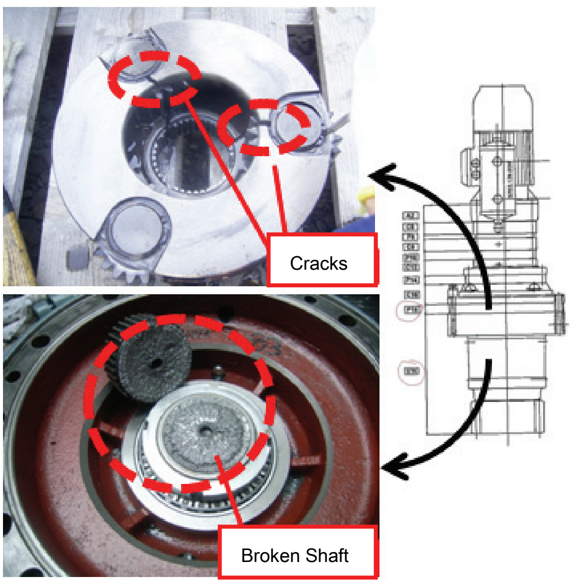

Figure 3 - Damage Condition of Yaw Components

Next the occurrence frequency of high TI is investigated. Using all 7 years of SCADA data, the total number of data points which exceed the IEC class A standard is shown in Figure 5 for the same two turbines, T7 and T5. Comparing with turbine T5, T7 is displaying a significantly higher occurrence frequency. Also in the same figure, the level of exceedance or the difference in the value of TI between the IEC and the data is categorized into three different colour bands. T7 records more data counts of high TI than T5. In fact, T7 has the highest occurrence frequency out of all 16 turbines. Therefore it is highly probable that the yaw related failures are associated with the turbulent wind conditions at T7 position.

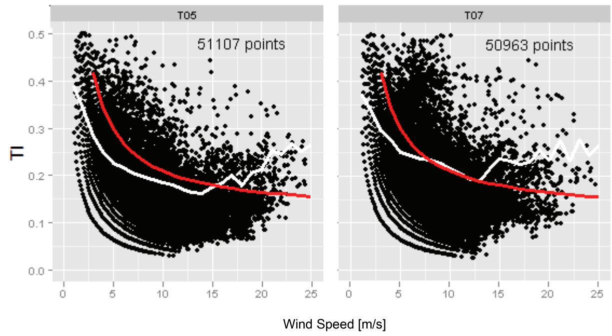

Figure 4 - Turbulence Intensity of T5 and T7
First Year of Data, Data Counts in top right of graphs
Red Line is IEC Class A Standard (2nd Edition)
White Line is Average + 1σ

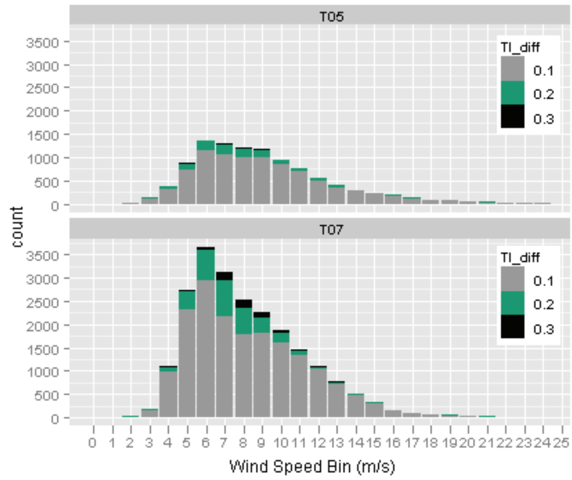

Figure 5 - Data Count of Turbulence Intensity Exceeding IEC Class A Standard (2nd Edition)

In order to determine the wind direction where turbulent wind is blowing, turbulence intensity is plotted under different wind directions sectors, W to NW (270 to 320 degrees) and ESE to SSE (110 to 160 degrees) as shown in Figure 6 and Figure 7 respectively.

