WIND TURBINE AERODYNAMIC ANALYSIS IN WAKE FLOW

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ABSTRACT

Large wind farm has been developed for amount of power supply by green energy resources. However, power production in the wind farm is not as much as its expectation because of the effects of turbine wakes. In the wake region, the life of turbine system is reduced by unsteady dynamic loading distribution induced by velocity fluctuations and aerodynamic power is less than 60% of original turbine performance due to the momentum losses. [1] Thus, there are many activities to minimize the aerodynamic power losses in the wind farm. One of the most important parts is to predict accurately wind velocity profile in the wake region. Therefore, we have developed the model for the prediction of velocity profile in the far wakes. The wake model based on boundary layer equation is applicable in both uniform and non-uniform velocity distribution. The calculated velocity profile in the wake region is used for the analysis of turbine performance as an input. We have used both unsteady blade element momentum theory and vortex lattice method for the aerodynamic analysis. Velocity recovery rate can be defined as recovered velocity to reduced velocity. The value of the velocity recovery rate is higher when turbulent intensity is higher in the same distance from the upstream turbine. The aerodynamic power has higher value in the condition of higher turbulent intensity in the far wakes due to the rapid velocity recovery.

KEYWORDS

Wind farm, Far wake, Wind profile, Atmospheric stability, Velocity recovery rate

1. INTRODUCTION

Projects on the construction of large wind farm have been developed for the need of a great amount of energy supply by wind. Unlike onshore, since offshore wind farm has little the side effect such as a tip speed limitation, noise regulations and various visual effects, its popularity has been increasing. The extra-large offshore wind farm has been also arisen such as Horns Rev(160MW, 2003) and Nysted(165.6MW, 2004). However, the power produced from large wind farm is lower than its expectation because the power reduction occurs due to momentum loss in wake region generated from an upstream turbine. There are not only the power losses due to the velocity deficit but also the reduction of system life because of unsteady dynamic loading distributions which cause continuous fatigue loading. [1]

Far wake models for prediction of velocity profile and turbulence characteristics have been developed. There are simple methods such as roughness length model which supposes the turbine acting as the ground roughness and Jensen's model which assumes that the wake is expanding with a linear magnitude. Ainslie developed simple and accurate wake model based on axisymmetric boundary layer equation and Crespo suggested UPMWAKE which solves 3D turbulent boundary layer with k-ε turbulence model. [2] UPMWAKE has advantage of accurate calculation for turbulent characteristics; however, it has the difficulty of a use in the stage of farm layout design since it needs much of computation time. Eddy viscosity model developed by Ainslie, on the other hand, needs less computation cost. Besides, it shows good accurate results for the velocity profile in the wake. Therefore, we have integrated the numerical models for a prediction of farm efficiency and carried out the analysis of aerodynamic performance of the turbine in the wake with EVM and BEMT or VLM. Atmospheric stability theory is also applied for an inflow velocity with a shear. We also derive a parameter, velocity recovery rate, whose value is helpful in farm layout design.

2. NUMERICAL METHODS

There are three stages in order to predict the turbine performance in far wakes. At first, blade element momentum theory (BEMT) or vortex lattice method (VLM) is used. With the results of the performance of the turbine, a velocity profile can be obtained with the far wake model. The profile at specific position behind the upstream turbine is used as an inflow velocity to the downstream turbine. The aerodynamic analysis model, in the last stage, is used again.

BEMT is simple and it is widely using as an engineering model because it employs simple one dimensional momentum equation and blade element theory. Few computation cost is most advantage part; however, when an axial induction factor is exceed the range of 0.4, which break the one dimensional momentum disk assumption and a state of the flow begins to start the turbulent wake state from the windmill state, Glauert's empirical formula is used for the correction of thrust coefficient.[3] The other of the aerodynamic analysis tool is wind turbine flow, aeroacoustic, and structure analysis (WINFAS) developed by Aeroacoustic noise control laboratory in Seoul national university. WINFAS is the unsteady vortex lattice methods and especially designed to correct the effective angle of attack and circulation distribution in the stalled and separated flow. [4] These aerodynamic tools give the information on thrust coefficient and the velocity on the rotor plane so that those are necessary input variables to EVM.

