Wind Farm Wake Influence Analysis Based on Actual Engineering

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ABSTRACT

Wake is a significant factor influencing wind power generation, and it is a risk factor that must be addressed early in the development of wind power projects. A more accurate assessment of wake can reduce the risk of wind energy project construction**.** This paper conducts research using data from the production met mast of a wind farm in Tianjin. The data of met mast truly records the wind speed attenuation caused by the wind turbine's wake. The free wind speed time series at the height of the hub is created using model-based data reconstruction and Markov chain restoration using wind data at a height of 30m, where the met mast is not affected by the wake. Using the free wind speed as input data and various wake models for simulation, it is discovered that the coupled wake model has a relatively higher accuracy.

Keywords:

Wind-turbine wakes, wake model, met mast, Eddy Viscosity wake model, ASM-EV wake model

INTRODUCTION

Wind energy, as a renewable energy, has attracted the attention and promotion of all countries around the world due to the rapid growth of energy demand and the rapid consumption of fossil fuels. China stated in 2020 that it would be carbon neutral by 2060[1]. In order to achieve this goal, China has implemented a number of policies. China's total installed wind power capacity will reach 328.48GW by 2021[2], according to the National Energy Administration of China. According to studies, the carbon dioxide emission intensity of wind energy in China is more than 98% lower than that of traditional fossil fuels, and the emission reduction effect can reach 84-98%[3].

Regarding the driving factors for wind power installation, the main positive factors for wind power installation were technological factors and environmental factors, while economic factors and resource endowments showed positive spatial spillover effects. In terms of carbon emission reduction potentials, the carbon emission reduction potentials of China's wind power installation have increased year after year[4].

Wake is a major cause of wind farm power loss. Accurate evaluation of wind farm wake effect is critical for optimal arrangement, unit selection, and wind farm design, among other things. As a result, the influence of wake between units has become increasingly important in preliminary development and design work such as wind turbine layout. The wind energy field currently has a large number of mature wake models, such as the Park wake model[5] and Fuga wake model[6] in the WAsP (Wind Atlas Analysis and Application Software)[7][8], the EV wake model (Eddy Viscosity Wake Model)[9] in the WindPRO[10]. With the rapid development of wind power projects in recent years, researchers have not stopped researching and developing wake models, shifting from a single wake model to a coupled wake model[11]. Such as DAWM (Deep Array Wake Model) [12] and ASM-EV (Area Slowdown Eddy-Viscosity wake model) [13] in the Openwind[14], LWF (Large wind farm wake model)[15] in the Meteodyn WT[16]. Philippe Beaucage et al. (2012) validated six wake models in two offshore wind farms, with the DAMW wake model providing the most accurate assessment of wind turbine wake[17]. Beatriz Caadillas et al. (2023), the extended strategies are compared with large-eddy simulations of the flow through a cluster of three wind farms located in the German sector of the North Sea, as well as real measurements of wind power within these wind farms, to test the rationality of the DAWM model in capturing additional blocking and wake losses in real wind farm clusters[18]. Zhang J et al. (2023) used the EV wake model, DAWM wake model, and ASM-EV wake model to validate the power generation of mountain wind farms. The results showed that the coupled model outperformed the traditional wake model in terms of simulation accuracy [19].

In this paper, wind measure data from a met mast in a wind farm are processed and analyzed using Windographer, in accordance with the industry standard GB/T 18710-2002 “Methodology of wind energy resource assessment for wind farm“[20] and the requirements of the wind data processing part of IEC61400-1 Wind energy generation systems 2019[21]. The free-flow wind speed at 105m height of met mast is first restored by analyzing the correlation of wind speed in different height layers of the same met mast. The wind speed results under different wake models are then calculated in four typical time periods using the Modified Park wake model, the EV wake model, and the ASM-EV. This paper investigates the evaluation effect of the three wake models on the influence degree of the wake by comparing the wind speed affected by the wake with the free flow wind speed after reduction in the same period.

WAKE MODEL

MODIFIED PARK WAKE MODEL

Park wake model is a linear wake model suitable for flat terrain based on the one-dimensional momentum conservation principle of ideal wind turbine proposed by Katic and N.O.Jensen of Ris laboratory in Denmark[22]. It is a one-dimensional linear wake model that does not account for turbulence. The model assumes that:

(1) the initial diameter of the wake area is the diameter of the wind turbine from behind the wind wheel;

(2) the wake rate increases linearly; and

(3) the distribution of wake velocity on the cross section is uniform.

