Experimental investigations on the Aerodynamics and Aeromechanics of wind turbines for floating offshore applications

Morteza Khosravi

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Experimental investigations on the aerodynamics and aeromechanics of wind turbines for floating offshore applications

by

Morteza Khosravi

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Co-majors: Aerospace Engineering, Wind Energy Science Engineering and Policy

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Ames, Iowa
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ABSTRACT

There are many advantages in floating wind turbines in deep waters, however, there are also significant technological challenges associated with it too. The dynamic excitation of wind and waves can induce excessive motions along each of the 6 degrees of freedom (6-DOF) of the floating platforms. These motions will then be transferred to the turbine, and directly impact the wake characteristics of the floating wind turbines, and consequently the resultant wind loadings and performances of the wind turbines sited in offshore wind farms.

In the present study, a comprehensive experimental study was performed to analyze the performance, loading, and the near wake characteristics of a rigid wind turbine model subjected to surge, heave, and pitch motions. The experimental study was performed in a large-scale atmospheric boundary layer wind tunnel with a scaled three-blade Horizontal Axial Wind Turbine model placed in a turbulent boundary layer airflow with similar mean and turbulence characteristics as those over a typical offshore wind farm. The base of the 1:300 scaled model wind turbine was mounted on translation and rotation stages. These stages can be controlled to generate surge, pitch and heave motions to simulate the dynamic motions experienced by floating offshore wind turbines. During the experiments, the velocity scaling method was chosen to maintain the similar velocity ratios (i.e., the ratios of the incoming airflow flow to that of turbine base motion) between the model and the prototype.

During the experiments, a high resolution digital particle image velocimetry (PIV) system was used to achieve flow field measurements to quantify the characteristics of the turbulent vortex flow in the near wake of the wind turbine model. Besides conducting “free run” PIV measurements to determine the ensemble-averaged statistics of the flow
quantities such as mean velocity, Reynolds stress, and turbulence kinetic energy (TKE) distributions in the wake flow, ‘‘phase-locked’’ PIV measurements were also performed to elucidate further details about evolution of the unsteady vortex structures in the wake flow in relation to the position of the rotating turbine blades. The effects of the surge, heave, and pitch motions of the wind turbine base on the wake flow characteristics were examined in great details based on the PIV measurements. The findings derived from the present study can be used to improve the understanding of the underlying physics for optimal mechanical design of floating offshore wind turbines, as well as the layout optimization of floating offshore wind farms.

Although, the mean power measurement results show little difference between the oscillating turbine and the bottom fixed turbine, but the excessive fluctuations in the power output of the oscillating turbine is anticipated to greatly reduce the power quality of such floating turbines. The load measurements also show substantial amount of difference both in terms of mean and the fluctuating components. The results of the wake study reveal that the wake of a wind turbine subjected to base motions, is highly dependent on which direction the turbine is oscillating. In the case of the moving turbine, the wake accelerates as the turbine is moving with the flow, hence, reducing the power extraction by the turbine. A decrease in Reynolds shear stress and the turbulent kinetic energy production was noted as the turbine was oscillating with the flow. However, as the turbine was moving into the flow, these effects reverse, and causes a deceleration in the wake of the moving turbine, hence increases the power production by the turbine, and increase the Reynolds shear stress and the turbulent kinetic energy.
Finally, the wake flow field (x/D < 2.5) measurements behind a two-bladed Darrieus type VAWT were also carried out by using a high-resolution PIV system, and the results obtained at two different horizontal (x-y) planes, at the equator height (H/2) and above the equator height (3H/4), for four different tip speed ratios (λ = 2, 2.5, 3 and 3.5) of the VAWT were then evaluated and compared. The wake of the VAWT is found to be significantly different to that of the HAWT’s. At lower tip-speed-ratio (i.e. TSR 2) the wake tends to be very asymmetric and skewed with relatively higher amount of momentum in the wake in comparison to higher tip-speed ratios (i.e. 3 or 3.5). As tip-speed ratio increases, there is a tendency in flow stagnation in the wake and eventually flow reversal would occur at higher tip-speed-ratios. The wake dynamics (i.e., the instabilities inherent in VAWT) behind the VAWTs would lead to a much faster wake recovery in comparison to the HAWTs.
CHAPTER 1
GENERAL INTRODUCTION

Offshore Wind Energy

Wind has the capability of becoming a major contributor in the world’s energy production. In the United States, the production of electricity through onshore wind has already become one of the fastest growing energy sources. The increasing popularity of using wind as a renewable source of energy is in response to the limited supply of fossil fuels, environmental concerns over the use of non-renewable energy sources, and to reduce our dependence on foreign oil (MANWELL, 2012).

Due to the availability of suitable lands with higher wind speeds, the middle portion of the U.S. provides a unique condition for onshore wind farm developments. Although the wind resource in this area has the potential of providing substantial amount of clean energy for the entire nation, but the challenges associated with transporting this generated electricity to higher demand areas of the coastal regions would put a limit on how much electricity can actually be produced in this part of the country (Jonkman, 2007).

Wind turbines can also be installed offshore. Offshore wind energy is one of the most abundant and promising sources of energy that can provide substantial amount of clean, domestic, and renewable energy. The United States is especially fortunate to be surrounded by vast waters on both sides of the nation. This provides a unique opportunity for offshore wind farm developments in this country. There is over 4000 GW of wind potential within 50 nautical miles of the U.S. coastlines (Musial et al, 2010). The abundant U.S. offshore wind resources have the potential of powering the high populated areas in the coastal regions where the energy cost and demand is much higher than many other locations in the
United States. Figure 1, illustrates the average U.S. wind speeds for both onshore and offshore taken at the height of 100 meters (a), and the U.S. bathymetry distribution (b).

Figure 1: The U.S. wind resources for onshore and offshore (a), and the bathymetry distribution (b) (http://apps2.eere.energy.gov/wind/windexchange/)
Although, offshore wind farms have many advantages over their onshore counterparts, but the most promising feature of an offshore wind farm is the vast availability of areas for such activities, considering 71% of the Earth is covered by water. This allows for large scale developments usually in the range of 1 GW near the load centers of coastal regions. (Hau, E.)

Other advantages include, but not limited to:

- The wind farms can be placed close enough to the shore so that transporting the generated electricity will not be costly or difficult, and at the same time they can be placed far enough offshore so that the visual and sound pollutions will not impact the coastal residents.

- The size of the offshore wind turbines are not limited by inland transportation constraints assuming the turbines can be manufactured near the coasts, and therefore multi megawatt turbines usually in the range of 5-10MW can easily be installed offshore.

- Stronger and steadier wind speeds at lower altitudes can provide an opportunity for reducing the tower heights while maintaining or perhaps increasing the energy output.

- The lower turbulence intensities offshore than onshore results in less fatigue loads on the turbine components, hence reducing the cost of O&M.

As shown in Figure 2, offshore wind energy is divided into three categories, depending on the depth of water where the turbines are being installed. The depth of the water dictates the type of substructure technology needed to install the offshore wind turbines. In shallow waters (0 m to 30 m), the turbines are being fixed to the sea floor by means of a monopile
or gravity based foundations. In intermediate waters (30m to 60 m), the wind turbines are also being fixed to the sea floor but by different kind of substructures such as jacket or tripods. As the water depth increases beyond 60m, the cost of substructure increases substantially, making it almost economically infeasible to fix the turbines to the sea floor. Therefore, the turbines will need to be floated in deep waters.

By the end of 2014, there were 74 offshore wind farms operating in 11 European countries, yielding over 8 GW of electricity. All of these wind farms are located in shallow waters with depths less than 20 meters where the turbines are fixed to the sea floor (Corbetta G., 2015). Unlike the shallow European waters, the U.S. waters are, on the other hand, mostly deep (with the exception of a few regions in the East Coast and the Gulf of Mexico). Therefore, offshore wind farm development in the U.S. will most likely be based on the floating concept.
As shown in Figure 3, there are six degrees of freedom (6-DOF) associated with any floating structures, three in displacements (surge, sway, and heave) and three in rotations (roll, pitch, and yaw).

![Figure 3: Degrees of freedom associated with a floating turbine](image)

There are many advantages of floating wind turbines in deep waters. However, there are also significant technological challenges associated with it too.

The floating platforms that have been proposed for floating wind turbines include; semi-submersible, tension leg platform, and spar buoy. However, regardless of the type, floating platforms cannot easily provide high degrees of stability for mounting wind turbines. This is especially true for the Horizontal Axis Wind Turbines (HAWT). For a HAWT system, the mass of the floater is of the same order of magnitude as the mass of the nacelle and rotor assembly, and therefore, the center of gravity (C.G.) of a HAWT system is located at a much higher location in relation to their Center of Buoyancy (C.B.), hence, creating an unstable floating structure. Therefore, any external forces seen by the floater, will influence the rotor assembly, and any forces felt by the rotor assembly will be affecting the floater system.
In reality, any floating structure would need to be secured and mounted to the seafloor by means of mooring lines or tendons. The mooring lines are used to keep the turbines in place, and at the same time they increase the stability of the floating structure. The mooring line stability is achieved because, as the floating structure is being impacted by the external loading such as wind, wave, current, and etc., displacing the whole structure. As a result of this displacement, the mooring lines would go into high tensions. The high tensioned lines, would have two components. The horizontal component of the tension force, would be opposing the external loads, bringing the turbine to its original location. While, the vertical component of the tension force in the mooring lines, would be pointing downward, lowering the C.G. of the structure and bringing it closer to the C.B. hence, stabilizing the structure.

The dynamic excitation of wind and waves will induce excessive motions along each of the 6 degrees of freedom (6-DOF) of the floating platforms. These motions will then be transferred to the turbine, and directly impact the turbines’ performance, loading and consequently, the wake characteristics of the floating wind turbines. Both coupled and uncoupled motion study of the floating turbines are important and necessary, in order to determine the contributions of each motions along each of the DOFs to the overall performance, loading, and the wake characteristics of floating wind turbines. However, the current study focuses only on the effects of the uncoupled base motions on the performance and the near wake behavior of the oscillating turbine.

The current study considers only the effects of the floater motions (base motions) on the performance, loading, and the near wake behavior of a horizontal axis wind turbine.
Atmospheric Physics

The atmosphere is in motion at all times. The layer of atmosphere in close vicinity of a surface, whose velocity is affected by the viscous shear is called atmospheric boundary layer (ABL). A one-dimensional development of boundary layer on a flat plate is shown in Figure 4.

At any instant of time, the air particles move in all three directions, as follow:

\[(u, v, w) = (U + u', V + v', W + w')\]  \hspace{1cm} (1)

With \(u, v,\) and \(w\) being the total component of the velocity in \(x\) (stream-wise), \(y\) (lateral), and \(z\) (perpendicular to \(x\)-\(y\) plane) directions. The capital letters \(U, V,\) and \(W\) denote the mean components of the velocity, while \(u', v',\) and \(w'\) are the fluctuations about the mean. For the sake of consistency and to avoid any confusions, these notations have been followed closely throughout the current study.

As a result of the velocity gradient between the layers of flow, \(\frac{du}{dy}\), the shear stress \(\tau\) develops in the boundary layer. It is this shear stress that causes drag on immersed objects in the fluids.

The boundary layer is thinner over smooth surfaces (sea, ocean or ice) and much thicker over rough surfaces such as hilly, forested or urban terrains with buildings. Inside the boundary layer, the flow is dominated by surface friction and viscous effects. The wind velocity at the surface is zero due to the no-slip condition. The vertical exchange of
momentum and heat are related to the stability of the atmosphere. The stability of the atmosphere indicates whether the atmosphere develops turbulence or waves of growing amplitudes.

The stable stratification happens when the underlying surface is colder than the air, and hence the flow becomes laminar. Under this condition, a weak turbulence is generated by shear and destroyed by viscosity and buoyancy forces.

The unstable condition happens when the underlying surface is hotter than the surrounding air. This causes a vertical movement of air. In unstable conditions, due to the mixing from thermally generated eddies, the turbulent mixing happens at different layers of atmosphere.

At near neutral stability condition, we only have the mechanically generated turbulence which is mainly due to the surface drag.

There is a strong connection between ambient turbulence levels and the atmospheric stability. As the atmosphere becomes more stable (i.e. ambient turbulence levels decrease), the wake effects become more persistent (Hansen et al., 2012; Zhang et al., 2013; Abkar & Porte-Agel, 2014). The lower turbulence levels will induce deep array effects (pronounced for offshore environments) within the wind farm/array, causing greater velocity deficits; hence greater power deficits for downstream turbines. Therefore, deep array effect would lead to under-prediction of wake losses in large offshore wind farms (Barthelmie & Jensen, 2010).

The vertical variation of mean wind speed, also known as the wind speed profile or wind shear, is modeled using log law or power law. Equation 2, shows the logarithmic law under neutral stability condition as it is the case for wind tunnel testing. In this equation, $y_0$ is the roughness length (m) associated with the type of terrain, $z$ is the height above the
surface, \( k \) is the Von-Karman constant which is 2.5, and \( u_* \) is the frictional velocity specific to each terrain.

\[
U(y) = \frac{u_*}{k} \ln \left( \frac{y}{y_0} \right)
\]

(2)

The roughness height \( y_0 \) can be estimated using Charnock’s equation:

\[
y_0(U) = \frac{C u_*^2}{g} = \frac{C}{g} \left[ \frac{0.4U}{\ln \left( \frac{y_{hub}}{y_0(U)} \right)} \right]
\]

(3)

Where \( C \) is a constant coefficient between 0.011 for open sea and 0.034 for near coastal regions, \( g \) is the acceleration due to gravity. The value of \( y_0 \) is small and ranges between 0.001-0.003m for ocean surfaces.