Comparing the two sets of figures, high turbulence is dominantly found in the W to NW wind direction. Figure 8 reveals that undulating terrains exists in the W to NW direction from T7, and also indicted on the map is the direction of a photo taken towards T7. The photo is shown in Figure 9 in which the undulating terrain is clearly visible. It can be envisaged that flow separations and vortex formations can occur when wind is flowing through these undulating terrains.

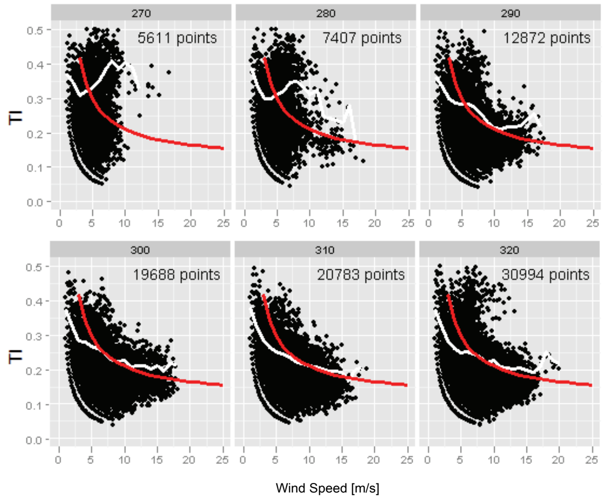

Figure 6 - Turbulence Intensity of T7 (W to NW)
Top Left: 270 degrees, Bottom Right: 320 degrees

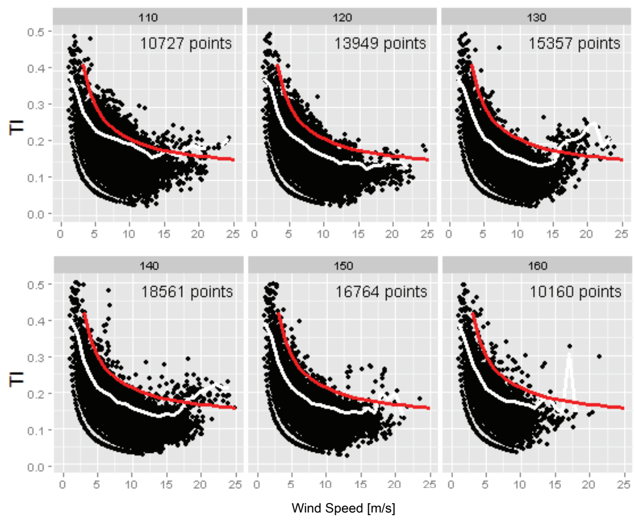

Figure 7 - Turbulence Intensity of T7 (ESE to SSE)
Top Left: 110 degrees, Bottom Right: 160 degrees