The power coefficient of the wind turbine in the actual project cannot reach the value of the ideal model, so it extends the improved Park wake model, namely the Modified Park wake model, which is more in line with the actual project. The model is widely used in software such as WAsP, WindPRO, WindFarmer, WindSim, WT, and others. The model assumes the wake boundary expands linearly with a width of D+2kx. The expression formula is as follow:

$$V_{down} = V_{up}\left[1 - \left(\sqrt{1 - C_t}\right)\left(\frac{D}{D + 2kx}\right)^2\right]$$

Where, $V_{down}$is the downwind wind speed, unit [m/s], V_{up} is the upwind wind speed, unit [m/s], C_t is the wind turbine thrust coefficient; D is the wind turbine impeller diameter, unit [m], x is the distance from the wind turbine, and k is the wake attenuation coefficient which formula is:

$$k = 1/2 \ln\left(\frac{Z}{Z_0}\right)$$

Where Z is the hub height of the wind turbine and Z_0 is the surface roughness.

Eddy Viscosity Wake Model

Ainslie's two-dimensional axisymmetric eddy current theoretical model (EVM wake model) assumes that the wake region is two-dimensional axisymmetric and that the coordinate system is cylindrical. To calculate the wake of an axisymmetric wind turbine, the eddy current viscosity constraint and time-averaged RANS formula are used. The model considers fluid turbulence in the flow field, the wind speed is non-linear in the cross-section direction, and the air flow is assumed to be incompressible. The wake region is divided into three sections in the model: the near wake region, the transition region, and the far wake region. The expression formula is as follow[9]:

$$1 - \frac{U}{U_0} = D_M exp\left\{-3.56\left(\frac{r}{b}\right)^2\right\}$$

Where, U_0 is the average wind speed of free flow, U is the wind speed at the distance r from the wake centerline, D_M is the initial wind speed attenuation at the wake centerline, b is the wake width parameter, the formula is as follows:

$$b = \sqrt{\frac{3.56C_T}{8D_M(1 - 0.5D_M)}}$$

Where, D_M is related to thrust coefficient C_T and turbulence intensity, and the expression formula is as follows:

$$D_M = C_T - 0.05 - (16C_T - 0.5)\frac{I}{1000}$$

Where *I* is the ambient turbulence intensity.

AREA SLOWDOWN EDDY-VISCOSITY WAKE MODEL

The Area Slowdown Eddy-Viscosity wake model (ASM-EV) considers the wind farm as a whole. The wind farm is related to the inversion layer at the top of the atmospheric boundary layer as an additional surface roughness and as a gravity wave generator, which means that even though the wind speed of the atmospheric boundary layer above the wind field is uniform, it is very sensitive to the decrease of the lower wind speed and the decrease of energy, so there will be changes in the pressure gradient and the generation of gravity waves. The model calculates the interaction force between atmosphere and wind farm based on the conservation of kinetic energy and the above influencing factors, which is a top-down simulation method of fluid kinetic energy. The basic equation is[13]:

$$\frac{v(t)}{v_0} = 1 + \left(\frac{v}{v_0} - 1\right) exp(-\alpha t)$$

Where v_0 is the free wind speed of upstream wind turbine at hub height, v is the wind speed of downstream wind turbine at hub height.

$$\alpha t = ku * z/\Delta z^2$$

Where z is PBL's height, h is wind turbine hub height, Δz= z – h, u* is the friction velocity.

TEST CASES

The research project chosen for this paper is located in Tianjin's Dagang District. The G132-5.0MW units have a blade length of 64.5m, a scavenging surface diameter of 132m, and a hub height of 105m.

Figure 1 depicts the relative position of the unit and the met mast (the recorder is NRG): the turbine unit is 50 ° (230 °) 190 m south of the met mast, and the turbine unit is 15 ° (105 °) 570m south-east of the met mast.