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Roughness length: m</th>
<th>Landscape features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>sea</td>
<td>0.0002</td>
<td>open water, tidal flat, snow with fetch above 3 km</td>
</tr>
<tr>
<td>2</td>
<td>smooth</td>
<td>0.005</td>
<td>featureless land, ice</td>
</tr>
<tr>
<td>3</td>
<td>open</td>
<td>0.03</td>
<td>flat terrain with grass or very low vegetation, airport runway</td>
</tr>
<tr>
<td>4</td>
<td>roughly open</td>
<td>0.10</td>
<td>cultivated area, low crops, obstacles of height ( H ) separated by at least 20 ( H )</td>
</tr>
<tr>
<td>5</td>
<td>rough</td>
<td>0.25</td>
<td>open landscape, scattered shelter belts, obstacles separated by 15 ( H ) or so</td>
</tr>
<tr>
<td>6</td>
<td>very rough</td>
<td>0.5</td>
<td>landscape with bushes, young dense forest etc. separated by 10 ( H ) or so</td>
</tr>
<tr>
<td>7</td>
<td>closed</td>
<td>1.0</td>
<td>open spaces comparable with ( H ), e.g. mature forest, low-rise built-up area</td>
</tr>
<tr>
<td>8</td>
<td>chaotic</td>
<td>over 2.0</td>
<td>irregular distribution of large elements, e.g. city center, large forest with clearings</td>
</tr>
</tbody>
</table>

Figure 5: Terrain classification and corresponding roughness length (Wieringa, 1992)
The power law is just another method used for modeling vertical variation of mean wind speed. Although, this model is mostly used in wind engineering applications, but there is not any theoretical basis associated with it. In equation 4, \( y_{ref} \) is the reference length (m) which is normally the hub height of the turbine, \( y \) is the height above the surface, \( U_{ref} \) is the wind speed associated with the reference height, and \( U \) is targeted velocity at height \( y \), and \( \alpha \) is what defines the shape of profile. The value of \( \alpha \) would be different for different kinds of terrains.

\[
\frac{U}{U_{ref}} = \left( \frac{y}{y_{ref}} \right)^\alpha
\]  

(4)

Turbulence intensity is another important parameter used when studying wind, which defines the magnitude of the wind fluctuations. The turbulence intensity, \( I_u(y) \), for the longitudinal wind fluctuation, \( u(y) \), is defined as:

\[
I_u(y) = \frac{\sigma_u}{U(y)}
\]  

(5)

Where \( \sigma_u(y) \) is the root mean square of \( u(y) \).

Offshore turbulence intensity can be determined using:

\[
I_u(y) = \frac{1}{\ln\left(\frac{y_{hub}}{y_{ref}(U)}\right)} + \frac{1.28(1.44I_{15})}{U}
\]  

(6)

Where \( I_{15} \), is the reference turbulence intensity calculated using the wind speed of 15 m/s, if the exact value is not specified, and 1.28 is the factor corresponding to the 90% quantile value of the turbulence intensity.
At lower altitudes, the turbulence intensity varies with height. Typically, longitudinal turbulence intensity decreases with increasing height near the ground, but it is almost constant at higher elevations above ground. Longitudinal turbulence intensity also decreases with increasing wind speed for the onshore cases. However, for offshore scenario, this is the opposite. For offshore cases, as shown in Figure 6, the turbulence intensity tends to increase with increasing wind speed. This is mainly due to the coupled relationship between the wind speed and the generated waves and currents, as these increase the roughness height.

Figure 6: Comparison between the onshore and offshore turbulence intensity


**Literature Review**

One of the major issues associated with placing turbines in an array or wind farm is that the wake produced by the front rows of turbines will be impacting the downstream turbines, hence, reducing the performance and increasing the fatigue load on the downstream turbines. These effects could result in up to 23% losses in the total wind farm power production (Barthelmie, et al., 2009). Therefore, it becomes important and necessary to study and investigate the wake dynamics of wind turbines in order to increase the performance of the wind turbines, increase the life time of the turbines, and ultimately, decrease the cost of wind energy.

The wake of a wind turbine is very complex and unsteady in nature. It contains many phenomenon such as tip vortices, vortex shedding, and the shear layer which influence the wake pattern and contribute to the unsteadiness of the flow in the wake.

In a wind farm, because the first row of turbines extract most of the energy from the incoming flow, hence the wake would become more turbulent, and contain lesser amount of energy when compared to the undisturbed incoming flow. The deficit velocity in the wake results in lower energy extraction by the downstream turbines. The increased turbulence in the wake of the turbines would increase the fatigue loading on the downstream turbines, resulting in lowering their lifetime. The study of the wake of the turbines are important and necessary so as to reduce the losses of energy extraction and reducing the fatigue loads on the downstream turbines.

The wake of a wind turbine is divided into near and far wake. The near wake refers to the region approximately one rotor diameter downstream of the turbine. In the near wake, the rotor characteristics such as the number of blades, blade aerodynamics such as stall or attached flows, tip vortices, etc. are present. The helical vortices induced by the rotating
blades are another important parameter of the near wake. The evolution of helical vortices is responsible for the behavior of the turbulent wake flow structures behind the wind turbines. The tip vortices are an important contributor to noise generation and blade vibration (Massouh and Dobrev 2007). The far wake is the region behind the near wake, where the actual rotor shape is less important, but the focus is on wake modeling, wake interference in wind farms, turbulence modeling, and topographic effects (Vermeer et al 2003).

Many studies have been done to understand the effects of the ambient turbulence intensity on the loading, performance, and wake patterns of horizontal axis wind turbines. Power losses due to the wake effects can reach up to 23% depending on the spacing and alignment of wind turbines (Barthelmie et al., 2009). Field measurements at Horns-Rev offshore wind farm revealed nearly 20% recovery on the maximum power deficit of the downstream turbines at higher ambient turbulence levels (Hansen et al., 2012). Barthelmie & Jensen (2010) also estimated that wind farm efficiency at Nysted wind farm will improve up to 9% in unstable conditions with higher ambient turbulence levels.

In a wind tunnel study performed by Ozbay et al (2012), an increase of 6% was reported in the power output of an onshore wind farm over a similar layout corresponding to offshore scenario and concluded that the higher ambient turbulence intensity is the sole responsible for such phenomena. The analysis done by Chamorro and Porte-Agel (2009) shows strong dependence between the velocity deficit and the atmospheric turbulence.

There is a strong connection between the tip vortex breakdown and the shear layer expansion. Lignarolo et al. (2013) showed that tip-vortices could act against the turbulent mixing; however, the break-down of these vortices could enhance turbulent mixing.
The higher turbulence generated in the wake imposes higher dynamic loads on the downstream turbines. The decay of the turbine-generated turbulence was found to be slower than the decay of the velocity deficit in the wake (Sanderse, 2009). Apart from the turbine-generated turbulence, ambient turbulence also plays a central role on the wind farm/array wake dynamics (Ozbay, 2014). The higher ambient turbulence levels not only impose additional dynamic loads on the wind turbines but also promote faster wake recovery (Wu et al., 2012).

Deep-water offshore environments are characterized by strong wind speeds (due to shallower boundary layer profiles), and lower turbulence intensities (due to smoother surface roughness of offshore environments). Generally, the higher and steadier wind speeds would result in higher energy production. The reduced ambient turbulence of offshore environment will help in reducing the fatigue loads on wind turbine components. But, reduced ambient turbulence will also reduce the entrainment of the turbulent kinetic energy (T.K.E.) from the high energy flow above, and therefore, it causes the wake to travel...
longer. Hence, the spacing between the offshore turbines may need to be larger in comparison to that of onshore wind turbines.

Jonkman et al. (2007) performed series of simulations to determine the structural response of the three different platforms for floating offshore wind turbines. The method included using FAST (Fatigue, Aerodynamics, Structures and Turbulence) for classical turbines with hydrodynamic wave-body interaction programs such as WAMIT (Wave Analysis at Massachusetts Institute of Technology). A comparison of three concepts of floating platforms with land-based turbines showed an overall increase of loadings on all turbine components due to the motions of the floating platforms. A preliminary study using the time averaged Unsteady Reynolds Averaged Navier-Stokes (URANS) method to simulate the aerodynamic interaction of the flow and pitch platform motion was performed by Matha et al. (2011). The effects of the mooring system dynamics on the turbine wake was explored for a case where the turbine pitched upwind and downwind in a uniform flow. Findings indicated that the wake of the floating turbine is susceptible to the floating conditions and the dynamics of the surrounding waves.

Rockel et al. (2014) performed a wind tunnel experiment to observe the influence of the platform pitch on the wake of a wind turbine. His results indicated that the platform pitch creates an upward shift in all components of the flow and their fluctuations. He concluded that the vertical flow created by the pitch motion as well as the reduced entrainment of kinetic energy from undisturbed flow above the turbine result in potentially higher loads and less available kinetic energy for a downwind turbine.

Sebastian et al. (2013) performed series of numerical simulations on floating wind turbines, and determined that the blade element momentum theory does not capture the unsteadiness generated in the flow due to significant changes in the angle of attack. Large
angle of attack changes were due to the additional motion of the floating platforms. Motion induced unsteadiness violates assumptions of standard blade element momentum theory and leads to inaccurate predictions of unsteady aerodynamic loads. He showed that pitching motion of the wind turbine causes the turbine to change from the windmill state to the propeller state.

**Motivations for the Current Study**

Studying the loading, performance, and the wake characteristics of wind turbines are not new topics. The wake of wind turbines provide useful information in regards to design optimization of wind turbine’s rotors, and help with the lay-out optimization of wind farms. However, most of these studies have been performed on the classical bottom-fixed turbines, as is the case for onshore wind farms. But as we are starting to saturate the suitable areas needed for onshore wind farm developments, there is an urge for going offshore for tapping some of the stronger and steadier winds offshore.

Although, there is a strong public resistance in the U.S. for going offshore for the purpose of wind energy extraction, but installing wind turbines at offshore locations is not a new phenomenon. Installing wind turbines in the waters have been going on for the past two decades in Europe. However, all of these wind turbines have been installed in shallow waters, where the turbines are fixed to the seafloor. Hence, any wake study of such turbines is essentially similar to the wake of onshore wind turbines, with the exception of the interaction between the wake and the changing roughness height, which would be the result of the coupled behavior between the wind speed and the wave dynamics.

However, in deep waters, the turbines would need to be floated. There are many advantages associated with installing wind turbines in deep waters. Deep water offshore
environment is characterized by higher wind speed and lower ambient turbulence, which could be very beneficial in terms of increased power extraction, and lowering the fatigue loads on floating offshore wind turbines. However, there are also significant technological challenges associated with floating wind turbines. The dynamic excitation of wind and waves will induce excessive motions along each of the 6 degrees of freedom (6-DOF) of the floating platforms. These motions will then be transferred to the turbine, and directly impact the turbines’ performance, loading and consequently, the wake characteristics of the floating wind turbines.

The effect of the floating motions on offshore wind turbine aerodynamics can be thought, as a stationary turbine operating in a highly unsteady and fluctuating flow. Therefore, it is anticipated that these motions would have significant influence on the entrainment of the T.K.E. in the wake, affecting the distance required between the offshore wind turbines, loading and the power extraction of the downstream turbines.

Finally, because of the lower center of gravity, lower mechanical complexity, and lower manufacturing cost, the VAWTs are being considered for floating offshore wind energy applications. Therefore, the last portion of this dissertation, investigates the wakes aerodynamics of a Darrieus type VAWT under different Tip-Speed-Ratios.

**Thesis Organization**

This thesis contains five chapters that are written in journal paper format. In addition, a general introduction (Chapter 1) is given at the beginning and a conclusion is provided as the last chapter of the dissertation (Chapter 7). Due to the format of this dissertation, some repetition might be found in the introduction and experimental setup part of each chapter.
Chapter 2, 3 and 4 discuss the performance, loading, and the wake characteristics of a small model turbine subjected to uncoupled surge, pitch, and heave motions. During the experiments, a high sensitive force/moment transducer was used for measuring both the static and dynamic loading experienced by the wind turbine model. The power output of the model turbine was also measured using a small DC motor which was placed inside the nacelle of the turbine. A high resolution digital particle image velocimetry (PIV) system was used to achieve flow field measurements to quantify the characteristics of the turbulent vortex flow in the near wake of the wind turbine model. Besides conducting ‘‘free run’’ PIV measurements to determine the ensemble-averaged statistics of the flow quantities such as mean velocity, Reynolds stress, and turbulence kinetic energy (TKE) distributions in the wake flow, ‘‘phase-locked’’ PIV measurements were also performed to elucidate further details about evolution of the unsteady vortex structures in the wake flow in relation to the position of the rotating turbine blades. In chapter 5, a couple motion analysis was performed to analyze the effects of full motion on the Aerodynamics and Aeromechanics of a model wind turbine.

Chapter 6 provides a comprehensive study on the Aerodynamics of a vertical axis wind turbine operating at different tip speed ratios.
CHAPTER 2

AN EXPERIMENTAL INVESTIGATION ON THE PERFORMANCE, LOADING, AND THE NEAR WAKE CHARACTERISTICS OF A WIND TURBINE MODEL SUBJECTED TO SURGE MOTIONS

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Abstract: There are many advantages in floating wind turbines in deep waters, however, there are also significant technological challenges associated with it too. The dynamic excitation of wind and waves can induce excessive motions along each of the 6 degrees of freedom (6-DOF) of the floating platforms. These motions will then be transferred to the turbine, and directly impact the performance, loading, and the wake characteristics of floating wind turbines.

A comprehensive experimental study was carried out to analyze the performance, loading, and the near wake characteristics of a wind turbine model subjected to surge motions. The current experimental study was performed in a large-scale atmospheric boundary layer wind tunnel with a scaled three-blade Horizontal Axial Wind Turbine model placed in a turbulent boundary layer airflow with similar mean and turbulence characteristics as those over a typical offshore wind farm. The base of the 1:300 scaled model wind turbine was mounted on a translation stage. The translation stage can be controlled to generate surge motions to simulate the dynamic motions experienced by floating offshore wind turbines. During the experiments, the velocity scaling method was chosen to maintain the similar velocity ratios (i.e., the ratios of the incoming airflow to that of turbine base motion) between the model and the prototype.

