Experimentelle und numerische Untersuchung von Turbulenz Auswirkungen auf die Leistung und Wirbelschleppen von Windenergieanlagen

Experimental and Computational Investigation of Turbulence Effect on Performance and Wake of Wind Turbines

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Key words; Environment, Experiments, Measurements, Wind turbine, Turbulence, wake, Blade Element Momentum (BEM), Lifting Line Theory (LLT)

Abstract

In wind turbine operation, it is exposed to various wind speeds and turbulence intensities. To maximize the performance of wind turbine under different wind condition, understandings of turbulence effect on wind turbine performance as well as on wake are required. In this study, two approaches to investigate the problem have been done. The experimental setup for generation and measurement of turbulence with specially designed laboratory scale wind turbine are made in a wind tunnel at the Institute of Fluid Mechanics, FAU Erlangen. The computational simulations are performed for NREL Phase VI wind turbine by using QBlade, which enables to simulate the aerodynamic and wake performance of wind turbines under range of turbulent flows. The different scales of turbulent flow are generated by installing different grids on the wind tunnel. The corresponding Power Coefficients (Cp) of a laboratory scale wind turbine are measured and compared at different Turbulent Intensities (TI). The results showed that power coefficients increases as the turbulence increased in the range of TI from 5% to 15%. The calculation results of time based Cp values and wake generation are performed with codes that implemented the Lifting Line Theory (LLT). Experimental and simulation results showed the same effect of turbulence on wind turbine performance and wake; high turbulence improves the power coefficient. Experimental investigations revealed penetrations of turbulent eddies within the rotor plane (between the blades) and the wake region, which energizes the wake and enhance the mixing with the surrounding, and hence, fast retrieving of flow that help in increasing the total power of a wind farm. Furthermore, the visualized wakes from both methods are compared.

Introduction

Understanding the effect of turbulent flow on wind turbine performance and wake is necessary for optimizing the wind turbine and wind farm performance which are exposed to various wind conditions. Investigating the impact of turbulence in reality is expensive in time and cost, hence, experimental work with laboratory scale supported with computational study of real scale are required for satisfactory understanding for turbulence effects. Downscaling of wind turbine involves power coefficient decrements, specially designed wind turbine with higher efficiency is proper for being investigated under generated turbulent flow by wind tunnels [1] [6]. Among many methods to generate the turbulent flow inside the wind tunnel [2], static grids with various opening sizes are used in this study.

As the method to overcome the scale limitation of experimental work, computational methods for generating turbulence and wind turbine simulation are used with several codes. The most well-proven and robust one is based on Blade Element Method (BEM) while CFD codes are also used frequently for wind turbine simulation. However, to compensate the accuracy of BEM and computation costs of CFD codes, codes based on LLT was used in this study [3]. The limits of Blade Element Momentum method, which is built upon many assumptions like rotor disc and inflow with perpendicular direction to

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the rotor, are supplemented by LLT. Due to its calculation of the induction from the wake is not confined by an annular averaged rotor disc model, precise calculation at every time step in the computational domain can be possible. Moreover, the vortex elements from previous time steps are contained in the history of flow in LLT model. This enables the simulation of transient propagation of geometries of wakes with increased accuracy. Although it compensates the aforementioned annular averaged induction computed from the momentum balance of BEM and wake simulations, its computational costs are much smaller than CFD simulation. The validity of LLT simulation was proven with comparison to the other methods such as BEM, panel codes and experimental data in reference [4] [5].

Experimental Setup

1. Turbulence generation

To conduct the experimental investigation of turbulent flow on wind turbine operation, different turbulence scales are generated inside the wind tunnel with laboratory scale wind turbine. The Closed-loop wind tunnel of Institute of Fluid Mechanics in FAU, Erlangen is used with different grids installation on its inflow section. The open test section size is width = 1.87m, height = 1.4m and length = 2m, Figure 1. The fine and coarse grids with the edge length of Mf = 8mm and Mc = 40mm, Figure 2, are installed.

