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**REVIEW**

# Review on Research about Wake Effects of Offshore Wind Turbines

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**ABSTRACT**

In recent years, the construction of offshore wind farms is developing rapidly. As the wake effect of the upstream wind turbines seriously affect the performance of the downstream wind turbines, the wake effect of offshore wind turbines has become one of the research hotspots. First, this article reviews the research methods of wake effects, including CFD numerical simulation method, wind turbine wake model based on roughness and engineering wake models. However, there is no general model that can be used directly. Then it puts forward some factors that affect the wake of offshore wind turbines. The turbulence intensity in offshore wind fields is lower than that in onshore wind fields. This makes the wake recovery length of offshore wind turbines longer than that of onshore wind turbines. Floating offshore wind turbines are simultaneously disturbed by wind loads and wave loads. Unsteady movement of the platform caused by wave loads. It affects the development and changes of the wake of wind turbines. In this regard, the focus of research on the wake effects of offshore wind farms will be the proposal of accurate prediction models for the wake effects of sea wind farms.

**KEYWORDS**

Wind energy; offshore wind turbines; wake effects; offshore wind farms

## 1 Introduction

In recent years, the energy crisis, environmental pollution and greenhouse gas emissions are becoming more serious with the massive use of fossil fuels. Renewable energy has the characteristics of environmental protection and energy saving [1]. Many countries focus on the development of renewable energy as an important way to promote low-carbon energy transition. Carbon emissions of the average life cycle of wind power is lower than other forms of power generation technology. Wind power utilization has become one of the key developments of various countries [2,3]. Since 1996, the average annual growth rate of global wind power installed capacity has been above 25%. By 2020, the total installed capacity of wind power in the world will reach 743 GW, of which the newly installed capacity will reach 90 GW [4]. It can be said that wind energy has become one of the fastest growing energy sources in the world.

Compared with onshore wind energy, offshore wind energy has the characteristics of large energy reserves, sustained resource stability, and mild environmental impact [5]. These characteristics promote the development of offshore wind farms. In addition, the development of offshore wind power in near and far sea areas can effectively alleviate the dependence of energy consumption on land resources. Since the installation of the first offshore demonstration wind turbine in Denmark in 1990, offshore wind power generation has developed rapidly in Europe [6]. The development of global offshore wind power has entered an accelerated stage.

In order to maximize the economic benefits within the limited area of the wind farm, it is necessary to arrange a sufficient number of wind turbines in a wind farm. Large-scale wind power by arranging a large number of wind turbine cluster and grid method. However, studies have found that the number of wind turbines is not directly proportional to the increase in the total power generation of the wind farm. When the number of wind turbines reaches a certain number, the increase of wind turbines actually lead to a decrease in the power generation of the wind farm. The reason for this phenomenon is that there is a very obvious mutual interference effect between the wind turbines in the wind farm. Some wind turbines are inevitably located in the wake area of other wind turbines. It increases the fatigue load of the wind turbine, reduces the output power, and affects the economic benefits and safe operation of the entire wind farm [7]. Therefore, it is necessary to consider the influence of wind turbine wake effects during the design and operation of offshore wind farms. Increasing the distance between the main wind direction units can reduce the mutual influence between the units. But shortening the distance between units can save the length of submarine cables and reduce project investment, while being able to accommodate more wind turbines. In the layout of offshore wind farms, the influence of wake flow between turbines should be minimized through optimization of wind turbine model selection. At present, the research on the wake of onshore wind turbines is relatively comprehensive and the research methods are relatively complete. However, the environment of offshore wind farms is very different from that of onshore wind farms. It is necessary to study the wake characteristics of wind turbines based on the specific characteristics of offshore wind farms. Based on the above current situation, this article reviews to the description of wake effects, wake research methods, and research status of offshore wind turbine wakes. And this article puts forward the difference between the wake research of offshore wind turbines and the wake research of onshore wind turbines. To facilitate future research on the wake effects of offshore wind turbines. This lays the foundation for the prediction of the state of offshore wind farms and the proposal of intelligent control technology under the wake effect in the future. It is of great significance for effectively improving the economic effects of offshore wind farms.

This study is organized as follows. Section 2 introduces a brief description of wind turbines wake effects. Section 3 introduces the current research methods of wind turbines wake. At present, the research method of offshore wind turbine wake still uses the research method of onshore wind turbine wake. They are mainly based on CFD numerical simulation method, roughness length based model, engineering wake mode, and wake superposition model. Section 4 presents the main characteristics of the offshore wind turbines wake under the different factors affect. These include the influence of the atmospheric boundary layer, the influence of blade control, the influence of roughness and Coriolis force, and other factors. Section 5 summarizes the current research status of offshore wind turbine wake and prospects for future research directions.

## 2 Brief Description to Wake Effects

In order to maximize the use of wind energy resources and meet economic feasibility, the construction of wind farms tends to be centralized and large-scale, where a large number of wind turbines will be arranged. When the wind flows through the wind turbines, the rotor absorbs energy from the free flow and converts it into mechanical energy. As a result, the wind speed drops and turbulence intensity increases in the downstream area of the wind turbine. This phenomenon is called the wake effect of wind turbines. Fig. 1 shows an aerial photo of the Horns Rev II offshore wind farm in Denmark [8]. It can be clearly seen that the wake of the wind turbines upstream to downstream wind turbines had a serious impact.

**Figure 1:** Horns Rev II offshore wind farm in Denmark [8]

When some wind turbines are in the wake area of the upstream turbines, the fatigue load of the wind turbines increases and the output power decreases. The wake affects the economic benefits and safe operation of the entire wind farm [9]. The energy loss caused by wake effects in large wind farms can usually reach 10% to 20% of the annual power generation [10]. When the wake is completely generated, the power generation of the downstream wind turbines can fall to 46% of that of the upstream wind turbines [11]. In wind farm with densely arranged wind turbines, some of the output losses caused by the wake effect can even reach more than 80% [12]. At the same time, the intensity of turbulence in the wake area is relatively high. On one hand, it increases the fatigue load of downstream wind turbines and reduce the life of blades and towers [13]. On the other hand, it also causes the output power fluctuations and flicker. The wake area generated by wind turbines can generally be divided into four areas, namely the induction area, the near-wake area, the transition area and the far-wake area, as shown in Fig. 2.