Although, the mean power measurement results show little difference between the oscillating turbine and the bottom fixed turbine, but the excessive fluctuations in the power output of the oscillating turbine is anticipated to greatly reduce the power quality of such floating turbines.
The load measurements also show substantial amount of difference both in terms of mean and the fluctuating components. The results of the wake study reveal that the wake of a wind turbine subjected to surge motions, is highly dependent on which direction the turbine is oscillating. In the case of the surge motion, the wake accelerates as the turbine is moving with the flow, hence, reducing the power extraction by the turbine. A decrease in Reynolds shear stress and the turbulent kinetic energy production was noted as the turbine was oscillating with the flow. However, as the turbine was moving into the flow, these effects reverse, and causes a deceleration in the wake of the moving turbine, hence increases the power production by the turbine, and increase the Reynolds shear stress and the turbulent kinetic energy.

**INTRODUCTION**

Offshore wind energy is one of the most abundant and promising sources of energy that can provide substantial amount of clean, domestic, and renewable energy. The United States is especially fortunate to be surrounded by vast waters on both sides of the nation. This provides a unique opportunity for offshore wind farm developments in this country. There is over 4000 GW of wind potential within 50 nautical miles of the U.S. coastlines [24], which is approximately four times the current U.S. power generation capacity. Offshore wind energy is divided into three categories, depending on the depth of water where the turbines are being installed at. The depth of the water dictates the type of substructure technology needed to install offshore wind turbines. In shallow waters (0 m to 30 m), the turbines are being fixed to the sea floor by means of a monopile or gravity based foundations. In intermediate waters (30m to 60 m), the wind turbines are also being fixed to the sea floor but by different kind of substructures such as jacket or tripods. As the water depth increases beyond 60m, the cost of substructure
increases substantially, making it almost economically infeasible to fix the turbines to the sea floor. Therefore, the turbines will need to be floated in deep waters [18].

By the end of 2014, there were 74 offshore wind farms operating in 11 European countries, yielding over 8 GW of electricity. All of these wind farms are located in shallow waters with depths less than 20 meters where the turbines are fixed to the sea floor [14]. Unlike the shallow European waters, the U.S. waters are, on the other hand, mostly deep with the exception of a few regions in the East Coast and the Gulf of Mexico. Therefore, offshore wind farm development in the U.S. will most likely be based on the floating concept.

There are many advantages of floating wind turbines in deep waters, however, there are also significant technological challenges associated with it too. There are six degrees of freedom (6-DOF) associated with any floating structures, three displacements (surge, sway, and heave) and three rotations (roll, pitch, and yaw). The dynamic excitation of wind and waves, will induce excessive motions along each of the 6-DOF’s of the floating platform. These motions will then be transferred to the turbine itself, and directly impact the turbines’ performance, loadings, and consequently the wake characteristics of such turbines.

The study of both coupled and uncoupled motions of the floating turbines are important and necessary to determine the contributions of each motions along each of the DOFs to the overall performance, loading, and the wake characteristics of floating wind turbines. In the current experimental study, advanced diagnostic technique methods were employed in order to elucidate the underlying physics of a wind turbine subjected to surge motions. As can be seen in Figure 1, the surge motion is defined as the linear translation of the turbine in streamwise direction. In the absence of a combined wind-wave basin, and in order to replicate the most dominant motions associated with a floating offshore wind turbines (FOWT), a 1:300 scaled model wind turbine was installed on a high precision 3-DOF motion simulator device.
in a well-controlled, closed loop, dry-boundary layer wind tunnel. The inflow conditions of the wind tunnel were matched to that corresponding to the deep-water offshore environment.

To better understand the effects of the surge motions to the overall performance, and loading, the results were then compared to those of a conventional bottom fixed wind turbine. Beside performance and loading, the near wake characteristics of the turbine subjected to surge motions was also studied. The wake of wind turbines contains many information relevant to design and optimization of wind turbines, and hence important to study. The wake of a wind turbine is divided into near and far wake [21].

![Figure 1: Illustration of turbine's oscillation in surge motion.](image)

The near wake refers to the region approximately one rotor diameter downstream of the turbine. In the near wake, the rotor characteristics such as the number of blades, blade aerodynamics such as stall or attached flows, tip vortices, etc. are present. The helical vortices induced by the rotating blades are another important parameter of the near wake. The evolution of helical vortices is responsible for the behavior of the turbulent wake flow structures behind the wind turbines. The tip vortices are an important contributor to noise generation and blade vibration [4]. The far wake is the region behind the near wake (any region behind 1 diameter downstream of the rotor), where the actual rotor shape is less important, but the focus is on wake modeling, wake interference in wind farms, turbulence modeling, and topographic effects [2].
Many studies have been done to understand the effects of the ambient turbulence intensity on the loading, performance, and wake patterns of horizontal axis wind turbines. Power losses due to the wake effects can reach up to 23% depending on the spacing and alignment of wind turbines [17]. Field measurements at Horns-Rev offshore wind farm revealed nearly 20% recovery on the maximum power deficit of the downstream turbines at higher ambient turbulence levels [20]. Barthelmie et al [16], also estimated that wind farm efficiency at Nysted wind farm will improve up to 9% in unstable conditions with higher ambient turbulence levels.

In a wind tunnel study performed by Ozbay et al [15], an increase of 6% was reported in the power output of an onshore wind farm over a similar layout corresponding to offshore scenario and concluded that the higher ambient turbulence intensity is solely responsible for such phenomena. The analysis done by Chamorro and Porte-Agel [5], shows strong dependence between the velocity deficit and the atmospheric turbulence.

Rockel et al. [3], performed a wind tunnel experiment to observe the influence of the platform pitch on the wake of a wind turbine. His results indicated that the platform pitch creates an upward shift in all components of the flow and their fluctuations. He concluded that the vertical flow created by the pitch motion as well as the reduced entrainment of kinetic energy from undisturbed flow above the turbine result in potentially higher loads and less available kinetic energy for a downwind turbine.

Sebastian et al. [1], performed series of numerical simulations on floating wind turbines, and determined that the blade element momentum theory (BEM) does not capture the unsteadiness generated in the flow due to significant changes in the angle of attack. Large angle of attack changes were due to the additional motion of the floating platforms. Motion induced unsteadiness violates assumptions of standard blade element momentum theory and leads to
inaccurate predictions of unsteady aerodynamic loads. He showed that pitching motion of the
wind turbine causes the turbine to change from the windmill state to the propeller state.

**EXPERIMENTAL SETUP AND PRECEDURE**

a) **AABL Wind Tunnel**

The present experimental study is performed in the large-scale Aerodynamic/Atmospheric
Boundary Layer (AABL) wind and gust tunnel located in the Department of Aerospace
Engineering at Iowa State University. The AABL wind tunnel is a closed-circuit wind tunnel
with a boundary-layer test section 20 m long, 2.4 m wide and 2.3 m high, optically transparent
side walls, and with a capacity of generating a maximum wind speed of 40 m/s in the test
section. Arrays of chains were laid-out on the wind tunnel’s floor on the upstream side of the
wind turbine model in order to match the flow to that of offshore environment. The boundary
layer growth of the simulated ABL wind under almost zero pressure gradient condition was
achieved by adjusting the ceiling height of the test section of the wind tunnel. The oncoming
boundary layer wind velocity profile was fitted by using equation 1, where $z_{ref}$ is a reference
height (hub) and $U_{ref}$ is the wind speed at the reference height. The power law exponent ‘$\alpha$’
is associated with the local terrain roughness. Figure 2, shows the measured streamwise mean
velocity (normalized with respect to the hub height velocity, $U_{hub}$) and the turbulence intensity
profiles of the oncoming flow in the test section for the present study. The power law exponent
in Eq. 1 was found to be $\alpha = 0.10$, corresponding to the open sea boundary layer profile
according to the Japanese standard [25]. GL (Germanischer Lloyd) regulations define a
turbulence intensity of 0.12 at the hub height of offshore wind turbines; however, this value
was determined to be very conservative compared to field measurements. Therefore, for the
current experimental study, a turbulence intensity of 10% at the hub height of the model turbine was chosen.

\[ U(z) = U_{ref} \left( \frac{z}{z_{ref}} \right)^\alpha \]  

Figure 2: The simulated atmospheric boundary layer profiles in the wind tunnel.

b) Wind turbine model

Figure 3 shows, a 1:300 geometrically scaled model horizontal axis wind turbine (HAWT) of height 270 mm (81m in full scale) measured from the wind tunnel’s floor to the hub height of the turbine. However, the base of the turbine’s tower was extended beyond the tunnel’s floor to connect it to the motion simulator fixed underneath the tunnel (an additional height of 130mm). The rotor diameter for this scaled model was chosen as 300 mm (90m in full scale), and the turbine was developed using rapid prototyping method. The rotor blades were designed based on the ERS-100 prototype turbine blades developed by TPI Composites, Inc. The rotor blade has a constant circular cross section from the blade root to 5% blade radius (R), and three
NREL airfoil profiles (S819, S820, S821) were used at different span-wise locations along the rotor blade. The S821 airfoil profile spans between 0.208R and 0.40R, the S819 primary airfoil is positioned at 0.70R, and the S820 airfoil profile is specified at 0.95R. For optimal performance of the rotor, the blades were pitched by 3 degrees.

![Figure 3: The schematic of the model wind turbine used in the present study.](image)

The blockage ratio was calculated to be around 1.3%, which is well within the acceptable limit of 5%. The incoming freestream velocity, $U_\infty$, was set as 3.5m/s at the hub height of the turbine that provided a rotational speed of 17 Hz for the model turbine. The Reynolds number corresponding to the prototype wind turbines range between 500,000 to 6,000,000. However, the corresponding diameter based Reynolds number ($Re_D$) for this experiment was 71000 which was much lower than that of the large-scale wind turbines operating in the fields.

A tip-speed-ratio (TSR) of 4.5 was maintained throughout the test. The tip-speed-ratio, is the ratio between the rotational velocity of the turbine to the free-stream velocity.

$$TSR = \frac{\Omega R}{U_\infty}$$

where $\Omega$ is the angular velocity of the model turbine in rad/s.
Besides matching the TSR between the model and the prototype wind turbines, other scale relationships must also be maintained when dealing with floating wind turbines [10].

Froude number is the ratio between the inertial to gravitational forces. Matching Froude scale ($\lambda_{Fr} = 1$), is the method of choice when dealing with hydrodynamic testing of scaled model floating wind turbines.

By using Froude scaling, the wave forces and response of the floater will be correct (ignoring the scale effect in viscous forces). The wind loads on the turbine should also be scaled using Froude scaling, otherwise the floater motions will not be correct. In hydrodynamic testing, this is achieved by calibrating the correct wind forces, rather than the correct wind velocity. Therefore, once the Froude scaling is applied to the wind velocity, further adaptation of wind velocity will be required in order to achieve an acceptable thrust load on the turbine.

However, in wind tunnel model study of offshore wind turbine, the Froude scaling may not be an appropriate similitude method. This is mainly because the wind speed needs to be adjusted to obtain the correct wind loads on the turbine, if the range of motions on the scaled model turbine as determined using Froude scaling is to be maintained. Therefore, matching Froude number would not be able to accurately capture the characteristics of a floating turbine’s wake that is subjected to base motions.

A scaling method termed here as velocity ratio method was therefore chosen for the current study in order to capture the important characteristics of the wake of the turbine subjected to surge motions. The velocity ratio method was achieved by maintaining the ratio between the maximum velocity of the surge motion to the freestream velocity for both the model and the prototype.
\[
\left( \frac{U_{\text{surge}}}{U_{\infty}} \right)_{\text{prototype}} \sim \left( \frac{2Af}{U_{\infty}} \right)_{\text{model}}
\]

(3)

Where A is the amplitude of displacement and f is the frequency of oscillation in Hz for the surge motion.

c) Motion Simulator

The motion simulator device that was used for the current experimental studies included: an M-ILS150cc (to replicate the surge motion) high precision linear and rotation stages motion simulator manufactured by Newport Corporations. The motion simulator device was carefully installed under the test section floor of the wind tunnel to avoid any flow disturbances due to the presence of such device. The turbine was then placed on top of the motion simulator through a special cut in the tunnel’s floor, to prevent the air from leaking out of the tunnel.

The exact motion for the prototype turbine was determined using the previous numerical simulation results. Using Equation 5, the freestream velocity at the hub height of the scaled model turbine was set to 3.5 m/s, the constant surge velocity was chosen to be \(0.1 \frac{m}{s}\) with a displacement of \((-6\,\text{cm})\) and therefore, the frequency of oscillation was needed to be around 0.5 Hz. However, due to limitation of the motion simulator, this frequency was kept at 0.2 Hz instead.

d) Measurement Systems

The turbine’s power efficiency was determined using the voltage outputs of a small DC generator installed in the nacelle of the wind turbine and the corresponding electrical loading applied to the electric circuits. During the experiment, the voltage output of the DC generator was acquired through an A/D board plugged into a host computer at a data sampling rate of 1
kHz for two minutes. The normalized power output of the model wind turbine (i.e., normalized by the maximum power output of the bottom fixed turbine) were used in the present study for better comparison reasons.