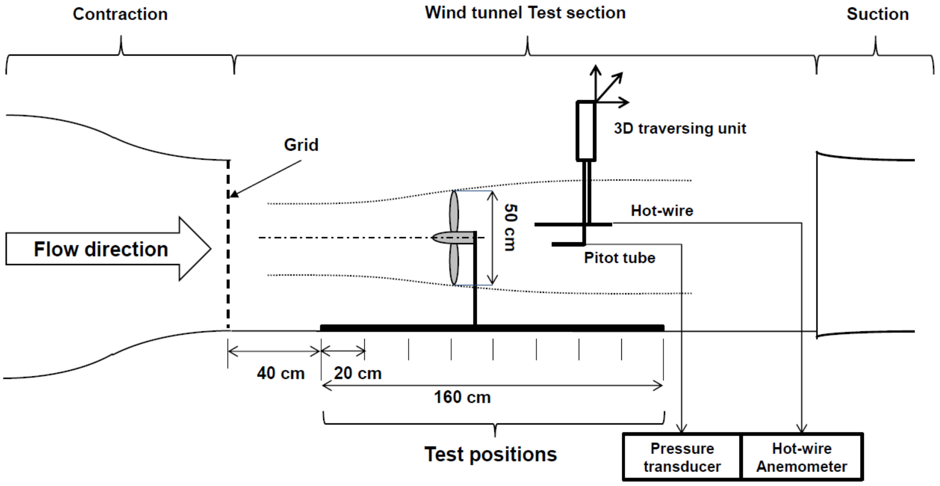


Figure 1. Wind tunnel at Institute of Fluid Mechanics, FAU, Erlangen [7]

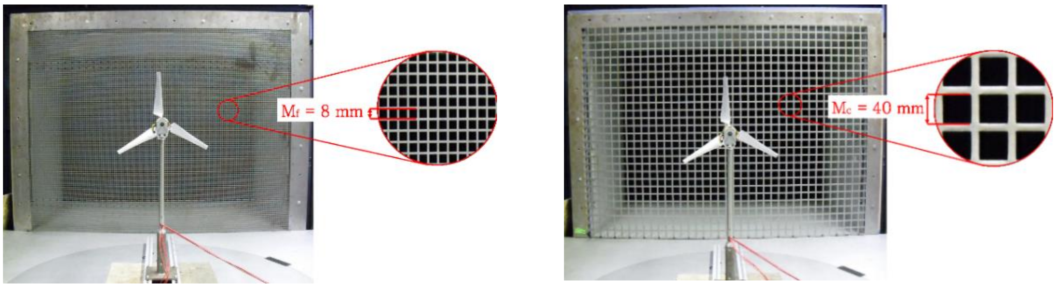


Figure 2. Different grid types on wind tunnel inflow section [7]

The turbulence scales are measured by the 3-D traverse system with traversing probes along the test section. Pitot-static tube and Hot-wire anemometry are fixed on the traversing system for velocity and turbulence measurements, respectively. Calibration of hot-wire is performed. The SETRA differential-pressure transducer connected to the Pitot-static tube. The single normal Hot-wire connected to an anemometer unit was for velocity fluctuation measurement by length 1mm , diameter 5 micrometer wire with constant temperature bridge CTA. For the credibility of the received data, the Sampling Rate (SR) was chosen as 20 *kHz* with T=120 sec which resulted in 2.4 million number of data. The turbulence scales depending on the grid types and measurement positions are illustrated in Figure 3.

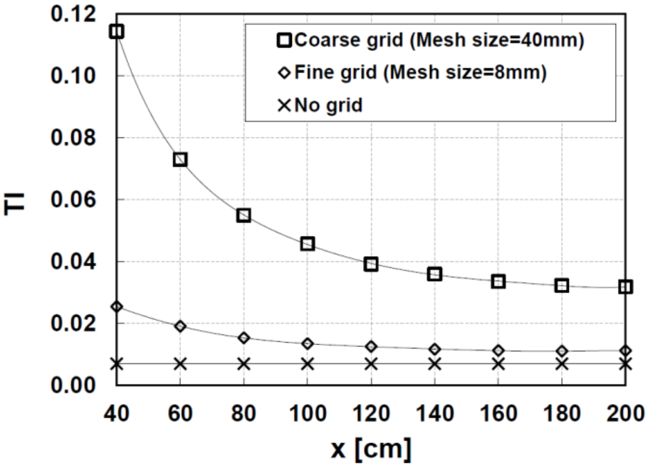


Figure 3. Turbulence Intensity generated by different grids and measurement points [7]