The induction area is the part from the front of the wind turbine to the vicinity of the wind turbine. The wind speed in the area gradually decreases and the pressure gradually increases. When the incoming flow passes the wind turbine, the turbine absorbs the kinetic energy of the incoming wind. This leads to a decrease in wind speed in the wake area downstream of the wind turbine. At the same time, there is a rapid pressure drop around the turbine plane. After the incoming flow passes through the wind turbine, the fluid pressure gradually recovers, and the speed is further reduced. The wind speed gradient between the low-speed fluid in the area and the external high-speed free flow forms a shear layer. When the wind turbine rotates, the wake vortex shed from the trailing edge of the blades form a complex vortex system composed of spiral vortex surfaces. The vortex system is composed of three parts: the root center vortex, the tip spiral free vortex and the attached vortex. The shear layer comprises a large number of large-scale vortices, leading to a bimodal curve of the turbulence intensity in the near-wake area. Turbulence in the shear layer causes the wake to continuously mix with the external free flow. Momentum of the external free flow is constantly added to the wake in this process, so that the speed loss of the wake is reduced. The blending process makes the width of the wake gradually increase, while the shear layer is also expanding. When the fluid pressure returns to atmospheric pressure, the velocity loss in the wake region reaches its maximum value, which marks the end of the near wake region. It is generally believed that the range of the near wake area is within the distance of 1D to 2 D downstream of the wind turbine. The characteristics of the flow field mainly depend on the parameters of the wind turbine and the flow characteristics of the atmosphere. The area of 2D-5D downstream of the unit, as the wake continues to develop downstream, the shear layer continues to expand to the centerline of the wake. This area is called the transition zone.

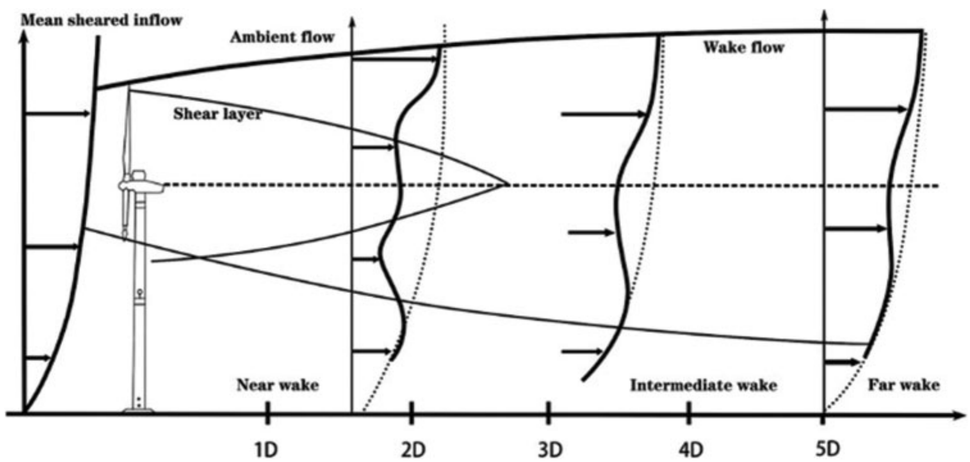


**Figure 2:** Flow development of wind turbine wake [14]

When the wake in the far wake zone enters the fully developed stage, there is almost no axial pressure gradient, and the velocity loss gradually decreases. Assuming that the wind shear of the atmosphere is neglected, it can be approximately considered that the radial velocity distribution on each wake cross section in the far wake region is axisymmetric (approximately Gaussian distribution). This assumption is widely used in various wake models. The magnitude of wake loss in the far wake region is affected by the operating conditions and thrust coefficient of the wind turbine. If the wind turbine is regarded as an obstacle, the thrust coefficient represents the resistance of the wind turbine to the incoming flow. The greater the thrust, the greater the velocity loss in the wake area and the wider the wake expansion. The speed recovery in the wake region mainly depends on the intensity of atmospheric turbulence and the magnitude of the additional turbulence in the wake region. Some studies [15–18] have shown that a higher wake turbulence intensity region will promote the exchange of momentum between the wake region and the external free stream, resulting in faster wake zone speed recovery. The atmospheric turbulence intensity of offshore wind farm is generally lower than onshore wind farms, and therefore the wind velocity in the wake region will recover more slowly. The propagation distance of the wake is larger than that of the onshore wind farm.

It can be seen from the above that the wake of the upstream wind turbine has a serious impact on the performance of the downstream wind turbine. In addition, the flow field distribution in the wake region is complex and chaotic, and it is affected by many factors. Therefore, simulation predictions are needed for the distribution of wakes.

## 3 Wake Research Methods

Accurate simulation of wake effects in wind farm is the basis for assessing wind farm power generation and economic benefits. Carrying out high-precision research on turbine wake simulation methods in wind farm is of great significance for wind farm power generation calculation and economic benefit evaluation, unit arrangement, and operation optimization control. The calculation methods for simulating the wake distribution in current relative studies can be divided into three categories, i.e., the wake simulation method based on CFD numerical simulation, the wake model based on roughness and the engineering wake model.

### *3.1 Wind Turbine Wake Simulation Based on CFD Numerical Simulation*

Except for the tip area, the wake characteristics of the wind turbine can be expressed by the Navier-Stokes equation of the incompressible fluid, and the governing equation is

$$\frac{\partial u_j}{\partial x_j} = 0$$
$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}(2\upsilon S_{ij}) + f_i \tag{1}$$

where $u$ is the speed, $x$ is the position vector, $P$ is pressure, $\rho$ is the fluid density, $\upsilon$ is the kinematic viscosity, $f_i$ is the force of an external body, $t$ is time, $i, j$ is the direction vector, $S_{ij}$ is the strain rate tensor that defined as

$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{2}$$

Navier-Stokes equations are used to describe the three-dimensional unsteady turbulent flow. With the continuous improvement of computer performance, computational fluid dynamics methods based on numerical discrete to solve Navier-Stokes equations have also been developed rapidly. As an important tool, CFD is widely used in the research of wind turbine wake field simulation, and has achieved rich results. The CFD method is currently the most accurate method for simulating the aerodynamic characteristics of the wake field. It can not only obtain detailed information about the velocity, pressure, and density distribution in the wake field of the wind turbine by solving, but also accurately simulate the influence of the complex turbulent flow characteristics on the wake of the turbine. According to the different modeling methods for describing turbulent pulsation, the methods of CFD to simulate turbulent flow mainly include Direct Numerical Simulation method (DNS), Large Eddy Simulation method (LES), Reynolds Average Navier-Stokes method (RANS) and Detached Eddy Simulation method (DES) [19,20].