For the wind turbine models used in the present study, an aluminum rod was used as the turbine tower to support the turbine nacelle and the rotor blades. Through a slot in the wind tunnel floor, the aluminum rod was connected to a high-sensitivity force-moment sensors (JR3, model 30E12A-I40) to measure the wind loads (aerodynamic forces and bending moments) acting on the wind turbine model. The JR3 was then attached to the motion simulator. The precision of the force-moment sensor cell for force measurements is ±0.25% of the full range (40 N). While the force-moment sensor mounted at the bottom of each turbine tower can provide time-resolved measurements of all three components of the aerodynamic forces and the moment (torque) about each axis, only the measured thrust coefficient, \( C_{Fx} \), and bending moment coefficient, \( C_{My} \), are given in the present study. The thrust coefficient (along the streamwise velocity direction) and associated bending moment coefficient were defined by using the expressions of 
\[
C_{Fx} = \frac{F_x}{\frac{1}{2} \rho U^2 \pi R^2}
\]
and 
\[
C_{My} = \frac{M_y}{\frac{1}{2} \rho U^2 \pi R^2 H}
\]
where \( \rho \) is the air density, \( U \) is the mean flow velocity at the hub height \( H \). The wind load data were acquired for five minutes at a sampling rate of 1,000 Hz for each tested case. A Monarch Instrument Tachometer was also used to measure the rotational speed of the wind turbine blades.

A 2-D Particle Image Velocimetry (PIV) technique was used (as shown in Figure 4) to capture whole-field information of the wake of both the bottom fixed turbine and the turbine with the surge motion. The coordinate system indicating three velocity components is also shown in Figure 4. The x-coordinate corresponds to the stream-wise direction with the origin located at the center of the tower of the turbine. The y-coordinate which is in lateral direction,
with its origin at the center of the nacelle. Using the right hand rule, the $z$-coordinate would then be perpendicular to the $x$-$y$ plane and will be pointing to the right side of the wind tunnel’s wall.

The flow was seeded with 1-5 μm oil droplets and the laser system used for illumination of the seeding particles was a double-pulsed Nd:YAG laser (Ever Green big sky laser series) emitting two 200 mJ laser pulses at a wavelength of 532 nm and with a repetition rate of 1 Hz. For a better accuracy in results, the laser sheet thickness was adjusted to be around 1 mm. Two high-resolution (2048×2048 pixels) charge-coupled device (CCD) cameras with axis perpendicular to the laser sheet was used for PIV image acquisition. The CCD camera and the double-pulsed Nd:YAG lasers were connected to a workstation via a digital delay generator that controlled the timing of both the laser illumination and the image acquisition.

Instantaneous PIV velocity vectors were obtained using a frame-to-frame cross correlation technique involving successive frames of patterns of particle images in an interrogation window with 32×32 pixels and an effective overlap of 50% to satisfy the Nyquist criterion. The ensemble averaged flow quantities such as mean velocity, turbulent-velocity fluctuations, normalized turbulent kinetic energy, and Reynolds shear stress distributions were obtained from approximately 1000 frames of instantaneous PIV measurements. The measurement uncertainty level for the velocity vectors was estimated to be within 2.0%, and that of the turbulent velocity fluctuations and turbulent kinetics energy was about 5.0%.
EXPERIMENTAL RESULTS AND DISCUSSIONS

The surge motion is believed to be the most dominant linear motion associated with a floating offshore wind turbine, and defined as the linear translation of the turbine along the wind direction (in stream-wise direction).

As shown in Figure 1, the three critical locations for the current study of the surge motion include; front (6 cm ahead of the neutral location), center (the neutral location), and the back location (6 cm behind the neutral location). The flow measurements were used to quantify the differences in the wake of the oscillating turbine in surge motion when the aerodynamic hysteresis occurs. In the hysteresis loop, the differences in the wake flow at the same surge condition were examined along the increasing surge location (i.e., the turbine is moving with the flow) and the decreasing surge location (i.e., the turbine is moving into the flow) branches.
A. Dynamic wind load measurement results

As previously described, a JR3 force-moment transducer was used in the present study that can provide the time-resolved measurements of all three component of the aerodynamic forces and moments about each axis. However, for the current study of the wind loads acting on turbine unit, static or dynamic, only the axial wind loads were considered, while other components of the loads can also be important factor in designing wind turbines and the floating platforms.

Figure 5, gives examples of the wind load measurement results in term of the instantaneous thrust coefficients for both the bottom fixed turbine and the moving turbine in surge motion. As can be clearly seen from the time histories of the measured instantaneous thrust forces given in Figure 5, these loads are highly unsteady with their magnitudes fluctuating significantly as a function of time. The wind loads acting on the bottom fixed turbine in Figure 5(a), were found to be significantly different to the loads seen by the turbine in surge motion 5(b). While the mean value of the wind loads acting on the turbine in surge motion (i.e., \(C_T=0.3950\)) is slightly higher than that of the bottom fixed turbine (i.e., \(C_T=0.3648\)), the fluctuation amplitudes of the surge motion were found to be significantly higher, which consequently increases the fatigue loads and ultimately reduces the life time of the moving turbine and the corresponding mooring lines of the floating platform which holds the turbine.

In Figure 6, the plot on the left corresponds to the power spectra of the measured instantaneous thrust forces acting on both model wind turbines (i.e. bottom fixed turbine and the oscillating turbine in surge motion) through a Fast Fourier Transform (FFT) analysis procedure. In the case of the bottom fixed turbine (i.e. red color), a dominant peak at \(f_0=17\) Hz can be identified which corresponds to the rotational speed of the turbines rotor blades at
the optimum tip-speed-ratio of $\lambda \approx 4.5$. The rotational frequency of $f_0 = 17$ Hz based on FFT analysis of the dynamic wind load measurements was found to agree very well with the independently measured rotational speed of the turbine blades by using a tachometer. However, in the case of the oscillating turbine in surge motion, multiple dominant frequencies are observed. As the turbine was oscillating with a very low frequency, the power spectra plot clearly shows a dominant frequency of 0.2 Hz. As the turbine was oscillating in surge motion, the relative velocity seen by the rotor and the effective angle of attack of the blades significantly change, contributing to significant fluctuations in the rotational frequency of the rotor are apparent in the power spectra plot.

Figure 5: Measurement results of dynamic thrust force acting on the model wind turbine. Left: bottom fixed turbine. Right: turbine in surge motion.
B. Power output performance measurements

As described before, the turbine’s power efficiency was determined using the voltage outputs of a small DC generator installed in the nacelle of the wind turbine and the corresponding electrical loading applied to the electric circuits. In the comparison of the power output performances, power output readings were normalized with the maximum power output, which corresponds to an (optimum) electric loading range of 25Ω.

As can be seen in Figure 7, even though the power output of the bottom-fixed turbine is relatively higher than the turbine in surge motion, but the difference is very small and falls well within the error range of the measuring tools. Therefore, the time averaged power output of both the bottom fixed turbine and the turbine in surge motion are both within the same limit. However, the quality of the power output of the turbine in surge motion would be significantly lower of that of the bottom fixed turbine due to the constantly changing relative velocity seen by the rotor blades due to the front and backward motion of the turbine unit in surge motion.
C. The near wake PIV measurement results

The flow field (x/D < 1.8) measurements behind a wind turbine subjected to uncoupled surge motion was carried out by using a high-resolution PIV system, and the wake results obtained at particular pitch angles were then compared to those of a classical bottom-fixed turbine. In order to make a one to one comparison between the wakes of the classical bottom-fixed turbine and the turbine in surge motion, the wake measurements of the moving turbine in surge motion were taken only when the turbine was passing the center location as either moving into the flow (left) or with the flow (right).

The measurement plane was composed of two fields with an overlap of 15mm length, and two CCD cameras were used to acquire images from these fields. Two fields were then merged in Tecplot to acquire the image in the measurement plane. Finally, ensemble averaged flow quantities, such as mean flow velocity, Reynolds stresses and Turbulence Kinetic energy, were analyzed.

Figure 8, shows the contour plots accompanied by their extracted data (at x/D = 0.8 and x/D=1.7) of the PIV measurements of the averaged stream-wise velocity (U/Uhub) profiles in
the wake of a bottom fixed turbine (a), and the center location for a turbine oscillating in surge motion: as it is moving with the flow (b), as it is moving into the flow (c), and the averaged of the forward and backward motion (d). Each of the contour plots are accompanied by their extracted data (at x/D = 0.8 and x/D=1.7) of the PIV measured normalized relative streamwise velocities.

As can be seen in Figure 8, there is clear evidence of the deficit in the velocity in the wake of both; the bottom fixed turbine and the moving turbine. This deficit is the result of energy extraction by the turbine itself. Double peaks are observed and understood as characteristic of the near wake profiles (X/D <1). But as we go farther down in the wake (X/D >1), the double peaks die out and become just a single peak. This single peak eventually dies out in approximately 15~20 diameter downstream of the turbine, where the flow gains its fullest momentum and becomes the undisturbed flow again. There is some overshoot at the top region of the profiles in the near wake regions, corresponding to the plots of both turbines which suggests that the flow is accelerating at near top-tip of the blade, and also could be an evidence of the blockage effect caused by the existence of the turbine itself.

From the extracted data of Figure 8b and 8c, during the surge motion, as the turbine is at the center location and is moving with the flow (to the right), it’s wake tends to accelerate when compared to the wake of the bottom fixed turbine, suggesting a reduced energy extraction by the rotor. However, when the turbine is moving into the flow (to the left), the wake of the turbine in surge motion decelerate when compared to the wake of the bottom-fixed turbine, suggesting an increase energy extraction by the rotor. This trend is anticipated to become more pronounced as we go down farther in the wake.

The averaged power output of the turbine in surge motion would become very similar to that of the bottom fixed turbine if we average the power over both directions of oscillation (see
Figure 7d). Even though, the overall power production of the turbine in surge motion is quite similar to that of the bottom fixed turbine, however, the power output of the turbine in surge motion would have significantly lower quality when compared to that of the bottom fixed turbine. This is caused by the movement of the turbine into the flow and with the flow which causes differences in the relative velocity seen by the rotor blades.

Figure 9, shows the Reynolds shear stress \((\tau = \frac{-u'v'}{u_{hub}^2})\) and the turbulent kinetic energy \((T.K.E. = \frac{1}{2} \left[ \frac{u'^2 + v'^2}{u_{hub}^2} \right])\) plots. The Reynolds shear stress deals with the transport of momentum from high energy flow above the rotor to the lower energy area of the wake region. The momentum flux which is the rate of change of momentum is also another indicator on how fast the higher energy flow above the turbine is being fed into the lower energy area of the wake region. Therefore, both the Reynolds shear stress and momentum flux are directly related on how fast the wake is recovering. The shear stress observed in the top tip (shear) layer of the oscillating turbine, and the areas covered were found to increase slowly as the wake flow advects downstream for the floating turbine. Therefore, the high momentum flow above the shear layer could mix with the wake flow characterized with greater velocity deficits. These momentum fluxes could play a significant role in wind farms having clusters of wind turbines by accelerating the wake recovery in the far wake region. As a result, downstream turbines could extract more energy from the disturbed flow.

T.K.E. is the kinetic energy per unit mass associated with the eddies in the turbulent flows. Once the momentum has been transported from high energy flow above the rotor, to the low energy areas in the wake of the turbine, then the process of mixing would be taking into account which is characterized by the turbulent kinetic energy. T.K.E. deals with the diffusivity effect which is responsible for enhanced mixing. By studying the Reynolds shear stress and T.K.E.,
one can determine on how fast the wake is recovering. The fluctuating components of the
oncoming boundary layer flow influences the turbulent wake flow structure significantly. For
a uniform flow, mean shear distribution in the turbine wake could be axisymmetric with strong
shear layer (associated with TKE production) at the levels of bottom-tip and top-tip. However,
for an oncoming boundary layer flow with non-uniform mean flow velocity distribution,
previous experimental and numerical studies showed that maximum TKE production would
occur at the top-tip level as a result of strong shear-produced turbulence and turbulent fluxes
(Hu et al. [8]; Zhang et al. [7]; Porte-Agel et al. [6]; Wu et al. [9]). Turbulent fluxes produced
due to wake induced turbulence were found to play an important role on the entrainment of
energy from the flow above the wind farm [23]. As can be seen in Figure 9, the Reynolds shear
stress and the T.K.E. production increases substantially when the turbine is moving into the
flow when compared to the bottom fixed turbine. However, as the turbine is moving with the
flow, this amount is much lower than the bottom fixed turbine. Therefore, it is anticipated that
the wake of the turbine in surge motion moving into the flow to recover much faster when
compared to the bottom fixed turbine, and recover slower when the turbine is moving with the
flow.

Figure 10, show the normalized phase-locked \( \frac{w_z D}{U_{hub}} \) vorticity distributions in the wake of
the bottom fixed turbine and the turbine oscillating in surge motion at a phase angle of \( \theta = 0^\circ \).
The vorticity \( w_z \) values were derived from the phase locked velocity distributions in the
streamwise and vertical directions by using the expression \( w_z = \frac{dV}{dx} - \frac{dU}{dy} \). The phase-locked
PIV measurements could be used to identify the unsteady vortex structures (i.e., tip and root
vortices, and vortices formed within the nacelle boundary layer) generated in the wake.
As shown in Figure 10, the tip vortices were formed in the strong shear layer located at the uppermost level of the wake. Interestingly, an additional array of concentrated vortices were found to shed from the inboard section located at approximately 50% - 60% of the blade span. The origin of these secondary vortices could be attributed to the design imperfection of the blades, which resulted in a separation in the flow and hence generating vortices. Furthermore, these vortex structures were found to expand outwards as they convect downstream and finally merge with those shedding from the blade tips. Moreover, these additional array of concentrated vortices were found to be larger and stronger than those generated by the blade tips. The vortices formed within the nacelle boundary layer with those shedding from the blade root section were found to dissipate much faster than those generated at the tip and inboard section of the blade.

There is a strong connection between the tip vortex breakdown and the shear layer expansion. Lignarolo et al. [22], showed that tip-vortices could act against the turbulent mixing; however, the breakdown of these vortices could enhance turbulent mixing.