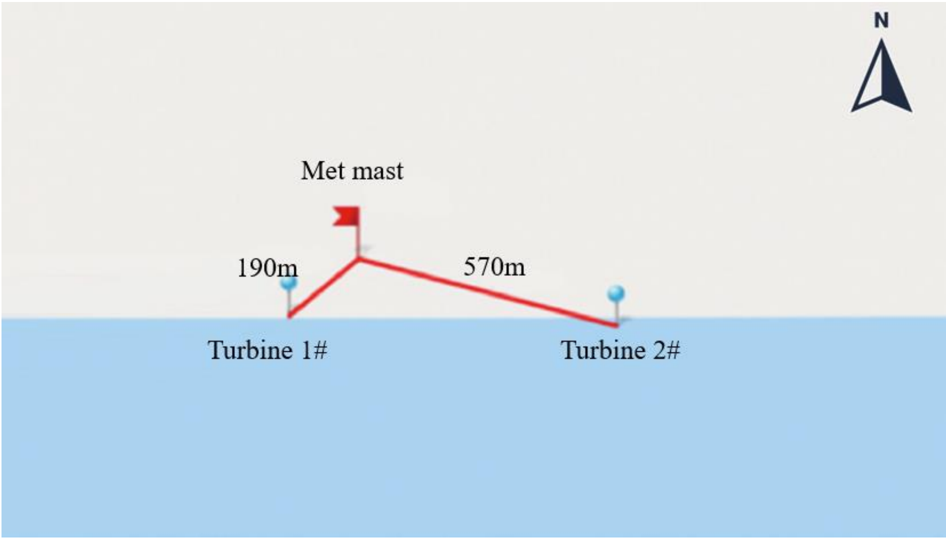

Figure 1 Relative position of met mast and wind turbine

The met mast is located in the plain area. The height of the mast is 105m and the sampling interval is 1s. The wind measuring equipment is NRG wind speed sensor. At present, the 10-minute wind data of the met mast in 2018 are collected. the equipment information and structure of the met mast are shown in Table 1 and Figure 2.

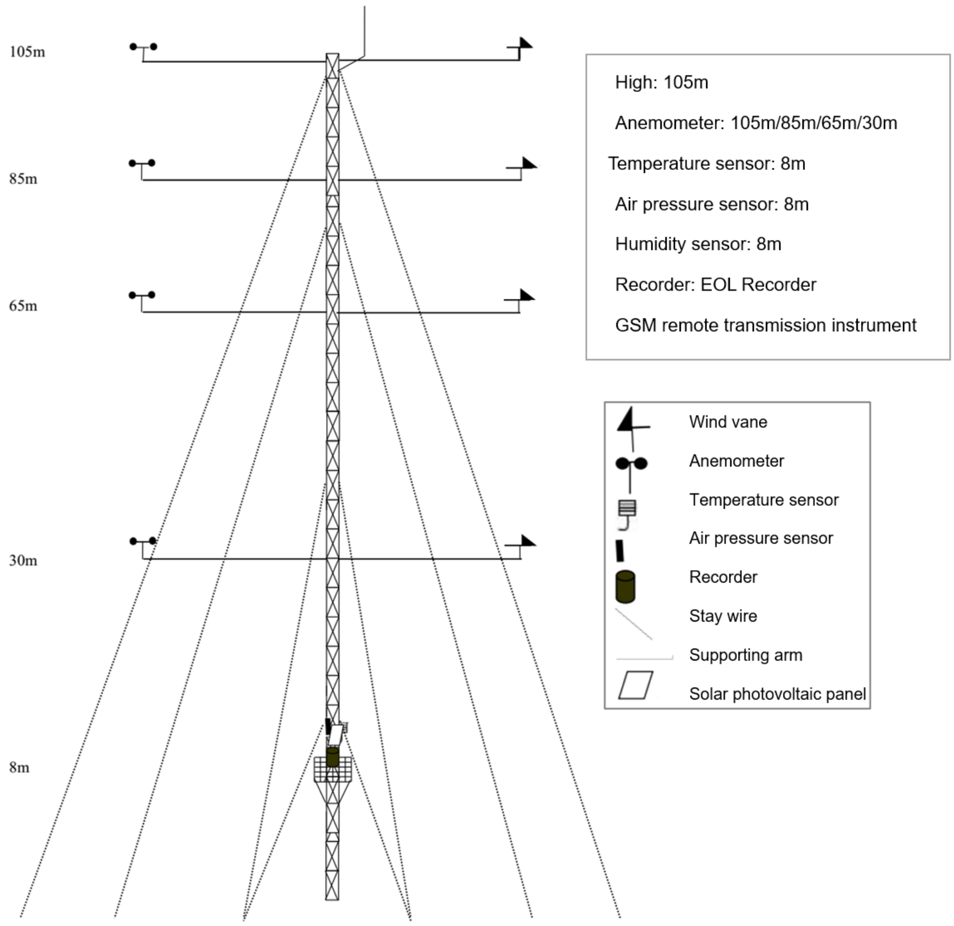

Figure 2 Schematic diagram of met mast structure

As shown in Figure 2, the met mast is equipped with anemometers and wind vanes at 105m, 85m, 65m, 50m and 30m, and thermometers, barometers and data recorders are installed at the height of 8m.