The governing equation of Ainslie's far wake model called eddy viscosity model (EVM) is based on axisymmetric boundary equation which is as following,

$$U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}=\frac{\varepsilon}{r}\left(\frac{\partial U}{\partial r}+\frac{\partial^2 U}{\partial r^2}\right) \quad (1)$$

$$\varepsilon = FK_1 b(U_0-U_c)+K_m \quad (2)$$

ε represents eddy viscosity which is modeled by the velocity scale, (U_0-U_c), and the length scale, wake width(b). Filter function is represented by F whose value is 1 after the downstream distance is over the 5.5 D. Km is the eddy diffusivity of the momentum in atmospheric neutral state. [5]

Finite differential equation can be derived by Crank-Nicolson method and which is following.

$$\begin{aligned} &k(h\varepsilon - rhv_{i,j})u_{i+1,j-1} + 4r(h^2u_{i,j} + k\varepsilon)u_{i+1,j} + k(rhv_{i,j} - 2r\varepsilon - h\varepsilon)u_{i+1,j+1} \\ &= k(rhv_{i,j} - h\varepsilon + 2r\varepsilon)u_{i,j-1} + 4r(h^2u_{i,j} - k\varepsilon)u_{i,j} + k(-rhv_{i,j} + h\varepsilon + 2r\varepsilon)u_{i,j+1} \end{aligned} \quad (3)$$

The equation (3) is tri-diagonal matrix type, $[A]_m+[B]_m+[C]_m=[R]_m$, which is simply solved by Thomas algorithm. Symmetric condition at the centerline, a hub location, and free stream velocity condition at the outer of wake are used as the boundary conditions. Upper side and lower side boundary conditions are differently applied in non-uniform inflow velocity condition.

Wind speed is not uniformly distributed with height. Temperature varies frequently due to the convection in the atmospheric boundary layer so that wind speed variations occur. Monin-Obukhov similarity theory divides the atmospheric conditions into a stable, an unstable, and a neutral state. Temperature and velocity distributions are used as following equation (4) and (5).

$$\overline{u(z)} = \frac{u_*}{\kappa}\left[\ln\frac{z}{z_0} - \psi_w\right] \quad (4)$$

$$\overline{\theta(z)} = \theta_0\frac{\theta_*}{\kappa}\left[\ln\frac{z}{z_0} - \psi_t\right] \quad (5)$$

Friction velocity is represented by u_* and von Karman constant is usually κ=0.41. Ψ_w and Ψ_t are the variables from Businger-Dyer relations. [6]

3. RESULTS

3MW turbine performance in the region of far wakes is analyzed with BEMT and VLM previously mentioned. Uniform velocity at hub height and wind shear made with the atmospheric stability theory are used. Wake velocity profiles at the downstream behind the turbine are obtained and Fig.1 shows those distributions.

Those wind shear profiles are from the state of unstable atmosphere with 8.5m/s at the hub height. r/D=0 refers to the hub height. Except for a black line, the results of Fig.1 are coming of governing equation with Gaussian velocity profile. [5] In common result from the numerical analysis on the wind turbine aerodynamic, a velocity deficit near the region of the hub is less compared to the surrounding flow. Since the numerical models cannot consider the nacelle effects to the velocity deficit, the assumption of Gaussian profile in the far wakes is more reasonable. A magnitude of the velocity is rapidly increasing when the wake goes to much far distance from the upstream turbine. The velocity of the flow in the rotor region is recovered by the interaction with the external flow and eddies in the wakes. [7] Fig.2 shows velocity distributions on the rotor plane at 7D downstream behind the turbine. Inflow velocity on the top of plane is quite recovered because of the outer flow's boundary condition.

The Fig.3 shows shaft torque variation with uniform wind speed for 3MW turbine in the region of far wakes with different turbine space. 'D' means the turbine diameter and each line is the result at the distance of N times the diameter. The shaft torque loss of the turbine at 3D is 48.1% to the upstream turbine, baseline 3MW turbine, due to the momentum losses. On the other hand, the turbine at 7D has 31.0% torque loss compared to the baseline turbine. This is the reason the velocity is recovered by the interaction of eddies with outer flow.

The results of the Fig.4 are qualitative comparison with the measurements at Horns Rev and the results of various numerical models. The normalized power is calculated by BEMT and the flow velocity in the wakes is predicted by using EVM. The geometry of the case is that all turbines are aligned with main wind direction and each distance between the turbines is 7D.