2. Performance measurement of the laboratory scale wind turbine

In order to keep maximum aerodynamic performance when scaling-down while investigating the effect of turbulence, wind turbine with high power coefficient is designed by implementing the Torque-Matched Aerodynamic Shape Optimization method. The generator is coupled to the rotor is considered in the optimization process. With a suitable designed controller it is possible to control the rotational speed of the wind turbine and measure the electrical and the mechanical powers [1] [7].

Computational Approach

To investigate the turbulent effect on the aerodynamic performance of wind turbine computationally, Qblade is used [8]. The Qblade is open source for wind turbine simulation. Since, the simulation can investigate larger scales of wind turbine than experiment, the NREL Phase VI Wind turbine is chosen, which is well documented for its modelling specifications and performance data.

1. Different turbulent flow

Qblade adopts the theory of Veers for generating its wind field [4]. The wind fields in the software are generated with geometry parameter as 6.0m, hub height 12m and wind parameter of mean wind speed as 13m/s, turbulence intensity 12 % etc, in accordance with the geometry and performance specification of NREL Phase VI wind turbine. The wind fields with turbulence intensity of 1, 5, 7, 10, 12% are visualized by Qblade, Figures 4, 5, 6.

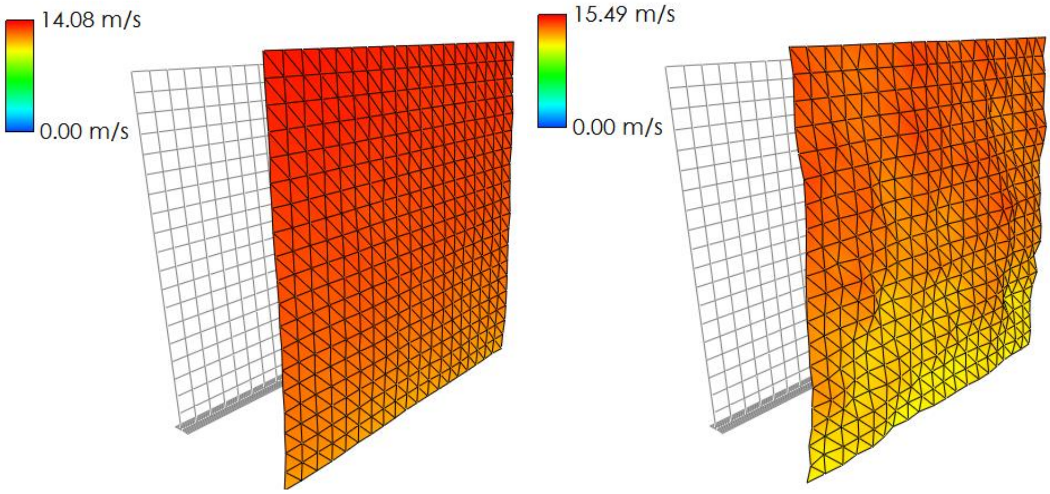


Figure 4. Wind field with Turbulence intensity 1% (left) and 5% (right).