TEST METHODOLOGY

First, determine the effect of the wake on the mast height and angle, as well as the plausibility of the measured data at 30m and 105m heights. After removing invalid data, two valid data time series are gathered. Then, using the pattern-based data reconstruction[23] and Markov chain[24], a set of free-stream wind speeds at a height of 105m is created, which is used as a comparative data source to validate the wake model in this paper.

DETERMINATION OF THE INFLUENCE ANGLE OF WAKE

The range of the influence sector of the wind turbine on the met mast is determined using the calculation formula given in the IEC 61400-12-1: 2017 standard[25], which is:

$$\theta = 1.3\arctan\left(\frac{2.5D_n}{L_n} + 0.15\right) + 10$$

where D_n is the diameter of the wind turbine and Ln is the linear distance between the unit and the met mast.

The influence angle is calculated using the actual distance between the met mast and the wind turbine in the project example: the met mast is 50 degrees (230 degrees) west of the met mast, and the wind turbine is 15 degrees (105 degrees) south of the met mast. The wake influence area of the turbine to the met mast is 90.70 degrees, that is, the wake area is 184.2 ° 275.0 °, and the wake area is 56.92 degrees, that is, the wake area is 76.5 ° 133.5 °.

Filter the experimental wind data time step, that is, the time step in which the wind turbine's wake affects the met mast, using the method described above (Table 2).

Table 1 The period when the met mast is influenced by the wake

Period	Actual waked wind speed at 105m [m/s]	Wind turbines affecting met mast
2018/09/16 15:20 ~ 22:00	3.25	1#
2018/12/12 12:00 ~ 22:50	3.62	1#
2018/08/27 14:00 ~ 21:00	4.10	2#
2018/10/15 14:40 ~ 19:40	3.19	2#

DETERMINATION OF WAKE INFLUENCE HEIGHT

Both sets' hub height and blade length are 105m and 64.5m, respectively, implying that the lowest point from the tip to the ground is 40.5m and the highest point is 169.5m from the ground.

When the wind is blowing from the southwest, it passes through the 1# wind turbine and reaches the meteorological mast. The meteorological mast is currently located in the wake area of the 1# wind turbine. When the wind is blowing from the southeast, it passes through the 2# wind turbine and reaches the meteorological mast. The meteorological mast is currently located in the wake area of the 2# wind turbine.

On August 27, the wind direction is southeast, with gusts ranging from 105 to 125 degrees. The met mast is located in the wind turbine's wake influence area. At this time, the wind speed at 30m is clearly greater than that at other height layers of the met mast.