The other models predict continuously reduced power; however, the measurements and the present prediction have almost uniform power level after the fourth turbine. The thrust coefficient at the upstream turbine affects the downstream turbine performance since the wake profiles are governed by the thrust force, the ambient turbulent intensity and the velocity on the rotor plane.

The results previously shown demonstrate that the turbine space is the most dominant variable to the farm efficiency. However, determining the turbine space in the middle of the layout design procedure is tediously time-consuming work. Hence, the use of a velocity recovery rate as a meaningful performance parameter rather than the direct use of geometric distance might be more helpful in the farm layout design. The velocity recovery rate can be defined as following.

$$R_v \equiv \frac{\mathit{Recovered}\ \text{velocity}}{\mathit{Reduced}\ \text{velocity}} = \frac{U_{w_x} - U_{w_i}}{U_\infty - U_{w_i}} \tag{6}$$

U_∞ is a free stream velocity and U_{wi} represents an assumed initial wake velocity at 2D reference height. The velocity at arbitrary downstream location is U_{wx}.

Fig.5 shows the velocity recovery rate with various ambient turbulent intensity values. Rv is higher with the increasing ambient TI value even the same distance from the upstream turbine. Since the flow with higher TI has more kinetic energy than that of the lower TI, the recovered velocity from the interaction between the eddies in the wakes and the outer flow is higher.

The normalized power shown in the Fig.6 is linearly increasing with the higher Rv as expected. There are also that the higher power can be obtained in the turbine with higher ambient TI. This is because of that initial wake velocity at 2D reference location has a higher value when the ambient TI level is higher.

4. CONCLUSIONS

Analysis of the wind turbine in far wakes has been carried out by numerical methods. Aerodynamic performance is obtained by using blade element momentum theory and vortex lattice method. Velocity field behind the region of the fully developed wake flow is calculated by the wake model based on axisymmetric boundary layer equation with eddy viscosity turbulence model. In the case of the condition of the wind shear, the boundary conditions are differently applied. Wind profile with a shear can be determined by using Monin-Obukhov similarity theory.

Power losses are reduced when the turbine space is increasing as expected and the results can be guaranteed that the methods in this study give a reasonable prediction throughout the qualitative comparison with Horns Rev measurement and the various numerical results. In addition, the velocity recovery rate is suggested as a parameter to reduce the computation cost during the optimization design on the wind farm. The result shows that the turbine performance can be changed even under the same velocity recovery rate because of the ambient turbulent intensity.