The numerical simulation of the fluid passing through the wind turbine is an outflow problem. Therefore, when using the CFD method to solve the wake field of the wind turbine, a larger calculation domain needs to be meshed discretely. This is calculated by the CFD method when simulating the wake field of the wind turbine. An important reason for the large amount. At present, there are mainly two methods for the modeling of wind turbine in the studies of simulating the wake field of wind turbines. The first method is to directly perform geometric entity modeling of the wind turbine, and then calculate all the wakes from the blade boundary layer to the far field boundary. Due to the complex shape of the blades, it is very difficult and time-consuming to divide high-quality body-fitted meshes. Some researchers have achieved good results by using Overset Grid, but generally only specialized flow solvers can support it [21–23]. At the same time, due to the increasing scale of wind turbines, more and more grids are required for the detailed simulation of the three-dimensional flow field of wind turbine, resulting in a large increase in computer resources and computing time required by the method. In addition to the grid, the method is also affected by many factors such as turbulence model, transition model, discrete format, boundary conditions and so on. The second method is to introduce the volume force momentum source term into the flow field to express the influence of the turbine blade or turbine on the flow. The aerodynamic characteristics of the blade and the flow field near the blade determine the volume force. Because this method no longer spends a lot of computing resources to solve the geometric surface flow field of the blade, it does not need to arrange a large number of grids in order to capture the details of the flow field near the blade, so the calculation time is greatly saved. Such methods include models such as actuation disk, actuation line, actuation surface, and actuation body according to the different ways of modeling the wind turbine.

The actuator disk model regards the wind turbine as a penetrable virtual disk that can withstand the pressure of the flow field. Blade element momentum theory (BEM) includes the theory of momentum and blade element theory. The generalized actuating disc model combines the concept of actuating disc with Euler equation or N-S equation, and uses CFD method to solve flow field information. The influence of the actuation disk is added to the flow control equation in the form of volume force. The volume force is uniformly distributed along the circumferential direction, and the distribution along the radial direction is usually based on the BEM. The volume force can be given in advance, or dynamically calculated based on flow field information and airfoil aerodynamic data, as shown in Fig. 3. Mikkelsen et al. [24] used the BEM method and the actuating disk model to numerically analyze the influence of the wind turbine. They believed that when the BEM method is applied to wind turbines with large torsion angles or large blade deflection, significant errors may be introduced. For the tapered actuator disk with constant normal load, the calculated interference factors change considerably along the radius of the disk. The BEM method cannot reproduce this situation. Furthermore, the BEM method underestimates power coefficient by up to 7% points at lower velocities. When studying the wakes of wind turbines, especially the interaction between the wakes of multiple wind turbines in large-scale wind farms, the axisymmetric actuator disk model is further extended to three dimensions [25].

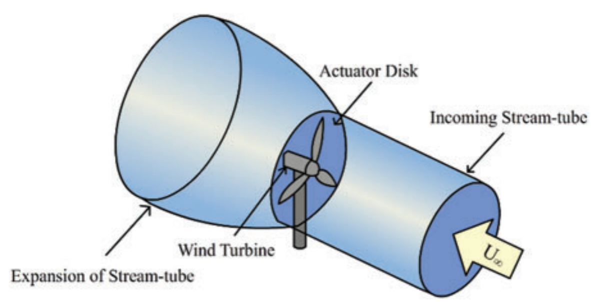


**Figure 3:** Actuator disk theory concept used for the mathematical modeling of the turbine

Since the volume force distribution of the actuating disk model has no circumferential change, it cannot reflect the influence of the number of blades. In order to overcome this shortcoming, Sorensen and Shen established the Actuator line method [26]. The basic principle of the actuation line method is similar to that of the actuation disk model. It also replaces the action of the rotor by volume force, while the distribution of volume force is on the blade axis. The calculation method of volume force is similar to the BEM method. First the blade is divided into a series of blade segments and represented by the volume force, and then the inflow velocity and angle of attack are determined according to the local flow information of the blade segments. Thirdly, the airfoil aerodynamic data table was looked up according to the AOC of the blade segments and obtained the lift drag coefficient. Finally, the force of the blade segment is added to the flow field as a volume force.

Actuator surface method introduces the volume force distribution along the chord direction on the basis of the actuation line, so that the flow field near the actuation surface is closer to the real blade. The main difficulty of the actuation surface method is how to determine the distribution of the volume force along the chord direction. At present, there are two main methods: Shen et al. used the airfoil surface pressure and friction force distribution calculated by the airfoil aerodynamic analysis software Xfoil as the chord distribution of the volume force [26], and Leclerc et al. obtained the chord distribution of the volume force by similar to Analysis Method of Thin Wing Theory [27]. The actuation surface method is far more complicated than the actuation line method, and the wake of the analog does not significantly increase, thus the practical application of relatively small.

Some scholars [28,29] used the actuation disk model and the actuation line model to calculate the velocity loss in the wake region of the wind turbine, and pointed out that the actuation disk can achieve the same calculation accuracy as the actuation line model in the flow field simulation of the far wake flow field. The actuation method does not model the blade entity, which avoids the trouble of dividing high-quality body-fitted meshes, and saves a large number of meshes required for blade boundary layer simulation. Moreover, it solves the difficulty that the CFD method needs to deal with multiple flow scales from the thickness of the blade boundary layer to the diameter of the wind turbine at the same time when it is used in the simulation of the wake of a wind turbine. Compared with the CFD method, the actuation method is more suitable for the study of the mutual influence of the wakes of multiple wind turbines.

### *3.2 Wind Turbine Wake Simulation Based on Roughness*

Roughness Length Based Model assumes that the upstream of the wind farm is the logarithmic wind profile caused by the roughness of the ground surface. Wind turbine as roughness elements increases the roughness of the wind farm in the region, to cause an impact on the incoming flow profile. According to the calculated speed profile, the wind speed and its output power in front of the wind turbine can be obtained. Emeis et al. [30] believed that when the incoming flow passes through the unit, the wind shear should not be a single profile, but a combination of two upper and lower wind profiles bounded by the hub height. Below the hub height, the wind shear is still only caused by the roughness of the ground surface. Considering the influence of atmospheric stability on wind shear, Pena et al. [31] proposed an Infinite Wind Farm Boundary-Layer (IWFBL) model. This model is a roughness wake model that is relatively widely used at present. In general, the roughness-based wake model is not commonly used in wind turbine wake simulation, but this type of model is more suitable for studying the impact of the entire wind farm on the characteristics of the atmospheric boundary layer and the wake influence of the upstream wind farm on the downstream wind farm in the large-scale wind power base.