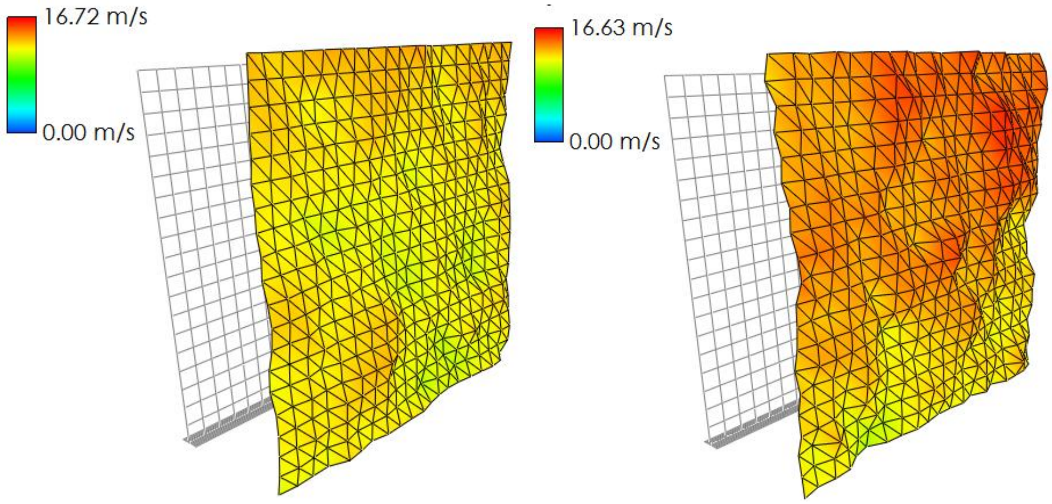


Figure 5. Wind field with Turbulence intensity 7% (left) and 10% (right).

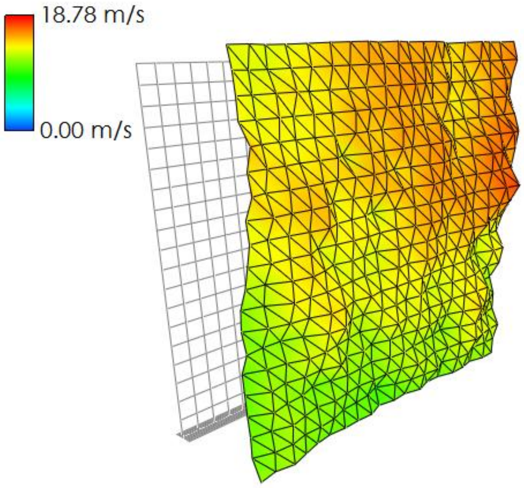


Figure 6. Wind field with Turbulence intensity 12%

2. Lifting Line theory with Vortex Wake Method

Under different flows, wind turbine performances are simulated using QLLT module in software. QLLT is based on AMSW codes, using generalized lifting line theory [5]. When the flow field around the 3D body described by a velocity vector $\vec{u}$, distribution of sources σ and vortices $\vec{\omega}$, the dimension reduction from volume integral to surface integral to line integral can be done for simplification, which is the core concept of the lifting line method. All vorticity and source singularities distributed on the figure surface and following wake can be lumped into the mean line of the figure and then it is combined into a single point at quarter chord. Corresponding combined model with a single point of lumped vorticity and sources is used for the lifting line method and the AWSM simulation module. According to the lifting line model, the bound vortices are located at the quarter position of the chord and at the trailing edge. The vortices are shed from trailing edge to downstream in AWSM flow model. Figures 7, 8.

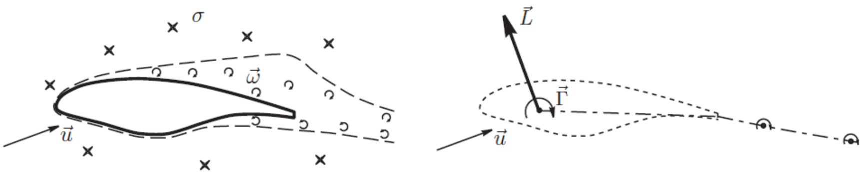


Figure 7. Dimension reduction of Lifting Line Theory [5]

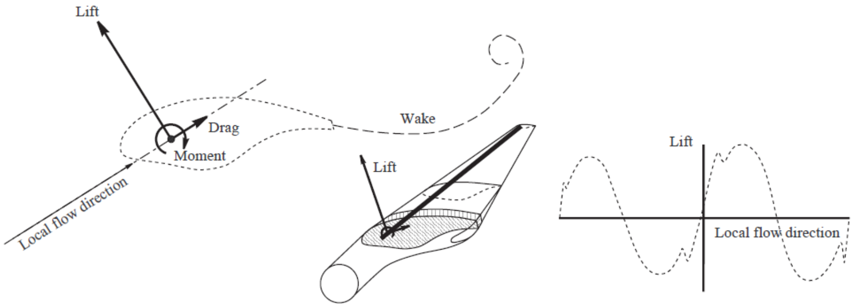


Figure 8. Generalized lifting line in LLT [5]

The vortex lattice is formed by the new vortex rings shed from the trailing edge and connected with the older vortex rings as time advances. The calculation of total external force on a body of fluid, vorticity of the fluid and vortex line element and velocity field associated with the volume, the vortex line strength deduction and method for representing the wake geometry are explained in [5] [6].