ACKNOWLEDGEMENTS

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FIGURES

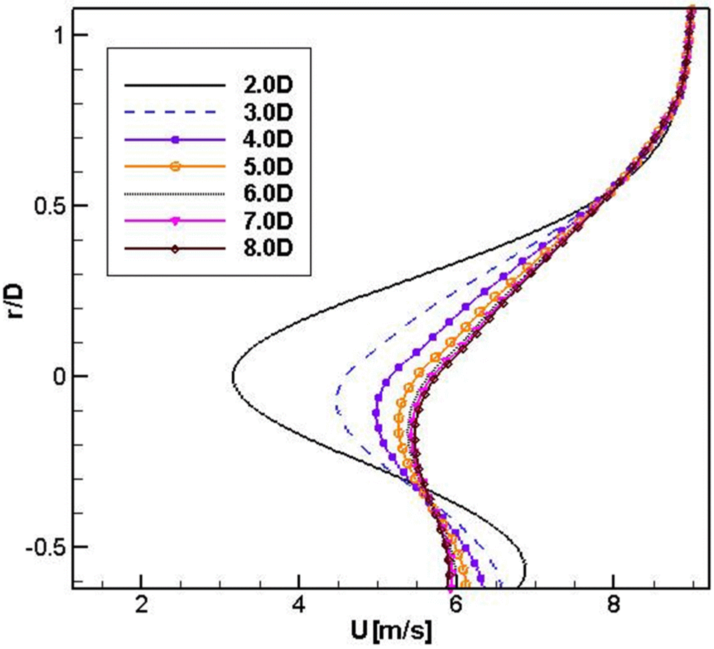

Fig. 1 Velocity profiles at each downstream distance

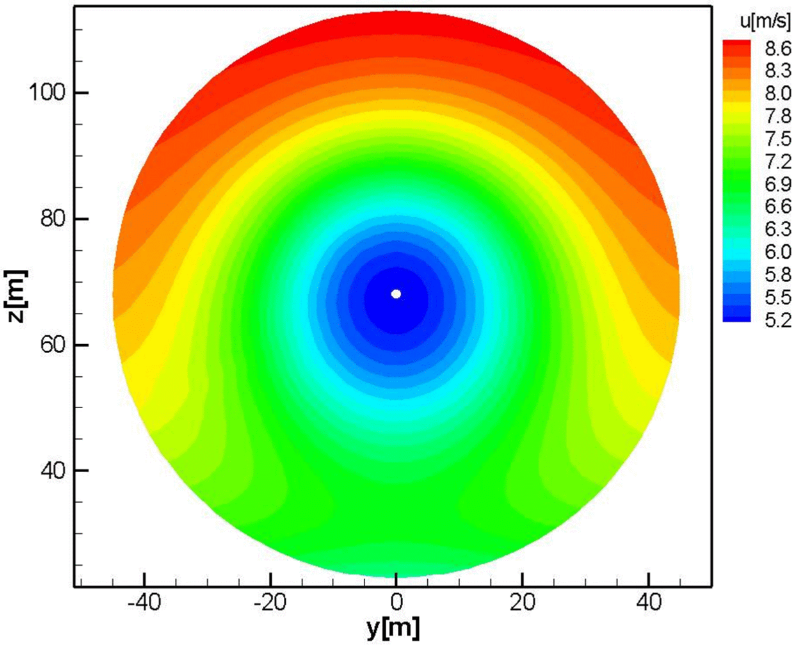

Fig. 2 Velocity profiles on the rotor plane at 7D downstream

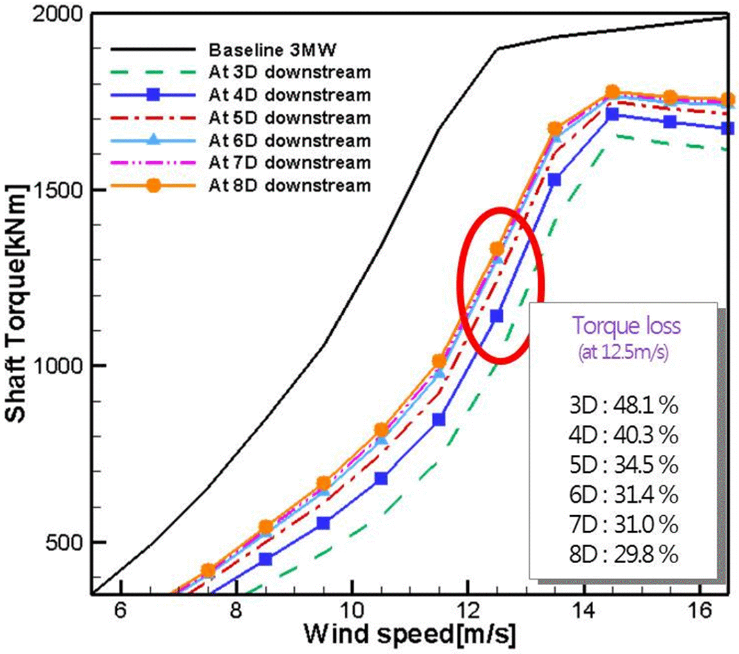

Fig. 3 Shaft torque variation with wind speed at each downstream turbine