### *3.3 Engineering Wake Mode*

Engineering wake model, also known as analytical wake model, dynamic wake model or empirical wake model, is the simplest and fastest calculation model for wind turbine wake distribution. This type of model is generally based on some idealized assumptions or an analytical formula for solving the wake velocity distribution of a single unit based on a large amount of experimental data. The derivation of this type of model assumes that the velocity of the wake area meets self-similarity. The velocity distribution on the interface of the wake area is generally uniform (one-dimensional wake model) or Gaussian (two-dimensional wake model), and the maximum value of velocity loss is determined by the unit thrust coefficient. The expansion speed of the wake region is related to atmospheric turbulence, additional turbulence generated by the shear layer in the wake region, and mechanical turbulence generated by the unit itself. The engineering wake model is simple in form and requires less calculation resources. However, their calculation accuracy depends on the adjustment of the empirical parameters in the model under different working conditions, which makes the engineering wake model unable to be universal in the wake simulation. On the other hand, a large number of assumptions and simplifications of the model itself make the model unsuitable for studying the details of the wake field distribution. Nevertheless, the absolute advantage in the calculation speed of the engineering wake model and its acceptable calculation accuracy make it widely used in wind farm engineering. In fact, the engineering wake model is specially designed for engineering applications, so the focus of this type of model is the calculation of the velocity distribution of the wind turbine's far wake flow field, while the calculation accuracy of the velocity in the near wake region is low.

In 1979, Lissiman [32] proposed the earliest engineering wake model based on the Abramovich [33] jet attenuation theory. After that, new wake models and improved forms of these models continued to emerge. The wake models commonly used in engineering at present are the Jensen wake model based on conservation of mass [34], the Frandsen wake model based on the momentum theorem [35], and the Larsen wake model obtained by solving the simplified Prandtl turbulence boundary layer equation [36]. The Jensen wake model is derived based on the principle of conservation of mass. The model assumes that the wake region expands linearly, the velocity distribution in the wake is uniform, and the expansion speed is linearly related to the downstream distance. The velocities on the cross section of the wake zone are equal (top hat distribution), and the magnitude of the velocity loss in the wake zone is related to the thrust coefficient of the wind turbine. The model is supplemented by the one-dimensional momentum theorem, and the Jensen wake model (also known as the Park wake model), which has been widely used in engineering until now, is obtained. Schematic diagram of the control volume in the Jensen model is shown in Fig. 4 [37]. Archer et al. [38] verified that the Jensen wake model and several other engineering wake models are applied to the output power of different offshore wind farm computer groups and compared with the measured data of the wind farm. Barthelmie et al. [10] took Horns Rev I offshore wind farm as the target wind farm, and compares with the calculation performance of the Jensen wake model and some wake models based on the CFD method. A series of comparative verifications show that the Jensen wake model has strong robustness. Although the calculation results in each case may not be entirely accurate, they can basically meet the engineering requirements. Now, the Jensen wake model is still the most common wake model in engineering due to its simplicity and relatively high calculation accuracy [39].

In 2006, Frandsen et al. [40] obtained a new wake model based on the law of conservation of momentum. This model is very different from the Jensen wake model in form, but the velocity distribution on the cross section of the wake area is still the top hat distribution, and the maximum wake loss is the same. Bastankhah et al. [41] tested the two-dimensional form of the Fandsen wake model using wind farm data and wind tunnel experimental data, which has been widely used in academic research. Xie et al. [42] believed that wake expansion is anisotropic. When they used the Gaussian distribution function to correct the velocity distribution in the wake region in two dimensions, they used different variances in the horizontal and vertical directions, which made the cross-sectional velocity of the wake calculated by their wake model elliptical. Through the comparison with wind tunnel experimental data and large eddy simulation calculation results, the above two models can obtain calculation results with higher simulation accuracy.

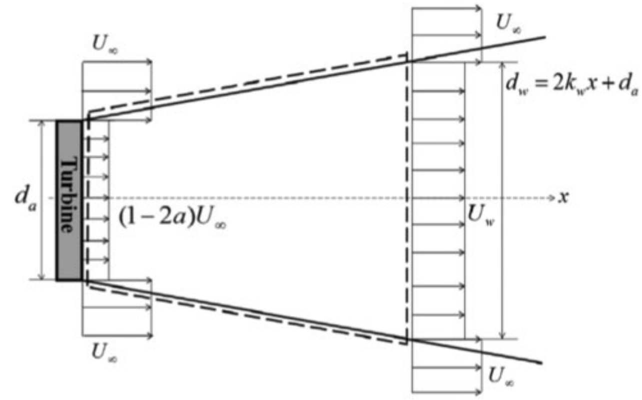


**Figure 4:** Schematic of the control volume in the Jensen model [37]

The Larsen wake model is a wake model recommended by European Wind Turbine Standards II (EWTS II) for wake calculations and was proposed in 1988 [43]. It assumes that the fluid is incompressible, and solves the simplified Prandtl turbulence boundary layer equations based on the self-similarity theory, thus obtaining a closed solution of the wind speed distribution in the wake region. The wake model is a two-dimensional wake model. Since wind shear is ignored, the velocity distribution in the wake region is axisymmetric. In 2009, Larsen [44] revised the original wake model by adding boundary conditions at the plane of the wind turbine and at 9.6D downstream of the wind turbine based on the results of wind tunnel experiments.

In recent years, the engineering wake model has been continuously revised and improved through various empirical formulas. It can quickly calculate the velocity distribution of the far wake flow field of wind turbines, so it is widely used in wind farm engineering applications. However, due to its own large number of assumptions and simplifications, the model is not suitable for studying the details of the wake field distribution.