The wind fields and wind turbine performances were set to be run for 30 seconds and Tip Speed Ratio is set to be 7, which is reference for the NREL Phase VI.

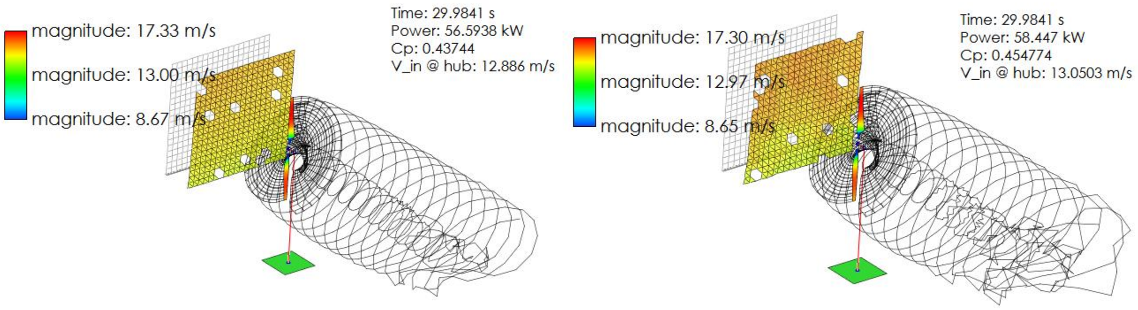


Figure 9. Turbulence, Wind turbine and Wake simulations of Qblade

Results and Discussion

1. Experimental Results

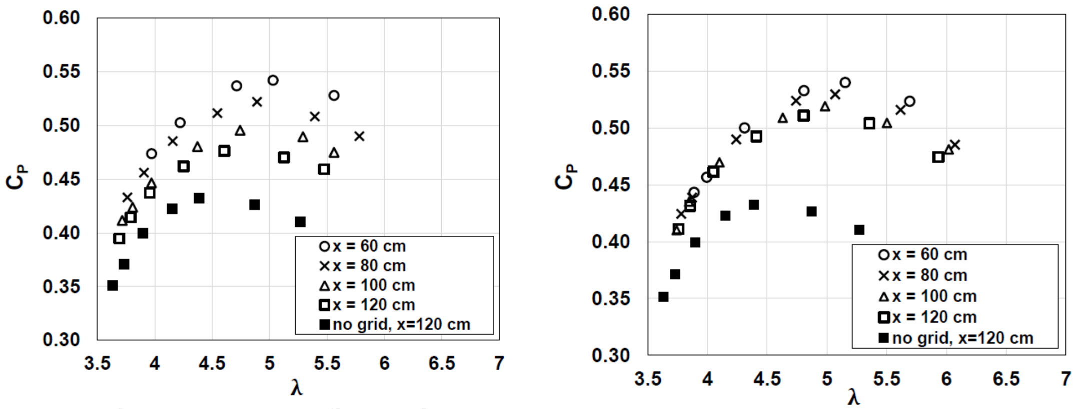
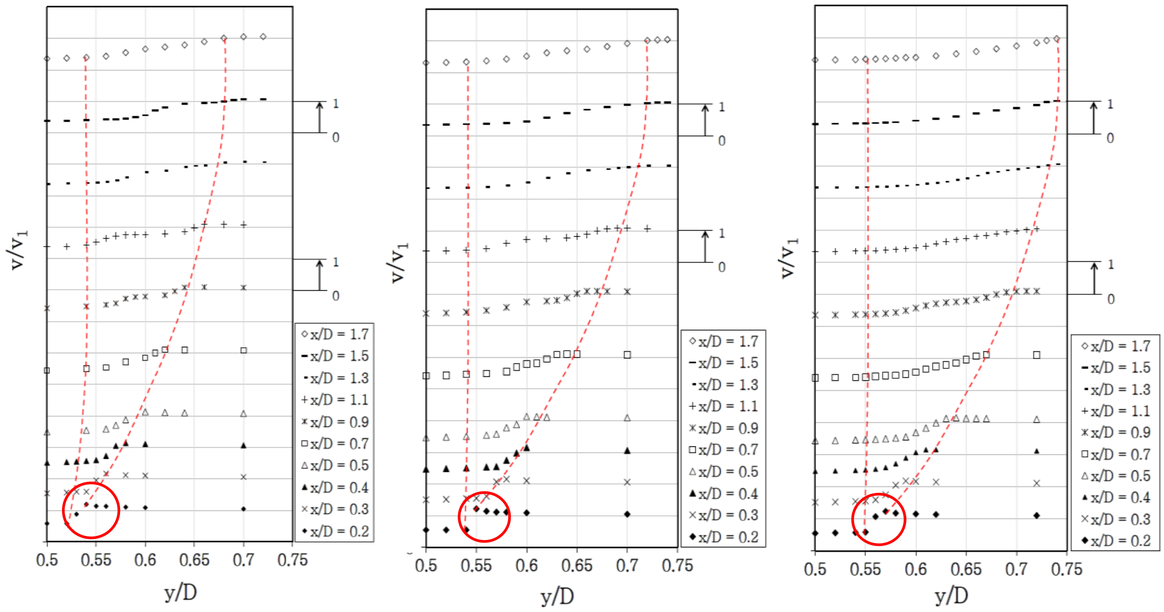