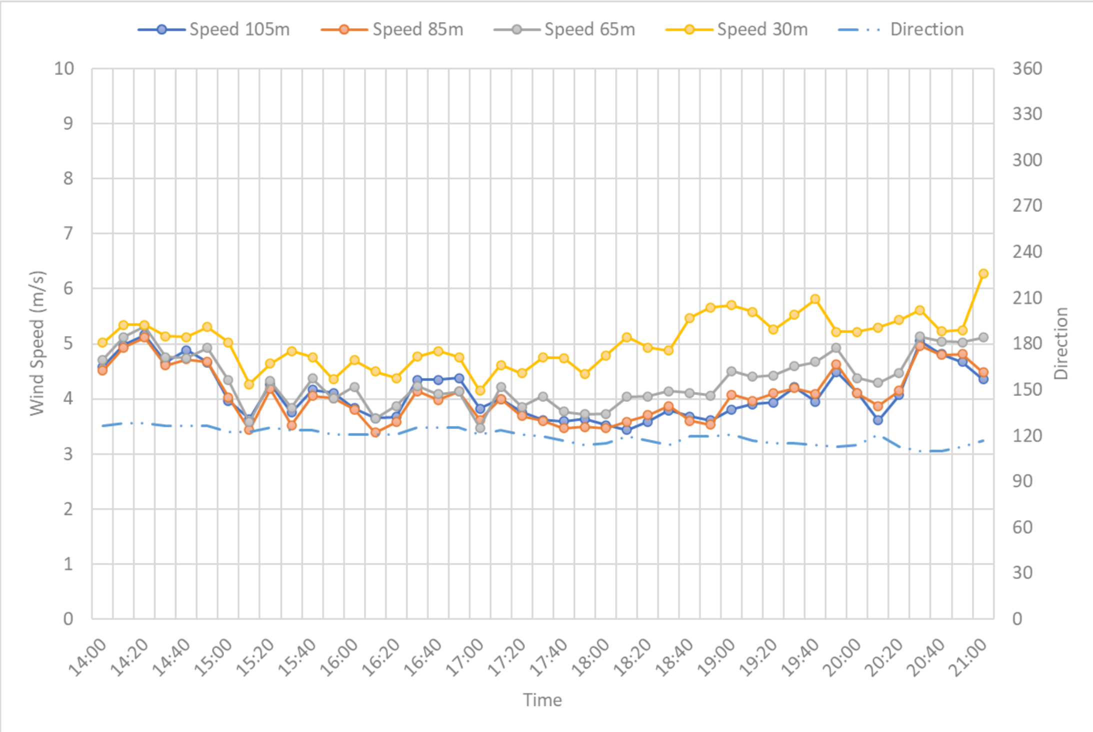

Figure 3 The influence of 2# Wind Turbine on Met Mast

As shown in figure 5, the wind direction is southwest from 11:00 to 22:00 on December 12, and the met mastis located in the wake influence area of the wind turbine. At this time, the wind speed at the height of 30m is obviously higher than that in other height layers of the met mast.

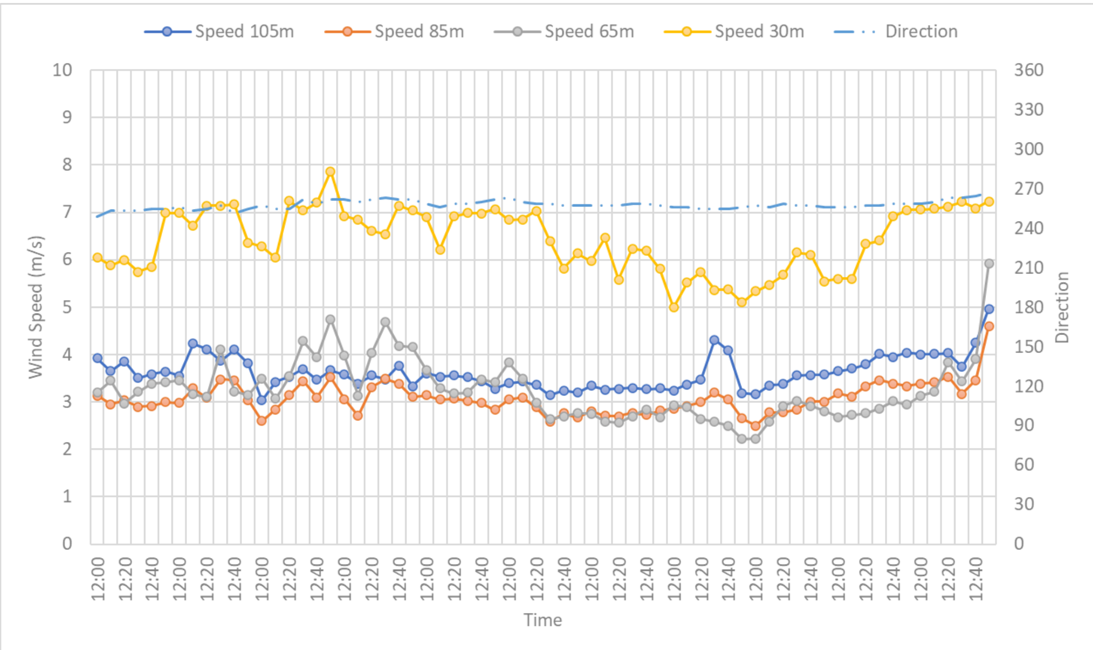

Figure 4 The influence of 2# Wind Turbine on Met Mast

The wind speed at the heights of 65m, 85m, and 105m has a significant downward trend when the meteorological mast is in the wake influence area, according to the results of the measured data analysis, while the wind speed at the height of 30m is less affected. The wind turbine blade sweep area's lowest point is 40.5m from the ground, which is 30m higher than the anemometer installed on the meteorological mast. Wake affects wind data at heights of 65m, 85m, and 105m.

RESULTS AND ANALYSIS

In this paper, the actual wind measurement data at the wind measurement mast's height of 30m is used as the reference value for calculating the degree of influence on the wake. The free wind speed at 105m is restored using pattern-based data reconstruction and Markov data reconstruction methods.

Import the time-series data of the free wind speed at 105m from the restoration above into Openwind software, and use each wake model to calculate the wind speed at 105m of the met mast, and compare it to the wind speed measured by the met mast to verify the wake model's applicability.

Figure 5 depicts a selection of data from 15:20 to 22:00 on September 16, 2018. The wind direction is currently between 230° and 267°, and the met mast is located in the wake area of the 1# wind turbine. When compared to the PARK model fitting data, the EV model and ASM-EV model fitting data fit the actual data better, but the fluctuations are more noticeable.