The effect of the hysteresis loop on the evolution (i.e., formation, shedding and dissipation) of the unsteady vortex structures for the bottom fixed turbine and the oscillating turbine are shown in Figure 10. The hysteresis loop was found to make no significant changes on the evolution of the unsteady vortex structures. However, slight changes in the shape and magnitude of the vortex structures can be seen. Furthermore, contrary to the bottom fixed turbine, the vortex shedding from the inboard and tip sections of the turbine blade were found to break-down/dissipate faster for the oscillating turbine. However, the behavior of the vortex shedding from the nacelle boundary layer and blade root section was pretty similar for the fixed and the turbine in surge motion.
Figure 8: Normalized stream-wise velocity (U/Uhub) profiles in the wake of a bottom fixed turbine (a), and the center location for a turbine oscillating in surge motion: as it is moving with the flow (b), as it is moving into the flow (c), and the average of the forward and backward motion(d).
Figure 9: Normalized Reynolds Shear Stress ($\frac{\overline{R_{uv}}}{U_{hub}}$) and Turbulent Kinetic Energy ($\overline{\frac{T.K.E}{U_{hub}}}$) plots in the wake of a bottom fixed turbine (a), and the center location for a turbine oscillating in surge motion: as it is moving with the flow (b), as it is moving into the flow (c), and the average of the forward and backward motions (d).
Figure 10: Normalized vorticity distribution $\left( \frac{w_z D}{U_{hub}} \right)$ plots in the wake of a bottom fixed turbine (a), and the center location for a turbine moving in surge motion: the averaged forward and backward motions (b), as it is moving with the flow (c), as it is moving into the flow (d).
CONCLUSION

A comprehensive experimental study was conducted to investigate the performance, loading and the near wake characteristics of a horizontal axis wind turbine subjected to surge motions. The results were then compared to those of a classical bottom fixed turbine. The current study was performed in a large-scale atmospheric boundary layer wind tunnel. The base of a 1:300 scaled model wind turbine was mounted on a translation stage. The translation stage was controlled to generate surge motions to simulate the dynamic surge motions experienced by floating offshore wind turbines. During the experiments, the velocity scaling method was chosen to maintain the similar velocity ratios (i.e., the ratios of the incoming airflow flow to that of turbine base motion) between the model and the prototype.

During the experiments, a high resolution digital particle image velocimetry (PIV) system was used to achieve flow field measurements to quantify the characteristics of the turbulent vortex flow in the near wake of the wind turbine model. Besides conducting “free run” PIV measurements to determine the ensemble-averaged statistics of the flow quantities such as mean velocity, Reynolds stress, and turbulence kinetic energy (TKE) distributions in the wake flow, “phase-locked” PIV measurements were also performed to elucidate further details about evolution of the unsteady vortex structures in the wake flow in relation to the position of the rotating turbine blades.

The results of the wake study reveal that the wake of a wind turbine subjected to surge motions, is highly dependent on which direction the turbine is oscillating. Furthermore, the velocity, frequency, and the range of oscillation also play an important role on the behavior and the wake pattern of the moving turbine. The wake of the oscillating turbine in surge motion, tends to accelerate as the turbine is moving with the flow, hence, reducing the power extraction
by the turbine. A decrease in Reynolds shear stress and the turbulent kinetic energy production was noted as the turbine was oscillating with the flow. However, as the turbine was moving into the flow, these effects reverse, and causes a deceleration in the wake of the moving turbine, hence increases the power production by the turbine, and increases the Reynolds shear stress and the turbulent kinetic energy. Averaging the wake results of both forward and backward motions of the turbine in surge motion produces results which are essentially the same as the wake of the bottom fixed turbine.

Although, the mean power measured by a small DC motor installed in the nacelle shows little difference between the oscillating turbine and the bottom fixed turbine, but the excessive fluctuations in the power output of the oscillating turbine is anticipated to greatly reduce the power quality of such oscillating turbines. The load measurements also show substantial amount of increase both in terms of mean and the fluctuating components for the oscillating turbine. Which consequently results in increased fatigue loads and decreased lifetime of the turbine and the associated floating components.

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CHAPTER 3

AN EXPERIMENTAL STUDY ON THE LOADING, PERFORMANCE, AND THE NEAR WAKE CHARACTERISTICS OF A WIND TURBINE MODEL SUBJECTED TO PITCH MOTIONS

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Abstract: Due to stronger wind speeds at lower altitudes and lower ambient turbulence, floating wind turbines in deep water offshore environments can be beneficial in terms of higher energy production and lower fatigue loads on the turbines. However, there are significant technological challenges associated with floating wind turbines in deep waters. The dynamic excitation of wind and waves can induce excessive motions along each of the 6 degrees of freedom (6-DOF) of the floating platforms. These motions will then be transferred to the turbine, and directly impact the loading, performance, and the wake characteristics of the floating wind turbines in an offshore environment.

In the present study, a comprehensive experimental study was performed to analyze the loading, performance, and the near wake characteristics of a wind turbine model subjected to uncoupled pitch motions. These experimental studies were performed in a large-scale atmospheric boundary layer wind tunnel with a scaled three-bladed Horizontal Axial Wind Turbine model placed in a turbulent boundary layer airflow with similar mean and turbulence characteristics as those over a typical offshore wind farm. The base of the 1:300 scaled model wind turbine was mounted on a rotation stage. The rotation stage can be controlled to generate pitch motions to simulate the dynamics of pitching motions experienced by floating offshore wind turbines.
A high resolution digital particle image velocimetry (PIV) system was used to achieve flow field measurements to quantify the characteristics of the turbulent vortex flow in the near wake of the wind turbine model. Besides conducting “free run” PIV measurements to determine the ensemble-averaged statistics of the flow quantities such as mean velocity, Reynolds stress, and turbulence kinetic energy (TKE) distributions in the wake flow, “phase-locked” PIV measurements were also performed to elucidate further details about evolution of the unsteady vortex structures in the wake flow in relation to the position of the rotating turbine blades. The effects of the pitch motions of the wind turbine base on the wake flow characteristics were examined in great details based on the PIV measurements. The performance of the scaled model wind turbine was measured using a small DC motor mounted in the nacelle assembly. A highly sensitive force/moment transducer was also mounted at the base of the turbine to measure the aerodynamic loading associated with the pitching turbine. For better understanding of the effects of pitching motion on the Aerodynamics and Aeromechanics of wind turbines, the results were then compared to those of a traditional bottom fixed turbine.

The results of the wake studies reveal that the wake of a wind turbine subjected to pitch motions, is highly dependent on which direction the turbine is oscillating. Furthermore, the velocity, frequency, and the range of oscillation also play an important role on the behavior and the wake pattern of the moving turbine. In the case of the pitching turbine, the wake accelerates as the turbine is moving with the flow, hence, reducing the power extraction by the turbine. A decrease in Reynolds shear stress and the turbulent kinetic energy production was noted as the turbine was oscillating with the flow. However, as the turbine was moving into the flow, these effects reverse, and causes a deceleration in the wake of the moving turbine, hence increases the power production by the turbine, and increases the Reynolds shear stress and the turbulent kinetic energy. The mean power measurement using a small DC motor
mounted in the nacelle, show little difference between the power extracted by turbine in pitch motion and the bottom fixed turbine. However, the fluctuations in the power output of the pitching turbine is greatly influencing the quality of power generated by such turbines. The mean thrust load experienced by both turbines are also quite similar. However, the fluctuations in the thrust loading experienced by the pitching turbine is much more than the bottom fixed turbine, hence increases the fatigue loads experienced by the pitching turbine.

**Experimental Setup**

The present experimental study was performed at the large-scale Aerodynamic/Atmospheric Boundary Layer (AABL) wind and gust tunnel located in the Department of Aerospace Engineering at Iowa State University. The AABL wind tunnel is a closed-circuit wind tunnel with a boundary-layer test section 20 m long, 2.4 m wide and 2.3 m high, optically transparent side walls, and with a capacity of generating a maximum wind speed of 40 m/s in the test section. Arrays of chains were laid-out on the wind tunnel’s floor on the upstream side of the wind turbine model in order to match the flow to that of offshore environment. The boundary layer growth of the simulated ABL wind under almost zero pressure gradient condition was achieved by adjusting the ceiling height of the test section of the wind tunnel. The oncoming boundary layer wind velocity profile was fitted by using Equation 1, where $y_{ref}$ is a reference height (hub) and $U_{ref}$ is the wind speed at the reference height. The power law exponent $'\alpha'$ is associated with the local terrain roughness. Figure 1, shows the measured stream-wise mean velocity (normalized with respect to the hub height velocity, $U_{hub}$) and the turbulence intensity profiles of the oncoming flow in the test section for the present study. The power law exponent in Equation 1 was found to be $\alpha = 0.10$, corresponding to the open sea boundary layer profile according to the Japanese standard (AIJ
or Architecture Institute of Japan). GL (Germanischer Lloyd) regulations define a turbulence intensity of 0.12 at the hub height of offshore wind turbines; however, this value was determined to be very conservative compared to field measurements. However, the values of $\alpha$, and the turbulence intensity for offshore locations are site specific and they can vary greatly depending on whether we are talking about the near coast or open seas. For the current experimental study, a turbulence intensity of 10% at the hub height of the model turbine was chosen.

$$\frac{U}{U_{ref}} = \left(\frac{y}{y_{ref}}\right)^{\alpha} \quad (1)$$

Figure 1: Measured stream-wise wind speed and the longitudinal turbulence intensity profiles

Figure 2 shows, a 1:300 geometrically scaled model horizontal axis wind turbine (HAWT) of height 270 mm (81m in full scale) measured from the wind tunnel’s floor to the hub height of the turbine. However, the base of the turbine’s tower was extended beyond the tunnel’s floor to connect it to the motion simulator fixed underneath the tunnel (an additional height of 130mm). The rotor diameter for this scaled model was chosen as 300 mm (90m in full scale),
and the turbine was developed using rapid prototyping method. The rotor blades were designed based on the ERS-100 prototype turbine blades developed by TPI Composites, Inc. The rotor blade has a constant circular cross section from the blade root to 5\% blade radius (R), and three NREL airfoil profiles (S819, S820, S821) were used at different span-wise locations along the rotor blade. The S821 airfoil profile spans between 0.208R and 0.40R, the S819 primary airfoil is positioned at 0.70R, and the S820 airfoil profile is specified at 0.95R. For optimal performance of the rotor, the blades were pitched by 3 degrees.

![Figure 2: The design parameters of the model wind turbine](image)

The blockage ratio was calculated to be around 1.3\%, which is well within the acceptable limit of 5\%. The incoming velocity, $U_\infty$, was set to 3.5m/s at the hub height of the turbine that provided a rotational speed of 17 Hz for the model turbine. The Reynolds number corresponding to the prototype wind turbines range between 500,000 to 6,000,000. However, the corresponding diameter based Reynolds number ($Re_D$) for this experiment was 71000 which was much lower than that of the large-scale wind turbines operating in the fields. A tip-speed-ratio (TSR) of 4.5 was maintained throughout the test. The tip-speed-ratio, is the ratio between the rotational velocity of the turbine to the free-stream velocity.
\[ \text{TSR} = \frac{\Omega R}{U_\infty} \]

where \( \Omega \) is the angular velocity of the model turbine in rad/s.

Besides matching the TSR between the model and the prototype wind turbines, other scale relationships must also be maintained when dealing with floating wind turbines (Martin et al, 2012). Froude number is the ratio between the inertial to gravitational forces. Matching Froude scale \( \lambda_{Fr} = 1 \), is the method of choice when dealing with hydrodynamic testing of scaled model floating wind turbines.

By using Froude scaling, the wave forces and response of the floater will be correct (ignoring the scale effect in viscous forces). The wind loads on the turbine should also be scaled using Froude scaling, otherwise the floater motions will not be correct. In hydrodynamic testing, this is achieved by calibrating the correct wind forces, rather than the correct wind velocity. Therefore, once the Froude scaling is applied to the wind velocity, further adaptation of wind velocity will be required in order to achieve an acceptable thrust load on the turbine.

However, in wind tunnel model study of offshore wind turbine, the Froude scaling may not be an appropriate similitude method. This is mainly because the wind speed need to be adjusted to obtain the correct wind loads on the turbine, if the range of motions on the scaled model turbine as determined using Froude scaling is to be maintained. Therefore, matching Froude number would not be able to accurately capture the characteristics of a floating turbine that is subjected to base motions.

A scaling method termed here as velocity ratio method was therefore chosen for the current study in order to capture the important characteristics of the wake of the turbine subjected to pitch motions. The velocity ratio method was achieved by maintaining the ratio between the
maximum velocity of the pitch motion to the freestream velocity for both the model and the prototype.

\[
\left( \frac{U_{\text{pitch}}}{U_{\infty}} \right)_{\text{prototype}} \sim \left( \frac{2Af}{U_{\infty}} \right)_{\text{model}}
\]  

Where \( A \) is the amplitude of displacement and \( f \) is the frequency of oscillation in Hz for the pitch motion. The motion simulator devices that were used for the current experimental study includes a URS50BCC (for pitch) high precision rotation stages motion simulator manufactured by Newport Corporations and was used to replicate the pitch motions of a floating wind turbine. As can be seen in Figure 3, the motion simulator device was carefully installed under the test section floor of the wind tunnel to avoid any flow disturbances due to the presence of such device. The turbine was then placed on top of the motion simulator through a special cut in the tunnel’s floor, to prevent the air from leaking out of the tunnel.