## 4 Main Wake Characteristics of Offshore Wind Turbine

### *4.1 Effect of Atmospheric Boundary Layer*

Offshore wind farms are characterized by high wind speed and low turbulence. Therefore, the wake model of onshore wind turbines cannot be used directly. It is necessary to revise the wake model by studying the wake characteristics of offshore wind farms. In the atmospheric boundary layer (ABL), there is a very strong interaction between the gas stream and the ground, the ground terrain conditions will directly affect the movement characteristics of the layer of the atmosphere. Due to the blocking effect of the ground, wind speed varies significantly with altitude. Average wind speed variation with height is called wind shear or wind profile. At present, most countries use the empirical exponential law distribution to describe the change of the average wind speed in the near-surface layer with height, exponentially distributed wind profile can be expressed as

$$U = U_{ref}\left(\frac{z}{z_{ref}}\right)^{\alpha} \tag{3}$$

where, $U$ is the average wind speed at the height $z$ from the sea surface; $z_{ref}$ is the reference height; $U_{ref}$ is the average wind speed at the reference height that is the reference wind speed; $\alpha$ is the wind speed profile index, and its value is determined by the corresponding topography.

Atmospheric stability is an important meteorological variable that affects the development of wind turbine wakes in offshore wind farms. Under the same average wind speed, the power difference of offshore wind turbines between stable and unstable stratification is as high as 20% [45]. Doerenkaemper et al. [46] changed the discontinuous surface characteristics of the sea surface through measurement and large eddy simulation, and concluded that the wake effect of the stable layered atmosphere is enhanced compared with the case of the unstable layered atmosphere. Compared with unstable conditions, the power loss is about 4% in the range of 7–11 m/s. But when the wind speed is higher than the rated wind speed, atmospheric stability no longer plays a role [47]. Fernando et al. [48] summarized the influence of ABL on the wake distribution of wind turbines. And they got some conclusions such as: The near-wake region, whose structure and dynamics are affected by the geometry and operation of the wind turbine, has a length of about two to four rotor diameters, depending on the turbulence intensity in the ABL. Meandering of the far-wake has been associated with the dynamics of relatively large (larger than twice the rotor diameter) turbulent eddy motions in the ABL. This connection has been used to develop models for the position of the instantaneous wake center and the unsteady loads on downwind turbines [48].

At present, when evaluating the wake phenomenon of a single wind turbine, it is mainly described by the expansion width of the wake and the insufficient value of the maximum power. Meanwhile, turbulence mixing plays an important role in the wake of the wind turbine during recovery. Numerical accuracy of atmospheric turbulence and near-wake has a great influence on the bend and recovery of the wake. Gao et al. [49] proposed an atmospheric turbulence generation method by improving the excitation line large eddy simulation method. Based on the dynamic k-equation large-eddy simulation (LES), this method uses a precursor method to generate atmospheric inflow turbulence, models the tower and nacelle wakes, and improves the body force projection method based on an anisotropic Gaussian distribution function. This method can produce typical offshore atmospheric turbulence conditions. Barthelmie et al. [10] showed that the power loss caused by the wake of offshore wind farms seems to be much larger than previously predicted. The reason is that the intensity of maritime atmospheric turbulence is lower than that of terrestrial atmospheric turbulence. The low turbulence intensity hinders wake recovery and reduces the power output of downstream wind turbines. In this regard, Frueh et al. [50] believed that the increase in turbulence intensity may be related to the distance and time scale of wind turbines. Argyle et al. [51] showed that the intensity of turbulence decreases with the increase of the wake resolution, and the change is small above 8D.

### *4.2 Effect of Roughness and Coriolis Force*

Unlike the surface drag coefficient on land that hardly changes with wind speed, the wave state on the sea is affected by wind speed. The surface drag coefficient of offshore wind farms increases with the increase of wind speed. At the same time, the wind speed is affected by the roughness of the sea surface. The relationship between them is more complicated. In engineering, the following empirical formula can be used to describe:

$$z_0 = \frac{au_*^2}{g} = \frac{aSDCu_{10}^2}{g} \tag{4}$$

where, $a$ is an empirical constant, generally between 0.01–0.02; g is the acceleration of gravity.

Measuring the wake of offshore wind farms by shipborne acoustic radar is another important method to study the wake effects of offshore wind turbines. Hasager et al. [52] conducted research on wind farm wake climatology based on ASAR environmental satellites. Conducted geolocation wake study for the Horns Rev offshore wind farm. Barthelmie et al. [53] evaluated the utility of sonar in determining the offshore wind speed profile by measuring the wake of the Danish offshore wind farm, and provided the first offshore wake measurement of wind turbines at different distances. At the same time, it is suggested that the velocity deficit is predicted by an empirical model based on land-based measurement of the transportation time depending on the surface roughness, so the measurement result is closer to the prediction result using land-based roughness instead of sea-based roughness. When the operation of the wind turbine stops, the velocity deficit disappears. The wake profile is measured as a decrease in wind speed. Although the turbulence is relatively low, the attenuation of the wake (with distance or transit time) is similar to the results determined by other wake studies in the coastal (onshore) environment. Compared with the empirical model of insufficient relative wind speed on transit time, the results of the sonar experiment are closer to the predicted insufficient speed on the 0.05 m roughness, instead of using the prediction of 0.0002 m sea roughness, as shown in Fig. 5. This may indicate that offshore wind farms in a coastal environment (3 kilometers from the coast) can be effectively modeled using wake models designed for onshore wind farms.

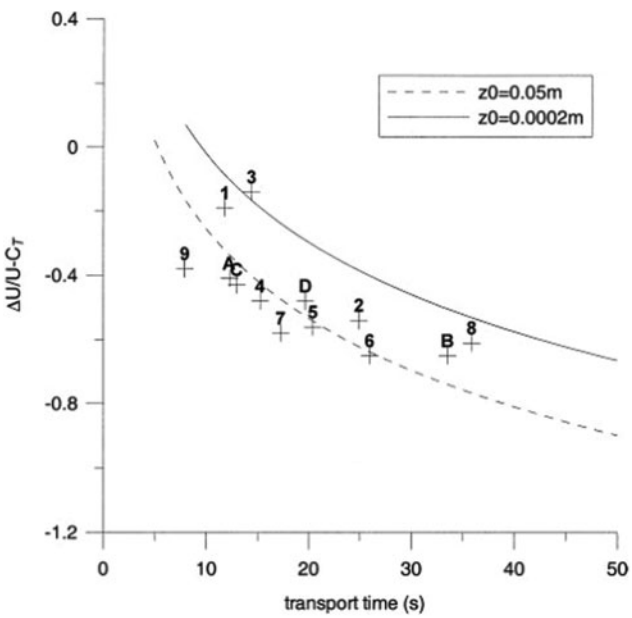


**Figure 5:** Relative velocity deficit and transport time calculated for two different roughnesses [representing onshore (0.05 m) and offshore (0.0002 m) and from the sodar data] [53]