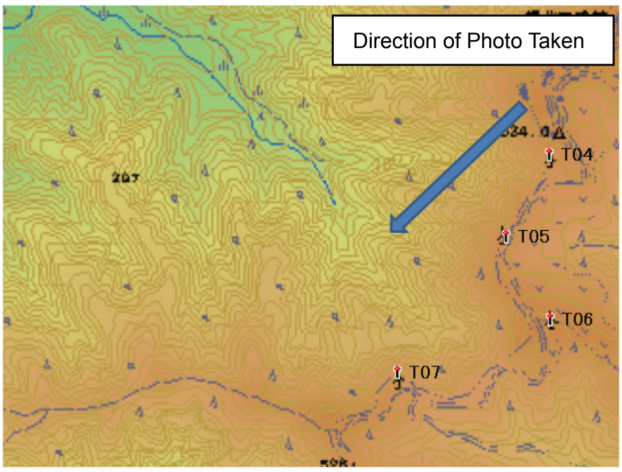

Figure 8 - Map showing terrain around T7 and arrow showing direction photo taken

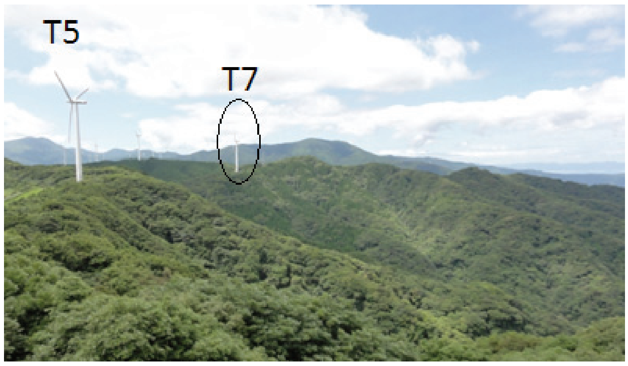

Figure 9 - Photo showing the Undulating Terrain W to NW from Turbine T7

4. CFD Analysis

To investigate the flow pattern, CFD analysis was carried out. In this study, the LES turbulence model is capable to faithfully reproduce complex flow patterns of flow separation and vortex formation. Details of the calculation method have already been described in previous publications [4] so it will not be stated here.

The CFD analysis domain is shown in Figure 10. The size of the domain: 5.6km along the flow direction (x), 6.3km perpendicular to the flow direction (y) and 3.1km in the vertical direction (z). The grid mesh along the x direction has an irregular intervals with mesh concentration applied in the vicinity of the turbine positions. Regular mesh interval is set for y direction. For vertical z direction, the mesh is concentrated near surface. Minimum mesh grid size for both x and y direction is 10m for z direction 1m. Computational grid was set at 401(x)×631(y)×61(z), a total of 15,434,891 grid points. The flow direction was set at 290 degrees with inflow wind speed at 7m/s. For other boundary conditions refer to the reference list [1-4].

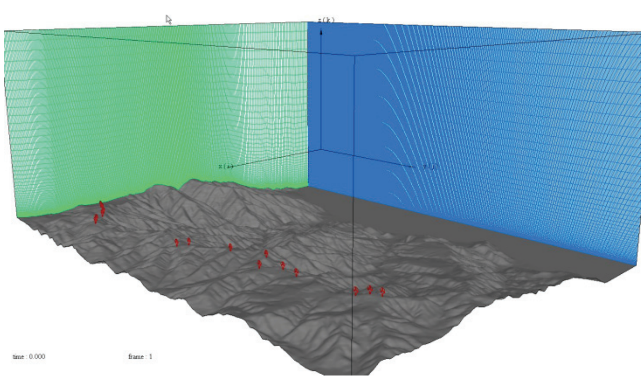

Figure 10 – Analysis Domain and the Grid Mesh

Hub height wind speed time series output from the CFD simulation is shown in Figure 11 for both turbines T5 and T7. Comparing with T5, a higher wind speed fluctuation is predicted at T7 position. Another CFD result is shown in Figure 12, an instantaneous moment of the velocity vectors on the vertical plane. Flow separation is not observed in the flow approaching T5. But for T7, it can be clearly observed due to the presence of the undulating terrain.

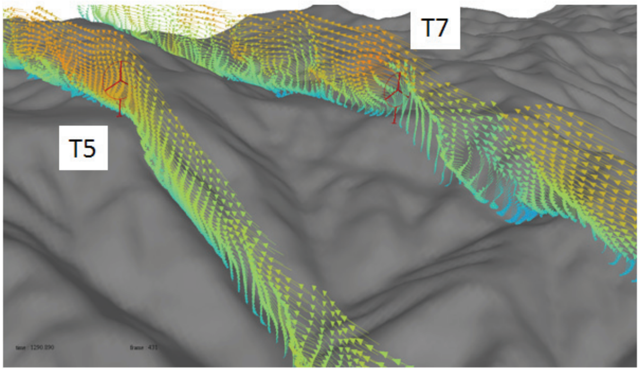

Figure 12 - Velocity Vector on vertical plane (instantaneous)

Also can be seen the vortex generated by the flow separation and the vortices travelling through the rotor of turbine T7. And on the horizontal plane, 7m/s of wind speed difference across the rotor is seen at T7 whereas for T5 there is virtually no difference, as shown in Figure 13. These horizontal and vertical wind speed differences translate into highly non-uniform and impulsive loads which were transferred from the blade to the yaw system. It is highly probable that the yaw system is not designed to cope with such non-uniform loads, and therefore the yaw system failed as a result.