![Figure 3: Illustration of turbine's oscillation in pitch motion.](image)

A 2-D Particle Image Velocimetry (PIV) technique was used (as shown in Figure 4) to capture whole-field information of the wake of both the bottom fixed turbine and the turbine with the pitch motion. The coordinate system indicating three velocity components is also shown in Figure 10. The flow was seeded with 1-5 \( \mu \)m oil droplets and the laser system used for illumination of the seeding particles was a double-pulsed Nd:YAG laser (Ever Green big sky laser series) emitting two 200 mJ laser pulses at a wavelength of 532 nm and with a
repetition rate of 1 Hz. For a better accuracy in results, the laser sheet thickness was adjusted to be around 1 mm. Two high-resolution (2048×2048 pixels) charge-coupled device (CCD) cameras with axis perpendicular to the laser sheet was used for PIV image acquisition. The CCD camera and the double-pulsed Nd:YAG lasers were connected to a workstation via a digital delay generator that controlled the timing of both the laser illumination and the image acquisition.

Instantaneous PIV velocity vectors were obtained using a frame-to-frame cross correlation technique involving successive frames of patterns of particle images in an interrogation window with 32×32 pixels and an effective overlap of 50% to satisfy the Nyquist criterion. The ensemble averaged flow quantities such as mean velocity, turbulent-velocity fluctuations,
normalized turbulent kinetic energy, and Reynolds shear stress distributions were obtained from approximately 1000 frames of instantaneous PIV measurements. The measurement uncertainty level for the velocity vectors was estimated to be within 2.0%, and that of the turbulent velocity fluctuations and turbulent kinetics energy was about 5.0%. As shown in Figure 3, the x-coordinate corresponds to the stream-wise direction with the origin located at the center of the tower of the turbine. The y-coordinate which is in lateral direction (pointing towards the ceiling), with its origin at the center of the nacelle. Using the right hand rule, the z-coordinate would then be perpendicular to the x-y plane and will be pointing to the right side of the wind tunnel’s wall.

**Results and Discussions**

Out of the six degrees of freedom associated with any floating offshore wind turbines, the pitch motion is believed to be the most dominant motion. As can be seen in Figure 3, the pitching motion is defined as the angular motion of the turbine along the wind direction (the stream-wise). The exact motions for the prototype turbine in pitch motion for the current study were determined using the previous numerical simulations results done on floating wind turbines. For the current study, the freestream velocity at the hub height of the scaled model turbine was set to 3.5 m/s. The turbine was pitched from -5 degrees to +5 degrees. The pitching speed at the base of the tower was set to the maximum amount that the motion simulator could perform to $20 \deg \ s^{-1}$ which resulted in a frequency of 0.3 Hz.

As previously described, a JR3 force-moment transducer was used in the present study that can provide the time-resolved measurements of all three component of the aerodynamic forces and moments about each axis. However, for the current study of the wind loads acting on turbine unit, static or dynamic, only the axial wind loads were considered, while other
components of the loads can also be important factor in designing wind turbines and the floating platforms. Figure 5, gives the wind load measurement results in term of the instantaneous thrust coefficients for both the bottom fixed turbine and the moving turbine in pitch motion. As can be clearly seen from the time histories of the measured instantaneous thrust forces given in Figure 5, these loads are highly unsteady with their magnitudes fluctuating significantly as a function of time. The wind loads acting on the bottom fixed turbine in Figure 5(a), were found to be significantly different to the loads seen by the turbine in pitch motion 5(b). While the mean value of the wind loads acting on the turbine in pitch motion (i.e., CT =0.3701) is slightly higher than that of the bottom fixed turbine (i.e., CT =0.3647), the fluctuation amplitudes of the pitching motion were found to be significantly higher, which consequently increases the fatigue loads and ultimately reduces the life time of the moving turbine and the corresponding mooring lines of the floating platform which holds the turbine.

Figure 6 corresponds to the power spectral density of the measured instantaneous thrust forces acting on both model wind turbines (i.e. bottom fixed turbine and the oscillating turbine in pitching motion) through a Fast Fourier Transform (FFT) analysis procedure. In the case of the bottom fixed turbine (i.e. red color), a dominant peak at f0 = 17 Hz can be identified which corresponds to the rotational speed of the turbines rotor blades at the optimum tip-speed-ratio of 4.5. The rotational frequency of f0 = 17 Hz based on FFT analysis of the dynamic wind load measurements was found to agree very well with the independently measured rotational speed of the turbine blades by using a tachometer. However, in the case of the oscillating turbine in pitch motion, multiple dominant frequencies are observed. As the turbine was oscillating with a very low frequency, the power spectra plot clearly shows a dominant frequency of 0.3 Hz. As the turbine was oscillating in pitch motion, the relative velocity seen
by the rotor and the effective angle of attack of the blades significantly change, contributing to significant fluctuations in the rotational frequency of the rotor are apparent in the power spectra plot.

Figure 5: Measurement results of dynamic thrust force acting on the model wind turbine. Left (5a): bottom fixed turbine. Right (5b): turbine in pitch motion.

Figure 6: Comparison between the power spectra of the thrust forces of the bottom fixed turbine and the oscillating turbine in pitch motion.

The turbine’s power efficiency was determined using the voltage output of a small DC generator installed in the nacelle of the wind turbine. Many studies have been done to understand the effects of the ambient turbulence intensity on the loading, performance, and wake patterns of horizontal axis wind turbines. Power losses due to the wake effects can reach
up to 23% depending on the spacing and alignment of wind turbines [17]. Field measurements at Horns-Rev offshore wind farm revealed nearly 20% recovery on the maximum power deficit of the downstream turbines at higher ambient turbulence levels [20]. Barthelmie et al [16], also estimated that wind farm efficiency at Nysted wind farm will improve up to 9% in unstable conditions with higher ambient turbulence levels.

In a wind tunnel study performed by Ozbay et al [15], an increase of 6% was reported in the power output of an onshore wind farm over a similar layout corresponding to offshore scenario and concluded that the higher ambient turbulence intensity is solely responsible for such phenomena. The analysis done by Chamorro and Porte-Agel [5], shows strong dependence between the velocity deficit and the atmospheric turbulence.

Figure 7, shows the normalized power output of the bottom fixed turbine and the pitching turbine. As can be seen in Figure 7, there is little difference between the mean power extractions by the two turbines. However, as can clearly be seen in Figure 8, the fluctuations in the power extraction of the pitching turbine is substantially higher than those of the bottom fixed turbine. It is important to note that these fluctuations will significantly impact the quality of power generated by such oscillating turbines.

![Figure 7: Performance comparison between the bottom-fixed turbine and the turbine in pitch motion.](image)

The flow field ($x/D < 1.8$) measurement in the wake of the pitching turbine was also carried out by using a high-resolution PIV system, and the wake results obtained at the center location were then compared to those of a classical bottom-fixed turbine.

The flow measurements were used to quantify the differences in the wake of the pitching turbine when the aerodynamic hysteresis occurs. In the hysteresis loop, the differences in the wake flow at the same pitching condition were examined along the increasing pitch angle (i.e., the turbine is pitching *with the flow*) and the decreasing pitch angle (i.e., the turbine is pitching *into the flow*) branches.

The measurement plane was composed of two fields with an overlap of 15mm length, and two CCD cameras were used to acquire images from these fields. Two fields were then merged in Tecplot to acquire the image in the measurement plane. Finally, ensemble averaged flow quantities, such as mean flow velocity, Reynolds stresses and Turbulence Kinetic energy, were analyzed.

Figure 9, shows the four pairs of contour plots accompanied by their extracted data (at $x/D = 0.8$ and $x/D=1.7$) of the PIV measurements of the averaged stream-wise velocity component.
U, normalized by the relative velocity experienced by the rotor at the hub height, for a classical bottom fixed turbine (a), the pitching turbine at the center location (0°) when moving with the flow (b), moving into the flow (c), and the ensemble averages of the forward and backward motions at the center location (d).

As can be seen in Figure 9, there is clear evidence of the deficit in the velocity in the wake of both; the bottom fixed turbine and the pitching turbine. This deficit is the result of energy extraction by the turbine itself. Double peaks are observed and understood as characteristic of the near wake profiles (X/D <1). But as we go farther down in the wake (X/D >1), the double peaks die out and become just a single peak. This single peak eventually dies out in approximately 15~20 diameter downstream of the turbine, where the flow gains its fullest momentum and becomes the undisturbed flow again. There is some overshoot at the top region of the profiles in the near wake regions which suggests that the flow is accelerating at near top-tip of the blade, and also could be an evidence of the blockage effect caused by the existence of the turbine itself.

From the extracted data of Figure 9b and 9c, during the pitching motion, as the turbine is at the center location and is moving with the flow (to the right), it’s wake tends to accelerate when compared to the wake of the bottom fixed turbine, suggesting a reduced energy extraction by the rotor. This trend is anticipated to become more pronounced as we go down farther in the wake. However, as the turbine is moving into the flow (to the left), the wake of the pitching turbine slows down in comparison to the bottom fixed turbine, suggesting an increase energy extraction by the rotor from the flow. When averaging both motions, there would be no difference between the wakes of the bottom fixed turbine and the pitching turbine (9d), suggesting an equal amount of power extraction by both turbines.
Sebastian et al. (2013), performed series of numerical simulations on floating wind turbines, and determined that the blade element momentum theory (BEM) does not capture the unsteadiness generated in the flow due to significant changes in the angle of attack. Large angle of attack changes were due to the additional motion of the floating platforms. Motion induced unsteadiness violates assumptions of standard blade element momentum theory and leads to inaccurate predictions of unsteady aerodynamic loads. He showed that pitching motion of the wind turbine causes the turbine to change from the windmill state to the propeller state.

Figure 10, shows the Reynolds shear stress \( \tau = \frac{-u'v'}{U_h} \) and the turbulent kinetic energy \( (T.K.E.) = \frac{1}{2} \left[ \frac{u'^2+v'^2}{U_h^2} \right] \). The Reynolds shear stress deals with the transport of momentum from high energy flow above the rotor to the lower energy area of the wake region. T.K.E. is the kinetic energy per unit mass associated with the eddies in the turbulent flows. T.K.E. deals with the diffusivity effect which is responsible for enhanced mixing. By studying both the Reynolds shear stress and the T.K.E., one can determine on how fast the wake is recovering. The fluctuating components of the oncoming boundary layer flow influences the turbulent wake flow structure significantly. For a uniform flow, mean shear distribution in the turbine wake could be axisymmetric with strong shear layer (associated with TKE production) at the levels of bottom-tip and top-tip. However, for an oncoming boundary layer flow with non-uniform mean flow velocity distribution, previous experimental and numerical studies showed that maximum TKE production would occur at the top-tip level as a result of strong shear-produced turbulence and turbulent fluxes (Hu et al., 2012; Zhang et al., 2012; Porte-Agel et al., 2011; Wu et al., 2012). Turbulent fluxes produced due to wake induced turbulence were found to play an important role on the entrainment of energy from the flow above the wind farm (Meyers and Meneveau, 2013).
As can be seen in Figure 10, there are relatively higher amount of Reynolds shear stress, and T.K.E. associated with the pitching turbine, as it is moving into the flow when compared to the bottom fixed turbine, and lower amount associated with the pitching turbine moving with the flow. This is an indication of faster wake recovery as the turbine is oscillating into the flow and slower wake recovery when the turbine in pitching with the flow. However, when averaging both motions (10d), there would be little difference between the wake recovery of a bottom fixed turbine and a pitching turbine.

Rockel et al. (2014) also found that the classical bottom fixed turbine with its rigid structure would enhance mixing thereby providing a faster recovery in the shear layer of the wake when compared to the pitching turbine. Therefore, the far wake region behind the fixed turbine and the pitching turbine would significantly differ, affecting the performance of the downwind turbines operating in the wake of the front row turbines. The power extracted by the downwind pitching turbines would be 14% - 16% lower (with front row turbines pitching to approximately 18°) than the turbines behind the bottom-fixed turbine.

However, recent study showed that the reduced range of the pitching angle for the floating turbine would provide almost the same far wake velocity pattern as for the bottom-fixed turbine. Therefore, downwind turbines behind the fixed and pitching turbine would perform almost the same.

Figure 11, shows the normalized phase-locked \( \left( \frac{w_x D}{U_{hub}} \right) \) vorticity distributions in the wake of the bottom fixed turbine and the turbine oscillating in pitch motion at a phase angle of \( \theta = 0^\circ \). The vorticity \( (w_z) \) values were derived from the phase locked velocity distributions in the streamwise and vertical directions by using the expression \( w_z = \frac{dv}{dx} - \frac{dU}{dy} \). The phase-locked
PIV measurements could be used to identify the unsteady vortex structures (i.e., tip and root vortices, and vortices formed within the nacelle boundary layer) generated in the wake.

As shown in Figure 11, the tip vortices were formed in the strong shear layer located at the uppermost level of the wake. Interestingly, an additional array of concentrated vortices were found to shed from the inboard section located at approximately 50% - 60% of the blade span. Furthermore, these vortex structures were found to expand outwards as they convect downstream and finally merge with those shedding from the blade tips. Moreover, these additional array of concentrated vortices were found to be larger and stronger than those generated by the blade tips. The vortices formed within the nacelle boundary layer with those shedding from the blade root section were found to dissipate much faster than those generated at the tip and inboard section of the blade.

There is a strong connection between the tip vortex breakdown and the shear layer expansion. Lignarolo et al. (2013) showed that tip-vortices could act against the turbulent mixing; however, the breakdown of these vortices could enhance turbulent mixing.