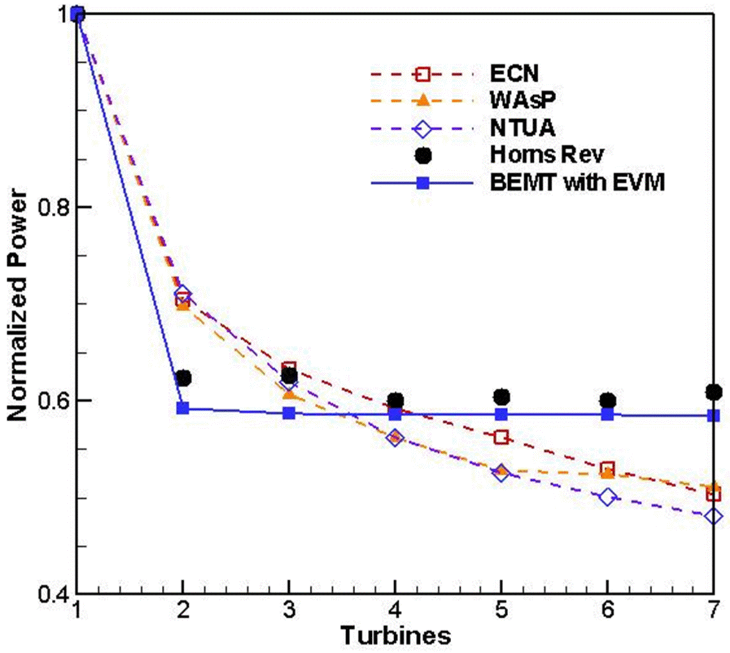

Fig. 4 Normalized power comparison in the exactly aligned turbines

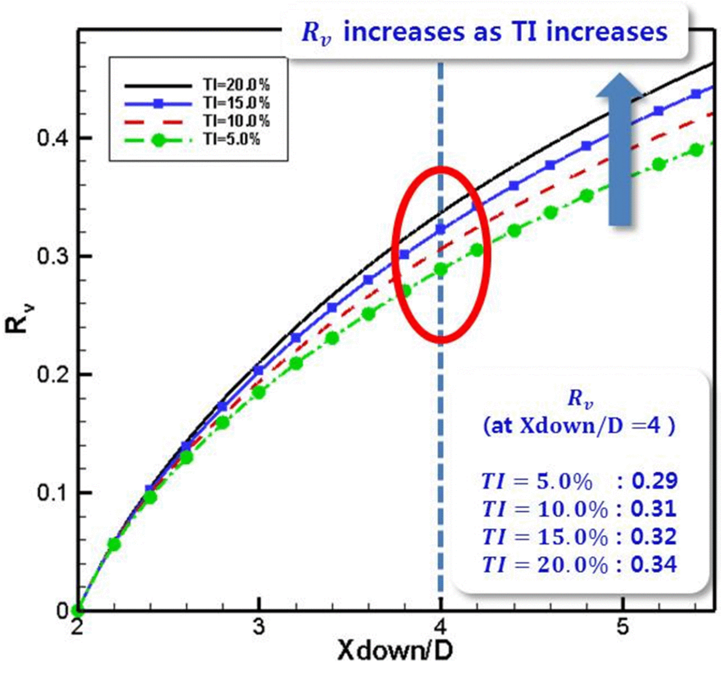

Fig. 5 Velocity recovery rate with ambient turbulent intensity

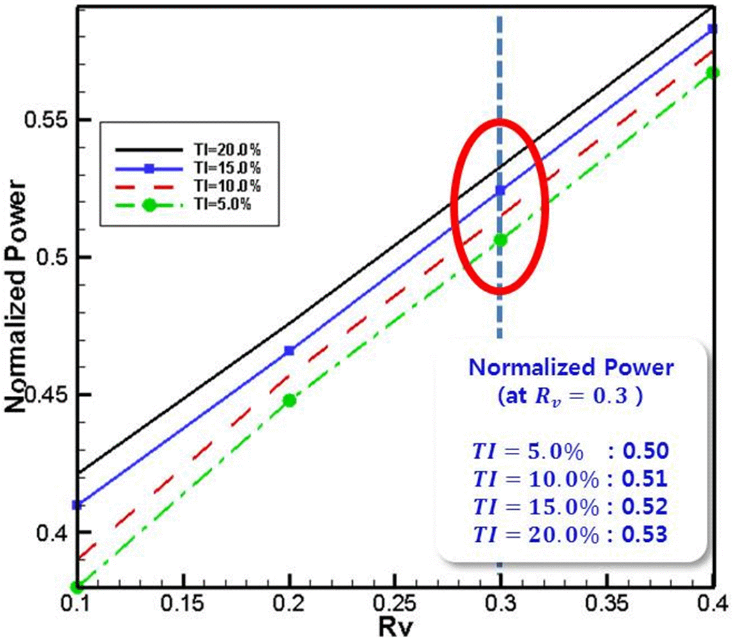

Fig. 6 Normalized power with the TI and various velocity recovery rates