Figure 10. The C_p values at fine and coarse grids with different wind turbine position for various turbulence intensity

Figure 10, shows the power coefficients of the laboratory scale wind turbine exposed to different turbulent scales by installing the turbine at 60, 80,100,120cm distances from the grids. The nearer the distance to the grid the higher the turbulence, the higher power coefficient, and hence, higher rotational speed of the same incoming wind velocity.



No Grid

Fine Grid

Coarse Grid

Figure 11. The normalized velocity behind the turbine with different grids installed in wind tunnel when x/D is axially and y/D is radially normalized value with diameter D of wind turbine

The axial velocity distributions in the wake region over different grids show wider area with the order of no grid, find grid and coarse grid. Reduced velocities behind the wind turbine is indication of higher power extraction, Figure 11. At higher turbulent flow an increase of wake recovery at the nearest axial distance (x/D) from the rotor plane. The turbulent flow increases the interaction between wake and surrounding by adding more energy entrainment to the wake region. This means more turbulence penetrating through the turbine rotor plane.

2. Simulation Results

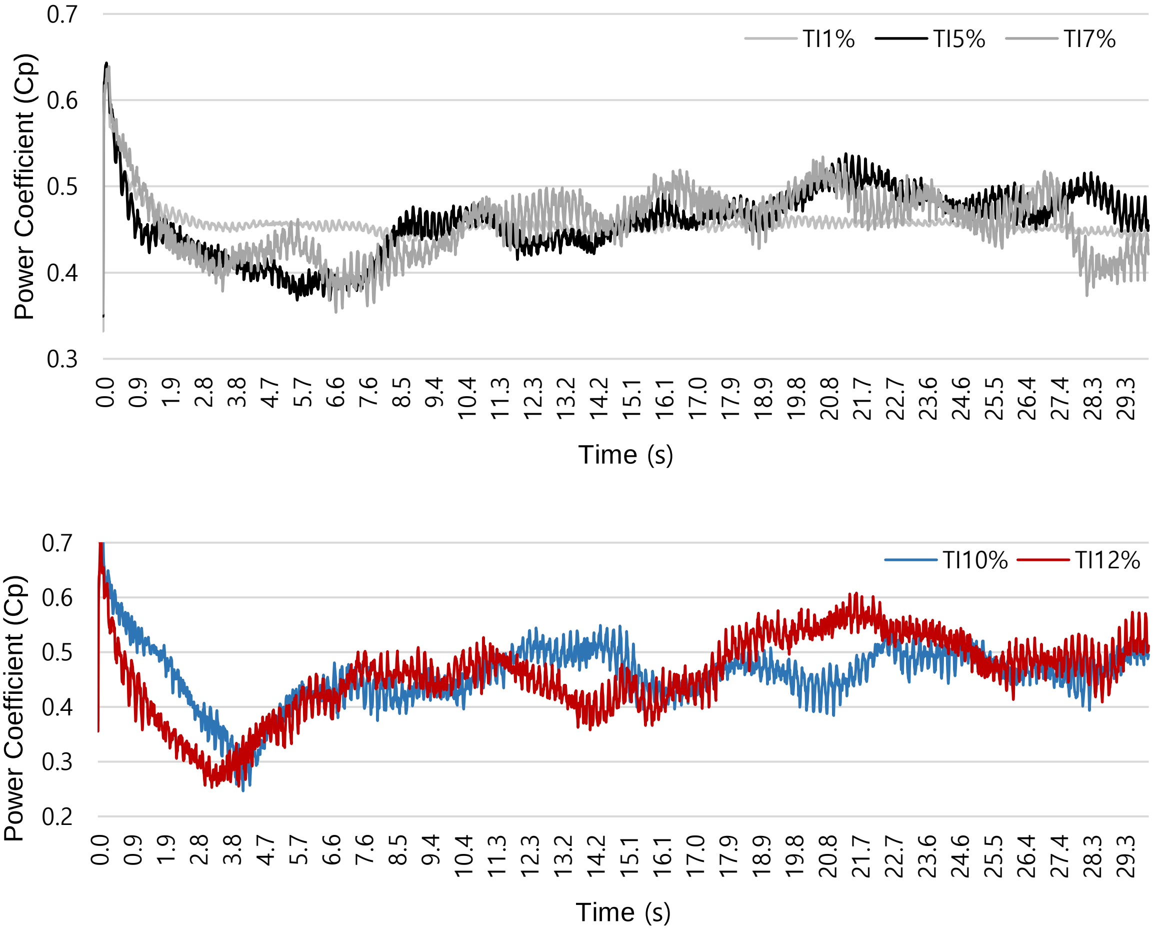


Figure 12. Power Coefficient (Cp) at different Turbulence Intensities with time domain

Power coefficients of wind turbine show an increase of fluctuations with higher maximum and lower minimum values as turbulence intensity increases. The fluctuation of power coefficients at each turbulence intensities resembles the fluctuating shape of inflow velocities, Figure 12.

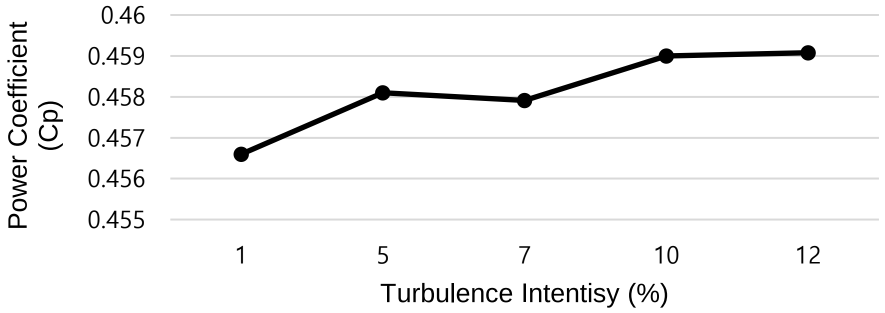


Figure 13. Averaged Power Coefficient (Cp) during 30s versus Turbulence Intensity

The Power Coefficient (Cp) at each turbulence intensities during 30s are averaged and compared to show the increasing turbulence effects on power coefficients. As turbulence scales increase, the power coefficient gets higher.