Coriolis force is the result of the rotation of the Earth. Some researchers often overlook the horizontal part of the earth's rotation when conducting wind turbine wake studies, which affect the balance of vertical momentum. The horizontal component results in systematic differences in the structure and statistics of stratified atmospheric boundary layers as a function of the direction of the geostrophic velocity. These differences are particularly relevant to atmospheric flows which include inhomogeneous roughness elements such as drag disks or wind turbines since the presence of these drag elements alters the balance between turbulent stresses and the Coriolis contributions in Reynolds stress budgets [54]. Affected by the Coriolis force, the wake of a wind turbine operating in the northern hemisphere is skewed to the right with respect to the direction of the incoming wind. Therefore, when the wind turbine makes a positive yaw, its wake moves further to the right, and the downstream wind turbine is less affected by the wake. However, a negative yaw pushes the wake to the left, counteracting the deflection caused by the Coriolis force. The downstream wind turbines are more exposed to the wake of the upstream wind turbines, and their power generation reduces. In this regard, Reza et al. [55] conducted research and found that in the presence of the Coriolis force, when all wind turbines rotate clockwise, the difference between the power generation of the two rows of front-row wind turbines with positive yaw and negative yaw is about 17%. When the Coriolis force was set to zero, this difference reduced to approximately 7%. When the turbines were set to rotate in the counterclockwise direction, the difference reduced to approximately 11%. When both factors were relaxed, the difference was reduced to approximately 5.5%. In addition, the influence of Coriolis force on the wake distribution of wind turbines in the southern hemisphere needs to be studied separately.

### *4.3 Effect of Blade Control*

Some researchers have proposed and studied several active wake control strategies to decrease the power loss of downstream wind turbines by steering or weakening the upstream wake. Ryan et al. reviews these strategies, including yaw control, pitch control, torque control, tilt control, and finally, cone angle control [56]. Among them, the cone angle control is the least effective method for increasing the total power output as the existing literature unanimously concludes that cone control leads to an overall power loss. Serrano et al. [45] proposed a new method based on optimizing the blade pitch strategy of offshore wind turbines to maximize the global energy output. This method considers the influence of the Gaussian wake model and additional turbulence. The individual pitch angle of each turbine is determined so that the total loss caused by the wake effect is minimized. Considering the influence of the wake between wind turbines, the pitch angle of each wind turbine is used as the optimized variable to maximize the total energy generated by the wind farm. Wang et al. [57] believed that through different control methods to change the wake direction, although the output power of the upstream wind turbine may decrease slightly, it can significantly increase the total output power of the entire wind farm. The wake deviation control strategy can globally optimize the offshore wind farm, and the yaw control strategy has better effects. For the tilt control strategy, the positive tilt angle is better than the negative tilt angle. Compared with the tilt control strategy, the yaw control strategy can obtain a larger total output power of offshore wind farms. For the total output power of offshore wind farms, the yaw and tilt control strategies have an optimal angle, which is usually 30° of the deviation angle. Under these circumstances, the output power of the upstream and downstream wind turbines is quite large. In general, the amount of the wake deflection has been found to increase with the increase of yaw angle and the increase of thrust coefficient [58,59]. This suggests that the yaw-angle control of wind turbines is more plausible for offshore wind farms, or for turbines operating in a stable boundary layer.

### *4.4 Effect of the Platform Movement*

At present, large-scale floating wind farms are developing rapidly. For this reason, it is necessary to understand and analyze the wake effects of floating wind turbines more accurately, especially the difference between the wakes of floating offshore wind turbines and stationary wind turbines. For floating wind turbines, Sebastian et al. [60] pointed out through preliminary research that the movement of the floating platform may cause changes in the working state of the wind turbine and the distortion of the wind turbine wake as shown in Fig. 6. However, the traditional BEM or GDW method cannot accurately simulate the above due to inherent limitations. Then they converted by frequency analysis further study the effects of exercise on a raft of aerodynamic characteristics of the blades and the possibility of the wind turbine entering the vortex ring state through the reduced frequency analysis. They developed a floating wind turbine aerodynamic load calculation program based on the free-run wake method, and studied the wake evolution and induction of three floating wind turbines and the change law of aerodynamic loads under various working conditions. The results showed that: the movement of the floating platform causes the wake largely different from that of the fixed wind turbine, and the pitch and yaw motion of the floating platform have a greater impact on the aerodynamic characteristics of the wind turbine [61,62]. Johlas et al. [63] used large eddy simulation with actuation line model to simulate the wake characteristics of NREL 5MW wind turbines installed on OC3-UMaine spar platform in different marine environments. The comparison and analysis of the wake characteristics of the fixed wind turbines show that the difference in wake characteristics between floating offshore wind turbines and stationary wind turbines is related to the average displacement of the platform, and the turbulence characteristics of the wake are related to the time-varying motion of the platform.

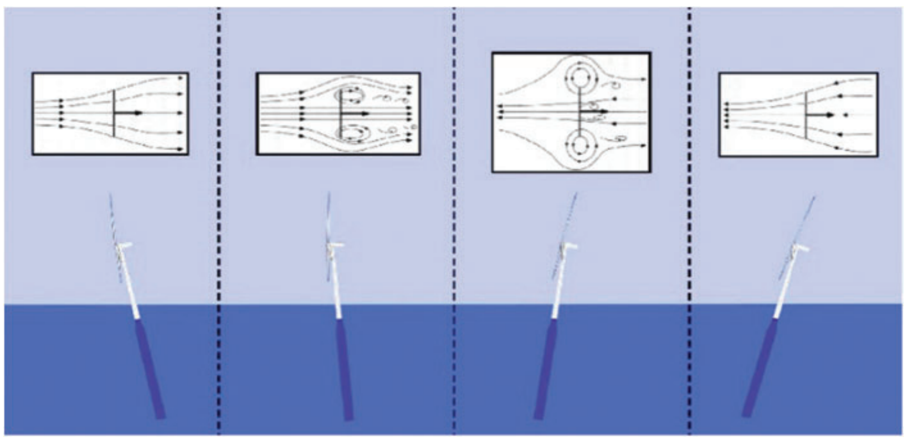

**Figure 6:** Schematic diagram of the change of the working state of the wind turbine caused by the movement of the platform [60]