The effect of the hysteresis loop on the evolution (i.e., formation, shedding and dissipation) of the unsteady vortex structures for the bottom fixed turbine and the oscillating turbine are shown in Figure 28. The hysteresis loop was found to make no significant changes on the evolution of the unsteady vortex structures. However, slight changes in the shape and magnitude of the vortex structures can be seen. Furthermore, contrary to the bottom fixed turbine, the vortices shedding from the inboard and tip sections of the turbine blade were found to break-down/dissipate faster for the oscillating turbine. However, the behavior of the vortices shedding from the nacelle boundary layer and blade root section was pretty similar for the fixed and the turbine in pitching motion.
Figure 9: Normalized stream-wise velocity (U/Uhub) profiles in the wake of a bottom fixed turbine (a), the center location for a pitching turbine as it is moving with the flow (b), as it is moving into the flow (c), and the averaged of forward and backward motion (d).
Figure 10: Normalized Reynolds Shear Stress ($R_{uv} \over U_{hub}^2$) and the Turbulent Kinetic Energy ($T.K.E. \over U_{hub}^2$) plots in the wake of a bottom fixed turbine (a), and the center location of a pitching turbine as it is moving with the flow (b), as it is moving into the flow (c), and the averaged of forward and backward motion (d).
Figure 11: Normalized vorticity distribution \( \left( \frac{w_g D}{U_{hub}} \right) \) plots in the wake of a bottom fixed turbine (a), and the center location for the pitching turbine: the averaged vorticity of forward and backward motions (b), as it is moving with the flow (c), and as it is moving into the flow (d).
CONCLUSION

A comprehensive experimental study was conducted to investigate the performance, loading and the near wake characteristics of a horizontal axis wind turbine subjected to pitch motions. The results were then compared to those of a classical bottom fixed turbine. The current study was performed in a large-scale atmospheric boundary layer wind tunnel. The base of a 1:300 scaled model wind turbine was mounted on a translation stage. The rotation stage was controlled to generate surge motions to simulate the dynamic pitch motions experienced by floating offshore wind turbines. During the experiments, the velocity scaling method was chosen to maintain the similar velocity ratios (i.e., the ratios of the incoming airflow flow to that of turbine base motion) between the model and the prototype.

During the experiments, a high resolution digital particle image velocimetry (PIV) system was used to achieve flow field measurements to quantify the characteristics of the turbulent vortex flow in the near wake of the wind turbine model. Besides conducting “free run” PIV measurements to determine the ensemble-averaged statistics of the flow quantities such as mean velocity, Reynolds stress, and turbulence kinetic energy (TKE) distributions in the wake flow, “phase-locked” PIV measurements were also performed to elucidate further details about evolution of the unsteady vortex structures in the wake flow in relation to the position of the rotating turbine blades.

The results of the wake study reveals that the wake of a wind turbine subjected to pitch motions, is highly dependent on which direction the turbine is oscillating. Furthermore, the velocity, frequency, and the range of oscillation also play an important role on the behavior and the wake pattern of the moving turbine. The wake of the oscillating turbine in pitch motion, tends to accelerate as the turbine is moving with the flow, hence, reducing the power extraction by the turbine. A decrease in Reynolds shear stress and the turbulent kinetic energy production
was noted as the turbine was oscillating with the flow. However, as the turbine was moving into the flow, these effects reverse, and causes a deceleration in the wake of the moving turbine, hence increases the power production by the turbine, and increases the Reynolds shear stress and the turbulent kinetic energy. Averaging the wake results of both forward and backward motions of the turbine in pitch motion produces results which are essentially the same as the wake pattern of the bottom fixed turbine.

Although, the mean power measured by a small DC motor installed in the nacelle shows little difference between the oscillating turbine and the bottom fixed turbine, but the excessive fluctuations in the power output of the oscillating turbine is anticipated to greatly reduce the power quality of such oscillating turbines. The load measurements also show substantial amount of increase in terms of the fluctuating components for the oscillating turbine, which consequently results in increased fatigue loads and decreased lifetime of the turbine and the associated floating components.

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CHAPTER 4

AN EXPERIMENTAL INVESTIGATION ON THE PERFORMANCE, LOADING, AND THE NEAR WAKE CHARACTERISTICS OF A WIND TURBINE MODEL SUBJECTED TO HEAVE MOTIONS

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Abstract: In the present study, a comprehensive experimental study was performed to analyze the loading, performance, and the near wake characteristics of a wind turbine model subjected to uncoupled heave motions. These experimental studies were performed in a large-scale atmospheric boundary layer wind tunnel with a scaled three-bladed Horizontal Axial Wind Turbine model placed in a turbulent boundary layer airflow with similar mean and turbulence characteristics as those over a typical offshore wind farm. The base of the 1:300 scaled model wind turbine was mounted on a translation stage. The translation stage can be controlled to generate heave motions to simulate the dynamics of heaving motions experienced by floating offshore wind turbines.

A high resolution digital particle image velocimetry (PIV) system was used to achieve flow field measurements to quantify the characteristics of the turbulent vortex flow in the near wake of the wind turbine model. Besides conducting “free run” PIV measurements to determine the ensemble-averaged statistics of the flow quantities such as mean velocity, Reynolds stress, and turbulence kinetic energy (TKE) distributions in the wake flow, “phase-locked” PIV measurements were also performed to elucidate further details about evolution of the unsteady vortex structures in the wake flow in relation to the position of the rotating turbine blades. The effects of the heave motions of the wind turbine base on the wake flow characteristics were examined in great details based on the PIV measurements.
The performance of the scaled model wind turbine was measured using a small DC motor mounted in the nacelle assembly. A highly sensitive force/moment transducer was also mounted at the base of the turbine to measure the aerodynamic loading associated with the heaving turbine. For better understanding of the effects of heaving motion on the Aerodynamics and Aeromechanics of wind turbines, the results were then compared to those of a traditional bottom fixed turbine.

The results of the wake studies reveal that the wake of a wind turbine subjected to heave motions, is highly dependent on which direction the turbine is oscillating. Furthermore, the velocity, frequency, and the range of oscillation also play an important role on the behavior and the wake pattern of the moving turbine. In the case of the heaving turbine, the wake accelerates as the turbine is moving upward, hence, reducing the power extraction by the turbine. A decrease in Reynolds shear stress and the turbulent kinetic energy production was noted as the turbine was oscillating upward. However, as the turbine was moving downward, these effects reverse, and causes a deceleration in the wake of the moving turbine, hence increases the power production by the turbine, and increases the Reynolds shear stress and the turbulent kinetic energy. The mean power measurement using a small DC motor mounted in the nacelle, show little difference between the power extracted by turbine in pitch motion and the bottom fixed turbine. However, the fluctuations in the power output of the heaving turbine is greatly influencing the quality of power generated by such turbines. The mean thrust load experienced by the heaving turbine is much greater than that of the bottom fixed turbine. The fluctuations in the thrust loading experienced by the heaving turbine is also much more than the bottom fixed turbine, hence increases the fatigue loads experienced by the heaving turbine.
INTRODUCTION

Offshore wind energy is one of the most abundant and promising sources of energy that can provide substantial amount of clean, domestic, and renewable energy. The United States is especially fortunate to be surrounded by vast waters on both sides of the nation. This provides a unique opportunity for offshore wind farm developments in this country. There is over 4000 GW of wind potential within 50 nautical miles of the U.S. coastlines [24], which is approximately four times the current U.S. power generation capacity. Offshore wind energy is divided into three categories, depending on the depth of water where the turbines are being installed at. The depth of the water dictates the type of substructure technology needed to install offshore wind turbines. In shallow waters (0 m to 30 m), the turbines are being fixed to the sea floor by means of a monopile or gravity based foundations. In intermediate waters (30m to 60 m), the wind turbines are also being fixed to the sea floor but by different kind of substructures such as jacket or tripods. As the water depth increases beyond 60m, the cost of substructure increases substantially, making it almost economically infeasible to fix the turbines to the sea floor. Therefore, the turbines will need to be floated in deep waters [18].

By the end of 2014, there were 74 offshore wind farms operating in 11 European countries, yielding over 8 GW of electricity. All of these wind farms are located in shallow waters with depths less than 20 meters where the turbines are fixed to the sea floor [14]. Unlike the shallow European waters, the U.S. waters are, on the other hand, mostly deep with the exception of a few regions in the East Coast and the Gulf of Mexico. Therefore, offshore wind farm development in the U.S. will most likely be based on the floating concept.

There are many advantages of floating wind turbines in deep waters, however, there are also significant technological challenges associated with it too. There are six degrees of
freedom (6-DOF) associated with any floating structures, three displacements (surge, sway, and heave) and three rotations (roll, pitch, and yaw). The dynamic excitation of wind and waves, will induce excessive motions along each of the 6-DOF’s of the floating platform. These motions will then be transferred to the turbine itself, and directly impact the turbines’ performance, loadings, and consequently the wake characteristics of such turbines.

The study of both coupled and uncoupled motions of the floating turbines are important and necessary to determine the contributions of each motions along each of the DOFs to the overall performance, loading, and the wake characteristics of floating wind turbines. In the current experimental study, advanced diagnostic technique methods were employed in order to elucidate the underlying physics of a wind turbine subjected to surge motions. As can be seen in Figure 1, the heave motion is defined as the upward and downward motion of the turbine. In the absence of a combined wind-wave basin, and in order to replicate the most dominant motions associated with a floating offshore wind turbines (FOWT), a 1:300 scaled model wind turbine was installed on a high precision 3-DOF motion simulator device in a well-controlled, closed loop, dry-boundary layer wind tunnel. The inflow conditions of the wind tunnel were matched to that corresponding to the deep-water offshore environment.

To better understand the effects of the heave motions to the overall performance, and loading, the results were then compared to those of a conventional bottom fixed wind turbine. Beside performance and loading, the near wake characteristics of the turbine subjected to heave motions was also studied. The wake of wind turbines contains many information relevant to design and optimization of wind turbines, and hence important to study. The wake of a wind turbine is divided into near and far wake [21].
Figure 1: Illustration of turbine's oscillation in heave motion.

The near wake refers to the region approximately one rotor diameter downstream of the turbine. In the near wake, the rotor characteristics such as the number of blades, blade aerodynamics such as stall or attached flows, tip vortices, etc. are present. The helical vortices induced by the rotating blades are another important parameter of the near wake. The evolution of helical vortices is responsible for the behavior of the turbulent wake flow structures behind the wind turbines. The tip vortices are an important contributor to noise generation and blade vibration [4]. The far wake is the region behind the near wake (any region behind 1 diameter downstream of the rotor), where the actual rotor shape is less important, but the focus is on wake modeling, wake interference in wind farms, turbulence modeling, and topographic effects [2].

Many studies have been done to understand the effects of the ambient turbulence intensity on the loading, performance, and wake patterns of horizontal axis wind turbines. Power losses due to the wake effects can reach up to 23% depending on the spacing and alignment of wind turbines [17]. Field measurements at Horns-Rev offshore wind farm revealed nearly 20% recovery on the maximum power deficit of the downstream turbines at higher ambient turbulence levels [20]. Barthelmie et al [16], also estimated that wind farm efficiency at Nysted wind farm will improve up to 9% in unstable conditions with higher ambient turbulence levels.

In a wind tunnel study performed by Ozbay et al [15], an increase of 6% was reported in the power output of an onshore wind farm over a similar layout corresponding to offshore
scenario and concluded that the higher ambient turbulence intensity is solely responsible for such phenomena. The analysis done by Chamorro and Porte-Agel [5], shows strong dependence between the velocity deficit and the atmospheric turbulence.

Rockel et al. [3], performed a wind tunnel experiment to observe the influence of the platform pitch on the wake of a wind turbine. His results indicated that the platform pitch creates an upward shift in all components of the flow and their fluctuations. He concluded that the vertical flow created by the pitch motion as well as the reduced entrainment of kinetic energy from undisturbed flow above the turbine result in potentially higher loads and less available kinetic energy for a downwind turbine.

Sebastian et al. [1], performed series of numerical simulations on floating wind turbines, and determined that the blade element momentum theory (BEM) does not capture the unsteadiness generated in the flow due to significant changes in the angle of attack. Large angle of attack changes were due to the additional motion of the floating platforms. Motion induced unsteadiness violates assumptions of standard blade element momentum theory and leads to inaccurate predictions of unsteady aerodynamic loads. He showed that pitching motion of the wind turbine causes the turbine to change from the windmill state to the propeller state.

EXPERIMENTAL SETUP AND PRECEDURE

a) AABL Wind Tunnel

The present experimental study is performed in the large-scale Aerodynamic/Atmospheric Boundary Layer (AABL) wind and gust tunnel located in the Department of Aerospace Engineering at Iowa State University. The AABL wind tunnel is a closed-circuit wind tunnel with a boundary-layer test section 20 m long, 2.4 m wide and 2.3 m high, optically transparent
side walls, and with a capacity of generating a maximum wind speed of 40 m/s in the test section. Arrays of chains were laid-out on the wind tunnel’s floor on the upstream side of the wind turbine model in order to match the flow to that of offshore environment. The boundary layer growth of the simulated ABL wind under almost zero pressure gradient condition was achieved by adjusting the ceiling height of the test section of the wind tunnel. The oncoming boundary layer wind velocity profile was fitted by using equation 1, where \( z_{ref} \) is a reference height (hub) and \( U_{ref} \) is the wind speed at the reference height. The power law exponent ‘\( \alpha \)’ is associated with the local terrain roughness. Figure 2, shows the measured streamwise mean velocity (normalized with respect to the hub height velocity, \( U_{hub} \)) and the turbulence intensity profiles of the oncoming flow in the test section for the present study. The power law exponent in Eq. 1 was found to be \( \alpha = 0.10 \), corresponding to the open sea boundary layer profile according to the Japanese standard [25]. GL (Germanischer Lloyd) regulations define a turbulence intensity of 0.12 at the hub height of offshore wind turbines; however, this value was determined to be very conservative compared to field measurements. Therefore, for the current experimental study, a turbulence intensity of 10% at the hub height of the model turbine was chosen.

\[
U(z) = U_{ref} \left( \frac{z}{z_{ref}} \right)^{\alpha}
\]

(1)

b) Wind turbine model

Figure 3 shows, a 1:300 geometrically scaled model horizontal axis wind turbine (HAWT) of height 270 mm (81m in full scale) measured from the wind tunnel’s floor to the hub height of the turbine. However, the base of the turbine’s tower was extended beyond the tunnel’s floor to connect it to the motion simulator fixed underneath the tunnel (an additional height of
130mm). The rotor diameter for this scaled model was chosen as 300 mm (90m in full scale), and the turbine was developed using rapid prototyping method. The rotor blades were designed based on the ERS-100 prototype turbine blades developed by TPI Composites, Inc. The rotor blade has a constant circular cross section from the blade root to 5% blade radius (R), and three NREL airfoil profiles (S819, S820, S821) were used at different span-wise locations along the rotor blade. The S821 airfoil profile spans between 0.208R and 0.40R, the S819 primary airfoil is positioned at 0.70R, and the S820 airfoil profile is specified at 0.95R. For optimal performance of the rotor, the blades were pitched by 3 degrees.