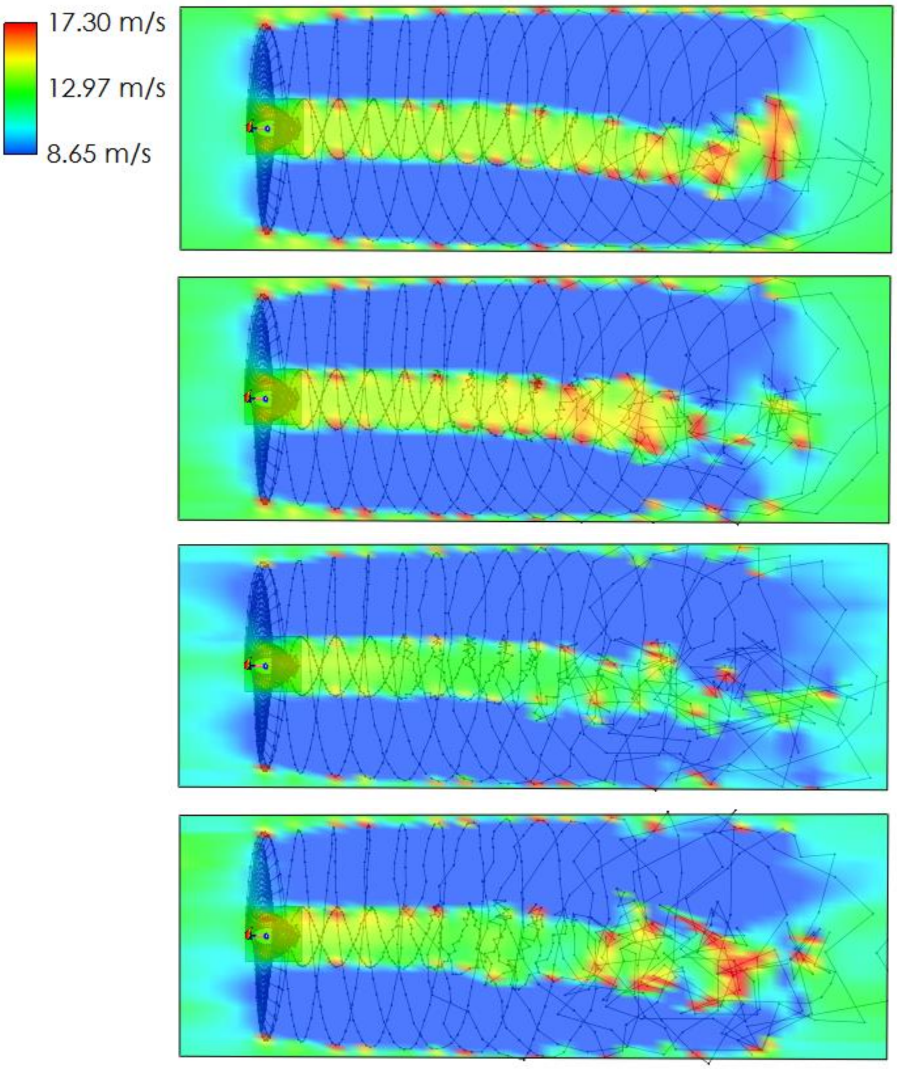


Figure 14. Velocity Cut Planes at the middle of wind turbine at different Turbulence Intensity 1, 5, 10, 12 % (From top to bottom)

The velocity cut planes with width 1diameter and length 3diameter illustrate the velocity distribution in the wakes at different turbulence scales, Figure 14. As the higher turbulent flows into the wind turbine, the rotating circles of wake are more broken with more unevenly distributed velocity at the rear part of the wake.

Conclusions

To understand how turbulent flow influences the wind turbine performance and wake, experimental and computational investigations are done. Both approaches show increase of power coefficients at higher turbulent flow. Higher rotational speed that is associated with increase of power coefficient is found from experimental work. Computational investigations prove the same outcomes of the experiments; higher power coefficient distributions at high turbulent flow for a constant rotational speed. The increased fluctuation of velocity indicates the penetration of turbulence in near wake region is found by experiment; where more broken wakes at rear part of wakes are found from computational work to indicate the turbulent flow effects. The wake is proven to have more energy and turbulence by both approaches.

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