In model experiments, Lee et al. [64] studied the unsteady wake characteristics of floating offshore wind turbines in low-speed wind tunnels. For wind turbines undergoing single-degree-of-freedom motion, only the flow direction motion including surge and pitch motion significantly affects the thrust and power output of the wind turbine [64]. The reason can be attributed to the correlation of the flow direction component of the motion-induced velocity for determining the effective angle of attack. These movements result in significant oscillations in aerodynamic performance, and the oscillation frequency is consistent with the frequency of the platform movement. As shown in Fig. 7, periodic deformations of the near wake and middle wake structure relative to the wake are observed. The evolution of the unsteady wake eventually leads to the rapid rupture of the spiral wake vortex and the significant distortion of the downstream far wake. Therefore, compared with stationary wind turbines, significant wake instability occurs in floating offshore wind turbines, and highly unstable wake vortices are generated. In addition, these changes result in an asymmetrical distribution of insufficient speed around the rotor area, resulting in unstable inflow conditions on the downstream wind turbines.

Xiong et al. [65] have conducted experimental research on the wake characteristics of the semi-submersible offshore wind turbine model through wind tunnels and wave flume. They believed that there is a strong interaction effect between the wake of the wind turbine and the wake of the platform. Fig. 8 shows profiles of the normalized difference $-\Delta\overline{u{\cdot}w_{i,0}}(x, z)$ in the wake. In general, $-\Delta\overline{u{\cdot}w_{i,0}}$ in Q2 increases in the upper part and decreases in the lower part. Therefore, the momentum is transported into the wake from the ambient fluid. It is noteworthy that $-\Delta\overline{u{\cdot}w_{i,0}}$ in Q2 increases in the region with $x \leq 3D$ and $z/\delta \leq 0.18$, indicating that a part of the energy is transported downward to the platform wake, compared to the incoming ABL. Therefore, compared to the wind turbine without the platform, the total energy is reduced for the wind turbine wake recovery. Moreover, the energy for the recovery of platform wake is reduced compared to the platform only situation. Energy transfer analysis confirmed the interaction effect between the wake of the wind turbine and the wake of the platform.