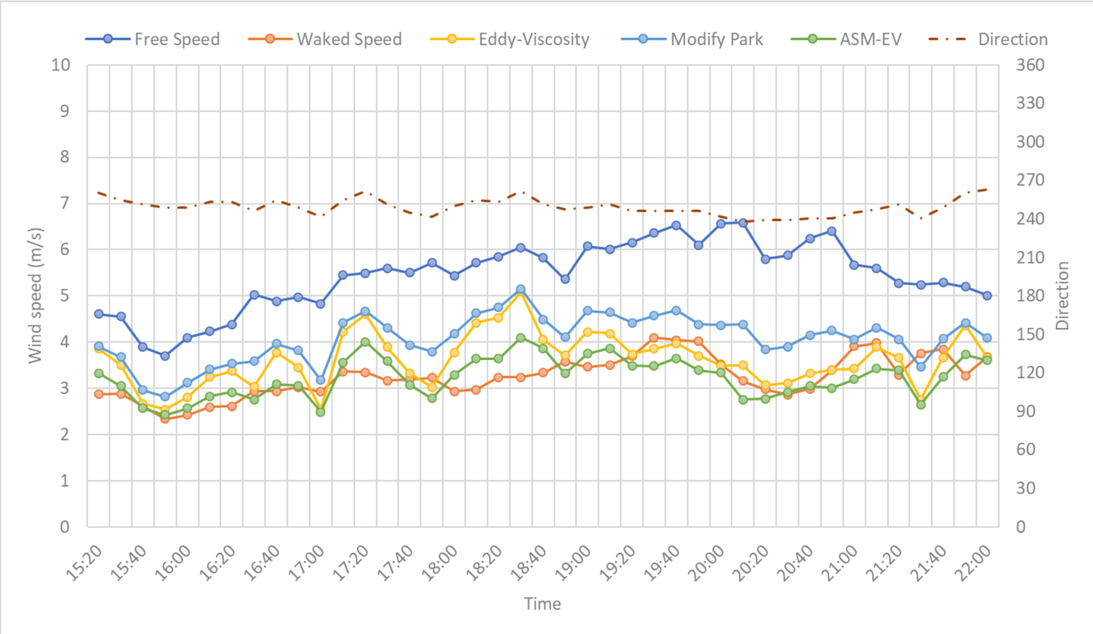

Figure 5 Comparison of calculation results of wake model (2018/09/16 15:20 - 22:00)

Figure 6 shows the wind speed and direction data for nearly 11 hours on December 12, 2018, from 12:00 to 22:50. The wind direction is currently between 240° ~ 260°, and the met mast is located in the wake of the 1# wind turbine. The wake model's fitting data is significantly higher than the actual data, while the ASM-EV model's fitting data is the closest to the actual data.