5. Conclusion

The relationship between the frequencies of the yaw related failures and turbulence intensity was investigated. It was found that turbine T7, which records the highest number of yaw failures, also records the highest count of turbulence intensity exceeding the IEC standard. CFD was carried out to reproduce the flow pattern. Flow separation and vortex generation can be clearly seen in the upstream of turbine T7 position. And the wind flow at turbine T7 position is of a turbulent nature - highly fluctuating wind speed at hub height together with large vertical and horizontal wind shear. The temporal and spatial variation of wind speeds is believed to be the cause of the numerous yaw failures experienced since operation started in early 2004.

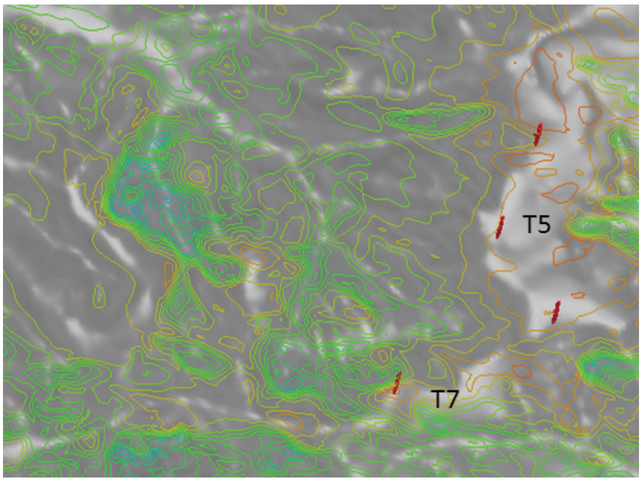

Figure 13 – Wind Speed Contours (1m/s interval) at hub height level (instantaneous)

Even under the same wind speed and same wind direction, variations are seen in turbulence intensity due to the influence of climatic factors. Although CFD is not capable of perfectly reproducing the flow in nature, it is here shown to be able to predict the very different flow patterns between the two turbines in consideration. The CFD findings are also in good agreement qualitatively with the turbulence intensity analysis. In summary, it can be concluded that for highly complex terrain sites, LES based CFD is a powerful and essential tool for both reliable simulation

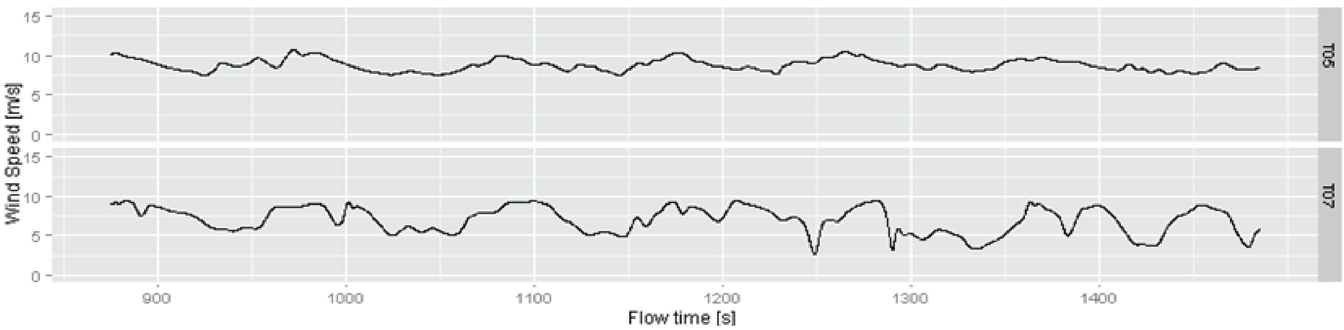

Figure 11 – Time Series of Wind Speed at Hub height for T5 and T7

of turbulent flow, and also for assessing the operational risk associated with turbulent wind conditions for existing operational wind farms and also for new wind farms under planning.

References

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