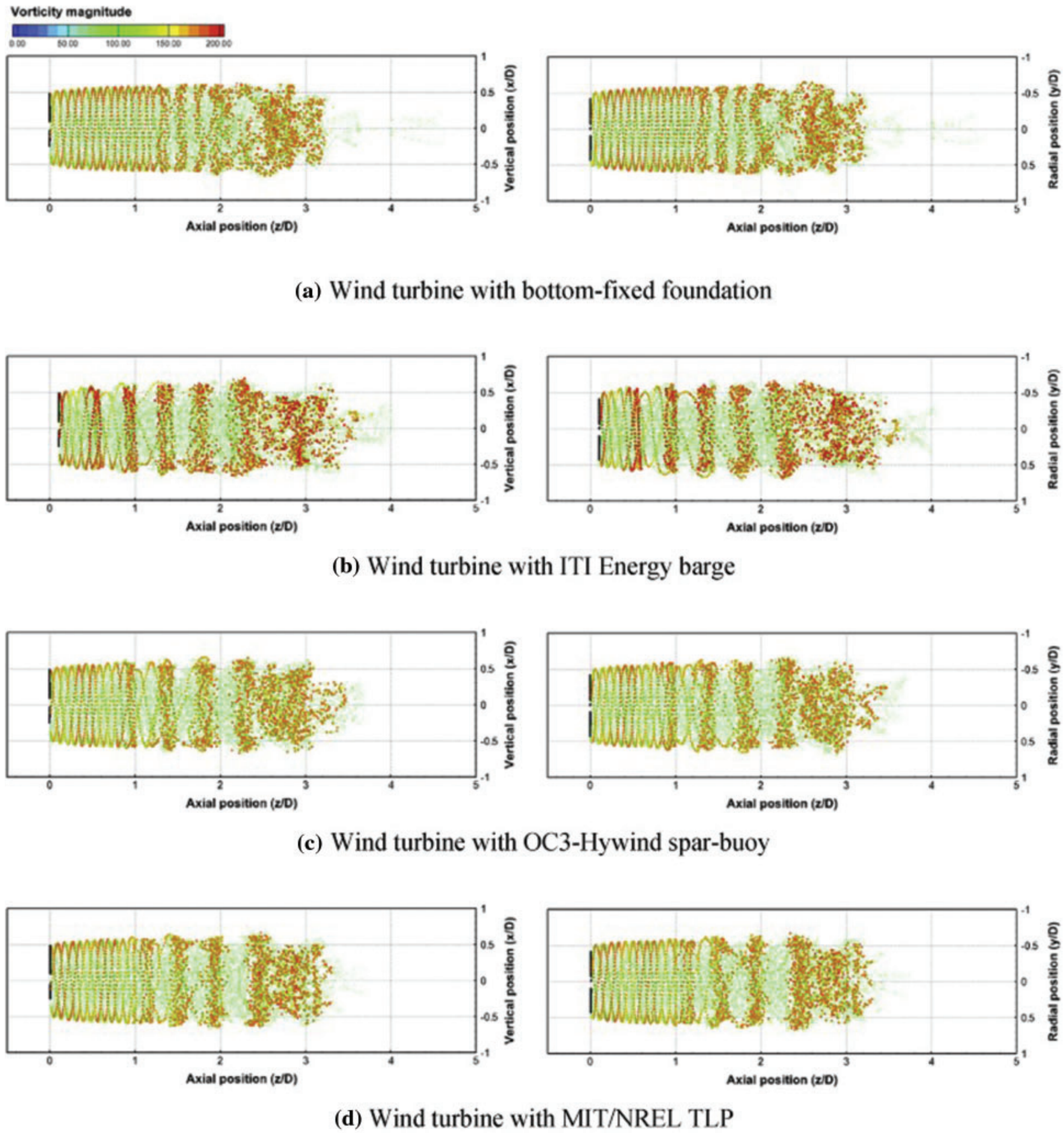


**Figure 7:** Wake structures of wind turbine under multiple-DoF motions [64]

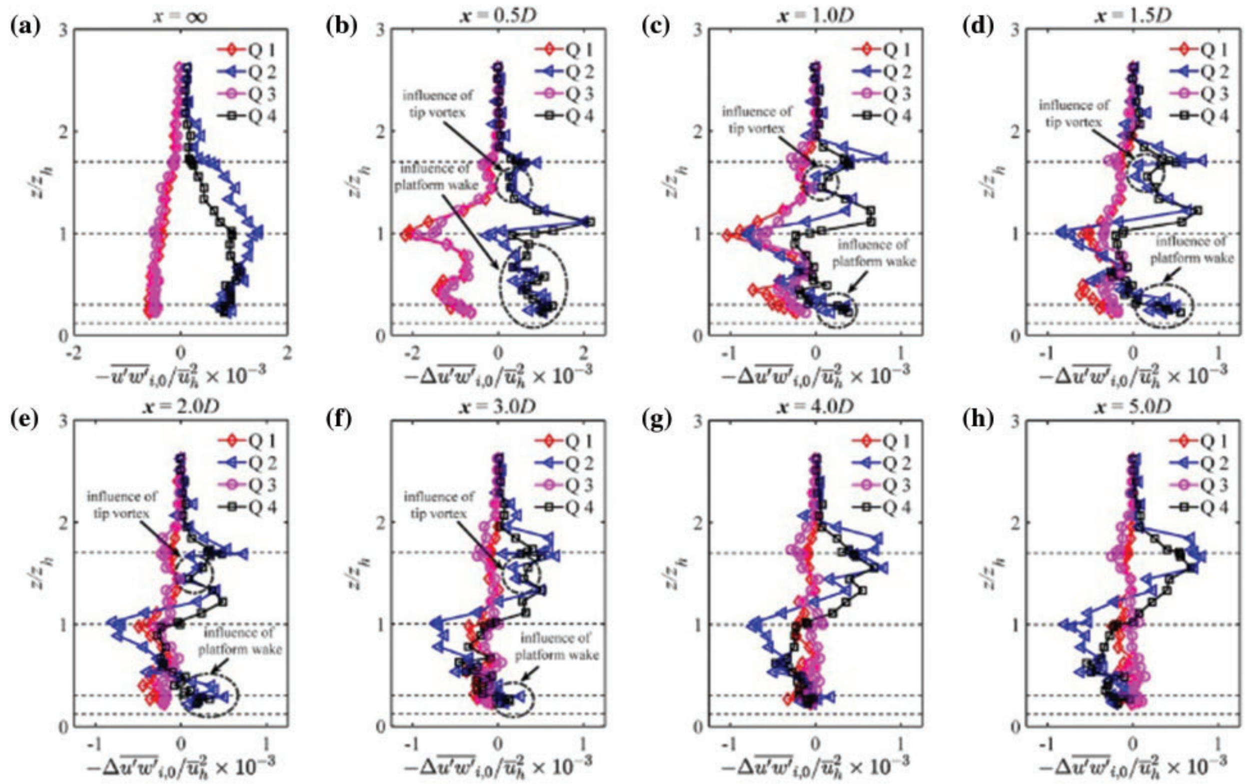


**Figure 8:** (a) Normalized event-averaged shear stress profile of incoming boundary layer in each quadrant, (b)–(h) difference of the normalized event-averaged shear stress profiles in each quadrant between the incoming boundary layer and wake at different downstream locations. Horizontal black dashed lines represent the heights of the upper tip, hub, lower tip and the top of the platform [65]

The changes caused by rotor motion are much smaller than those caused by turbulent fluctuations. Wang et al. [66] studied the effect of floating offshore wind turbines pitching motion on wake caused by ocean waves and found that the pitching motion of floating offshore wind turbines caused by waves would cause oscillations in turbulence intensity and Reynolds stress, and at the same time cause the upper edge of the wind turbine. The surrounding vertical speed was increased by 15%. The combined effect of the wind speed oscillation caused by the expansion and the speed of the turbine rotor disk caused by the pitching motion shifts the phase dependence of the expansion wave by nearly 180°. Han et al. [67] introduced the use of aerodynamic thrust to control the platform position of a large floating offshore wind turbine in the direction of surge and sway. Position control will help alleviate wake effects. Summarizing the above research work, the wake effect of floating wind turbines have new characteristics due to wave-induced motion. At present, some scholars have begun to pay attention to these issues and have carried out preliminary research. However, in order to fully understand the wake effect of floating wind turbines and the underlying mechanism, more in-depth research is needed.

## 5 Conclusion

This article reviews the research methods of wind turbine wake effects, and summarizes the current influencing factors of offshore wind turbine wakes. The key issue is how to propose a high-precision wake model for offshore wind farms and to improve the power generation efficiency under the influence of the wake effect.

Offshore wind farm wake effects research methods include wind tunnel experiment method, wind field measurement, simulation method based on CFD, and semi-empirical model based on experiment summary. The details of the wake distribution can be studied by the CFD method. The approximate distribution of the far-wake flow field can be studied through engineering empirical models. And through the wind tunnel experiment and wind field test methods to compare the calculation accuracy. Engineering wake model can describe the far-field wake information conveniently and quickly. However, it cannot capture the near-wake flow field, and it relies on experience. There is no universal wake flow model. CFD method can completely obtain the information of the near and far wakes. However, due to the large amount of computation, it is difficult to carry out micro-site optimization and other engineering calculations.

Offshore wind farms do not have uneven wind speed caused by irregular terrain. Wind farms can be deployed in larger areas. However, there is currently a lack of research on the wake effects of offshore wind turbines. There are certain difficulties in the study of offshore wind turbines wake effect and problems to be solved urgently in the future. First, the floating offshore wind turbines wake characteristics are affected by the floating platform motion. The influence of complex floating platform motion on the near wake and far wake characteristics needs to be resolved. Second, the current numerical calculation results of offshore wind farms wake lack the actual field test results accuracy. Offshore wind farm wake testing needs to be carried out to obtain reliable on-site wake data. Finally, the current wake model is basically derived from the onshore wake test results. It cannot accurately represent the wake characteristics of offshore wind farms. A high-precision wake prediction model suitable for offshore wind farms is yet to be proposed. In the future, high-precision predictions will be made for offshore wind farms. It can accelerate the deep-sea wind farms construction and improve the offshore wind farms energy efficiency.

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