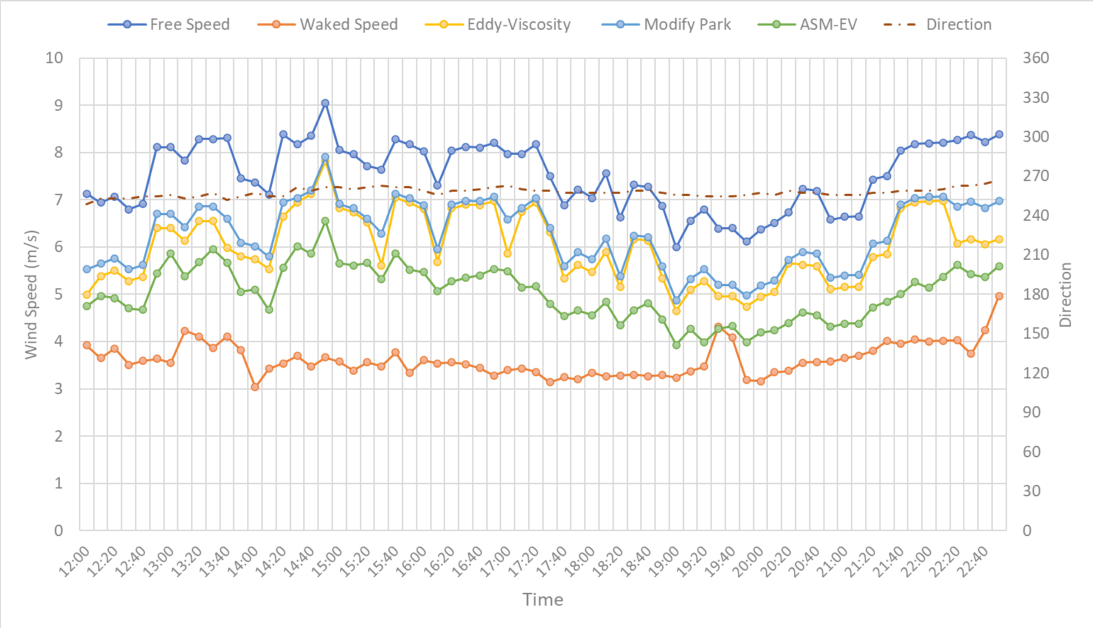

Figure 6 Comparison of calculation results of wake model (2018/12/12 12:00 - 22:50)

Figure 7 shows wind speed and direction data for nearly 7 hours on August 27, 2018, from 14:00 to 21:00, when the wind direction is between 105° ~ 130 °. The met mastis located in the wind turbine's wake. In a situation where the wind speed fluctuates little, the EV model is very close to the ASM-EV model fitting data trend. When the wind belt varies greatly, the EV model is overly sensitive to changes in wind speed, resulting in large fluctuations.

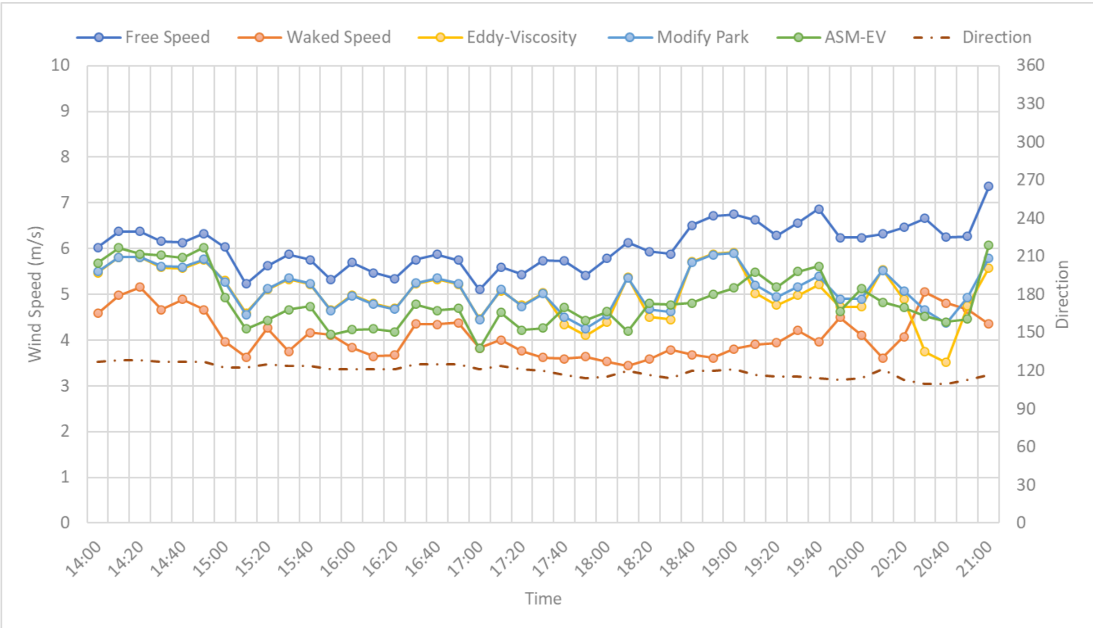

Figure 7 Comparison of calculation results of wake model (2018/08/27 14:00 - 21:00)

Figure 8 depicts 5-hour wind speed and direction data collected between 14:40 and 19:40 on October 15, 2018, when the wind direction is between 108° ~ 125°. The met mastis located in the wind turbine's wake. There are significant differences between the wake model's fit data and the actual data in the trend.

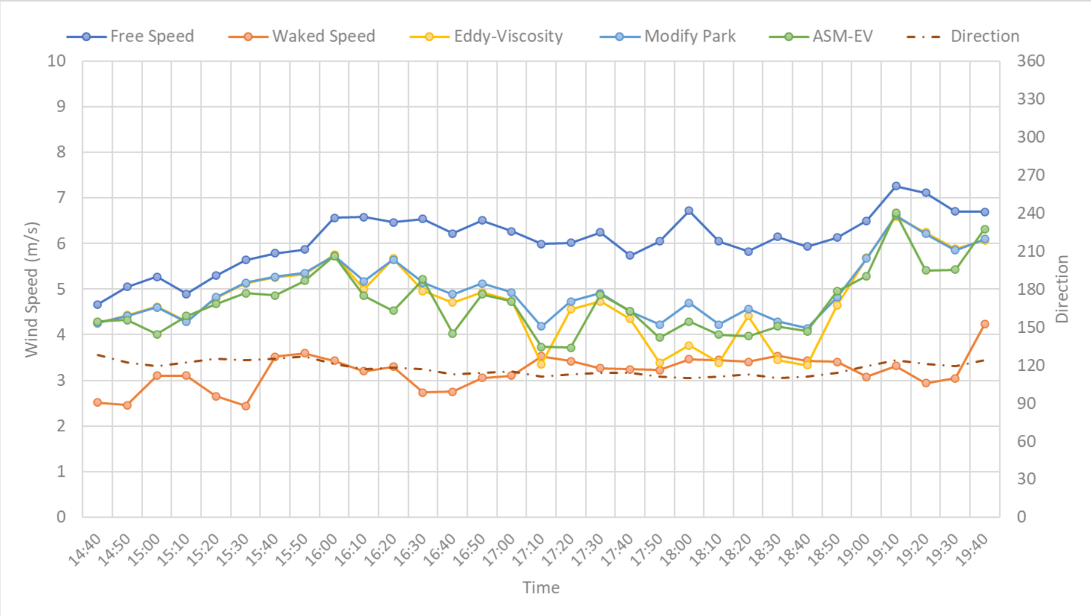

Figure 8 Comparison of calculation results of wake model (2018/10/15 14:40 - 19:40)

According to the statistical data in the Table.2, the wake models all underestimate the wake to varying degrees, with the ASM-EV model calculating the wind speed after the wake closest to the actual value. The wind speed after the wake calculated by the Modified Park wake model has a maximum deviation of 2.65m/s and a minimum deviation of 0.83m/s. The EV wake model calculates the wind speed after the wake with a maximum deviation of 2.39m/s and a minimum deviation of 0.37m/s. The ASM-EV model calculates the wind speed after the wake with a maximum deviation of 1.52m/s and a minimum deviation of 0.01m/s. The ASM-EV wake model's accuracy has increased by 10.17% when compared to the Modified Park wake model, and the EV wake model's accuracy has increased by 5.91%.

Table 2 Data statistics summary

Period	**2018/09/16 15:20- 22:00**	**2018/12/12 12:00-22:50**	**2018/08/27 14:00- 21:00**	**2018/10/15 14:40- 19:40**
Free wind speed [m/s]	5.44	7.52	6.05	5.97
Actual waked wind speed[m/s]	3.25	3.62	4.10	3.19
Wake Efficiency [%]	40.26%	51.86%	32.19%	46.57%
Waked speed by Modified Park	4.08	6.27	5.12	4.98
Wake Efficiency [%]	25.05%	16.67%	15.35%	16.52%
Waked speed by EV	3.62	6.01	5.02	4.77
Wake Efficiency [%]	33.43%	20.06%	16.96%	20.18%
Waked speed by ASM-EV	3.24	5.03	4.86	4.71
Wake Efficiency [%]	40.52%	33.06%	19.60%	21.11%

The 1# wind turbine is only 190 meters away from the met mast, and its wake has a 40.26% and 51.86% influence on the wind speed of the met mast. The 2# wind turbine is 570 meters away, and the influence of the 2# wind turbine's wake on the wind speed of the met mast is 32.19% and 46.57%, respectively.

CONCLUSION

This paper discusses the wake model by analyzing how much the wind turbine wake affects the met mast in the actual project.

1. When the wake calculation results of the time series are compared, each wake model underestimates the wind turbine's wake effect, with the deviation reaching 35.19%.
2. The ASM-EV wake model calculates wind speed that is closer to the measured wind speed than the Park wake model and the EV wake model. The accuracy of the ASM-EV wake model has increased by 10.17% when compared to the Modified Park wake model, and the accuracy of the EV wake model has increased by 5.91%.
3. The 1# wind turbine is closer to the met mast than the 2# wind turbine, and its wake has a greater impact on the met mast.
4. To facilitate quantitative analysis of the degree of wake influence, the measured data at 30m of the met mast is regarded as the value unaffected by wake, which has certain errors and uncertainties.

The research in this paper focuses on the short-term time window, as opposed to the full-year analysis. Wake analysis based on meteorological masts lacks the universality of large-scale wind farm wakes. We hope that the research in this paper can serve as a reference for peers, and we will continue to analyze more cases to improve the research's guiding significance for practical engineering.

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