![Figure 2: The simulated atmospheric boundary layer profiles in the wind tunnel.](image)

![Figure 3: The schematic of the model wind turbine used in the present study.](image)
The blockage ratio was calculated to be around 1.3%, which is well within the acceptable limit of 5%. The incoming freestream velocity, \( U_\infty \), was set as 3.5 m/s at the hub height of the turbine that provided a rotational speed of 17 Hz for the model turbine. The Reynolds number corresponding to the prototype wind turbines range between 500,000 to 6,000,000. However, the corresponding diameter based Reynolds number \( (Re_D) \) for this experiment was 71000 which was much lower than that of the large-scale wind turbines operating in the fields.

A tip-speed-ratio (TSR) of 4.5 was maintained throughout the test. The tip-speed-ratio, is the ratio between the rotational velocity of the turbine to the free-stream velocity.

\[
TSR = \frac{\Omega R}{U_\infty}
\]

where \( \Omega \) is the angular velocity of the model turbine in rad/s.

Besides matching the TSR between the model and the prototype wind turbines, other scale relationships must also be maintained when dealing with floating wind turbines [10].

Froude number is the ratio between the inertial to gravitational forces. Matching Froude scale \( (\lambda_{Fr} = 1) \), is the method of choice when dealing with hydrodynamic testing of scaled model floating wind turbines.

By using Froude scaling, the wave forces and response of the floater will be correct (ignoring the scale effect in viscous forces). The wind loads on the turbine should also be scaled using Froude scaling, otherwise the floater motions will not be correct. In hydrodynamic testing, this is achieved by calibrating the correct wind forces, rather than the correct wind velocity. Therefore, once the Froude scaling is applied to the wind velocity, further adaptation of wind velocity will be required in order to achieve an acceptable thrust load on the turbine.
However, in wind tunnel model study of offshore wind turbine, the Froude scaling may not be an appropriate similitude method. This is mainly because the wind speed needs to be adjusted to obtain the correct wind loads on the turbine, if the range of motions on the scaled model turbine as determined using Froude scaling is to be maintained. Therefore, matching Froude number would not be able to accurately capture the characteristics of a floating turbine’s wake that is subjected to base motions.

A scaling method termed here as velocity ratio method was therefore chosen for the current study in order to capture the important characteristics of the wake of the turbine subjected to surge motions. The velocity ratio method was achieved by maintaining the ratio between the maximum velocity of the surge motion to the freestream velocity for both the model and the prototype.

\[
\left( \frac{U_{\text{heave}}}{U_\infty} \right)_{\text{prototype}} \sim \left( \frac{2Af}{U_\infty} \right)_{\text{model}} \tag{3}
\]

Where \( A \) is the amplitude of displacement and \( f \) is the frequency of oscillation in Hz for the surge motion.

c) **Motion Simulator**

The motion simulator device that was used for the current experimental studies included: an M-ILS100cc (to replicate the heave motion) high precision linear and rotation stages motion simulator manufactured by Newport Corporations. The motion simulator device was carefully installed under the test section floor of the wind tunnel to avoid any flow disturbances due to the presence of such device. The turbine was then placed on top of the motion simulator through a special cut in the tunnel’s floor, to prevent the air from leaking out of the tunnel.
The exact motion for the prototype turbine was determined using the previous numerical simulation results. Using Equation 5, the freestream velocity at the hub height of the scaled model turbine was set to 3.5 m/s, the constant heave velocity was chosen to be \( \frac{0.1 \text{ m}}{s} \) with a displacement of \( (\pm) 2 \text{ cm} \) and therefore, the frequency of oscillation was needed to be around 0.5 Hz. However, due to limitation of the motion simulator, this frequency was kept at 0.32 Hz instead.

d) Measurement Systems

The turbine’s power efficiency was determined using the voltage outputs of a small DC generator installed in the nacelle of the wind turbine and the corresponding electrical loading applied to the electric circuits. During the experiment, the voltage output of the DC generator was acquired through an A/D board plugged into a host computer at a data sampling rate of 1 kHz for two minutes. The normalized power output of the model wind turbine (i.e., normalized by the maximum power output of the bottom fixed turbine) were used in the present study for better comparison reasons.

For the wind turbine models used in the present study, an aluminum rod was used as the turbine tower to support the turbine nacelle and the rotor blades. Through a slot in the wind tunnel floor, the aluminum rod was connected to a high-sensitivity force-moment sensors (JR3, model 30E12A-I40) to measure the wind loads (aerodynamic forces and bending moments) acting on the wind turbine model. The JR3 was then attached to the motion simulator. The precision of the force-moment sensor cell for force measurements is \( \pm 0.25\% \) of the full range (40 N). While the force-moment sensor mounted at the bottom of each turbine tower can provide time-resolved measurements of all three components of the aerodynamic forces and the moment (torque) about each axis, only the measured thrust coefficient, \( C_{Fx} \), and bending
moment coefficient, $C_{My}$, are given in the present study. The thrust coefficient (along the streamwise velocity direction) and associated bending moment coefficient were defined by using the expressions of 

$$C_{Fx} = \frac{F_x}{\frac{1}{2}\rho U^2 \pi R^2}$$

and

$$C_{My} = \frac{M_y}{\frac{1}{2}\rho U^2 \pi R^2 H}$$

where $\rho$ is the air density, $U$ is the mean flow velocity at the hub height $H$. The wind load data were acquired for five minutes at a sampling rate of 1,000 Hz for each tested case. A Monarch Instrument Tachometer was also used to measure the rotational speed of the wind turbine blades.

A 2-D Particle Image Velocimetry (PIV) technique was used (as shown in Figure 4) to capture whole-field information of the wake of both the bottom fixed turbine and the turbine with the surge motion. The coordinate system indicating three velocity components is also shown in Figure 4. The x-coordinate corresponds to the stream-wise direction with the origin located at the center of the tower of the turbine. The y-coordinate which is in lateral direction, with its origin at the center of the nacelle. Using the right hand rule, the z-coordinate would then be perpendicular to the x-y plane and will be pointing to the right side of the wind tunnel’s wall.

The flow was seeded with 1-5 μm oil droplets and the laser system used for illumination of the seeding particles was a double-pulsed Nd:YAG laser (Ever Green big sky laser series) emitting two 200 mJ laser pulses at a wavelength of 532 nm and with a repetition rate of 1 Hz. For a better accuracy in results, the laser sheet thickness was adjusted to be around 1 mm. Two high-resolution (2048×2048 pixels) charge-coupled device (CCD) cameras with axis perpendicular to the laser sheet was used for PIV image acquisition. The CCD camera and the double-pulsed Nd:YAG lasers were connected to a workstation via a digital delay generator that controlled the timing of both the laser illumination and the image acquisition.
Instantaneous PIV velocity vectors were obtained using a frame-to-frame cross correlation technique involving successive frames of patterns of particle images in an interrogation window with 32×32 pixels and an effective overlap of 50% to satisfy the Nyquist criterion. The ensemble averaged flow quantities such as mean velocity, turbulent-velocity fluctuations, normalized turbulent kinetic energy, and Reynolds shear stress distributions were obtained from approximately 1000 frames of instantaneous PIV measurements. The measurement uncertainty level for the velocity vectors was estimated to be within 2.0%, and that of the turbulent velocity fluctuations and turbulent kinetics energy was about 5.0%.

![Figure 4: Illustration of the PIV set-up.](image)

**Results and Discussions**

a) **Dynamic wind load measurement results**

As previously described, a JR3 force-moment transducer was used in the present study that can provide the time-resolved measurements of all three component of the aerodynamic forces and moments about each axis. However, for the current study of the wind loads acting on turbine unit, static or dynamic, only the axial wind loads were considered, while other components of the loads can also be important factor in designing wind turbines and the floating platforms. Figure 5, gives examples of the wind load measurement results in term of
the instantaneous thrust coefficients for both the bottom fixed turbine and the moving turbine in heave motion. As can be clearly seen from the time histories of the measured instantaneous thrust forces given in Figure 5, these loads are highly unsteady with their magnitudes fluctuating significantly as a function of time. The wind loads acting on the bottom fixed turbine in Figure 5(a), were found to be significantly different to the loads seen by the turbine in heave motion 5(b). While the mean value of the wind loads acting on the turbine in heave motion (i.e., $C_T=0.4488$) is significantly higher than that of the bottom fixed turbine (i.e., $C_T=0.3648$), the fluctuation amplitudes of the heave motion were also found to be significantly higher, which consequently increases the fatigue loads and ultimately reduces the life time of the moving turbine and the corresponding mooring lines of the floating platform which holds the turbine.

In Figure 6, the plot on the left corresponds to the power spectra of the measured instantaneous thrust forces acting on both model wind turbines (i.e. bottom fixed turbine and the oscillating turbine in heave motion) through a Fast Fourier Transform (FFT) analysis procedure. In the case of the bottom fixed turbine (i.e. red color), a dominant peak at $f_0= 17$ Hz can be identified which corresponds to the rotational speed of the turbines rotor blades at the optimum tip-speed-ratio of $\lambda \approx 4.5$. The rotational frequency of $f_0= 17$ Hz based on FFT analysis of the dynamic wind load measurements was found to agree very well with the independently measured rotational speed of the turbine blades by using a tachometer. However, in the case of the oscillating turbine in heave motion, multiple dominant low frequencies are observed. As the turbine was oscillating with a very low frequency, the power spectra plot clearly shows a dominant frequency of 0.32 Hz.
b) Power output performance measurements

As described before, the turbine’s power efficiency was determined using the voltage outputs of a small DC generator installed in the nacelle of the wind turbine and the corresponding electrical loading applied to the electric circuits. In the comparison of the power output performances, power output readings were normalized with the maximum power output, which corresponds to an (optimum) electric loading range of 25Ω.

As can be seen in Figure 7, even though the power output of the bottom-fixed turbine is relatively higher than the turbine in heave motion, but the difference is very small and falls well within the error range of the measuring tools. Therefore, the time averaged power output
of both the bottom fixed turbine and the turbine in heave motion are both within the same limit. However, the quality of the power output of the turbine in heave motion would be significantly lower of that of the bottom fixed turbine due to the constantly changing relative velocity seen by the rotor blades due to the upward and downward motion of the turbine unit in heave motion.

Figure 7: Performance comparison between the bottom-fixed turbine and the turbine in heave motion.

c) **The near wake PIV measurements results**

The flow field (x/D < 1.8) measurements behind a wind turbine subjected to only heave motion was carried out by using a high-resolution PIV system. The heave motion is defined as the linear translation of the turbine in vertical direction, perpendicular to the incoming flow. As shown in Figure 8, the turbine was set to oscillate in heave motion with a displacement range of (±) 2 cm about the neutral location. The three critical locations for the current study of the heave motion include; upper location (2 cm above of the neutral location), center (the neutral location), and the lower location (2 cm below the neutral location).

The range of the vertical motion (~ 4 cm) for the heaving turbine corresponds to 1/6.75 of the turbine hub height. The turbine was set to heave within this range at approximately 0.32 Hz. (i.e., at a speed of 10 cm/s). The flow measurements were also used to quantify the differences in the wake of the heaving turbine when the aerodynamic (wake) hysteresis occurs. In the hysteresis loop, the differences in the wake flow at the same vertical position of the
heaving turbine were examined along the increasing vertical path (i.e., the turbine is moving upwards from -2 cm to +2 cm) and decreasing vertical path (i.e., the turbine is moving downwards from +2 cm to -2 cm) branches.

![Figure 8: Illustration of turbine's oscillation in heave motion](image)

The measurement plane was composed of two fields with an overlap of 15mm length, and two CCD cameras were used to acquire images from these fields. The two fields were then merged in Tecplot to acquire the image in the measurement plane. Finally, ensemble averaged flow quantities, such as mean flow velocity, Reynolds stresses and Turbulence Kinetic energy, were analyzed.

Figure 9, shows the contour plots of the averaged stream-wise velocity (U/Uhub) profiles in the wake of a bottom fixed turbine (a), and the center location for a turbine oscillating in heave motion: as it is moving upward (b), as it is moving downward (c), and the averaged of the upward and downward motions (d). Each of the contour plots are accompanied by their extracted data (at x/D = 0.8 and x/D=1.5) of the PIV measured normalized stream-wise velocities.

As can be seen in Figure 38, there is clear evidence of the deficit in the velocity in the wake of both; the bottom fixed turbine and the oscillating turbine. This deficit is the result of the energy extraction by the turbine itself. Double peaks are observed and understood as characteristic of the near wake profiles (X/D <1). But as we go farther down in the wake (X/D >1), the double peaks die out and become just a single peak. This single peak eventually dies
out in approximately 15~20 diameter downstream of the turbine, where the flow gains its fullest momentum and becomes the undisturbed flow again. There is some overshoot at the top region of the profiles in the near wake regions which suggests that the flow is accelerating at near top-tip of the blade, and also could be an evidence of the blockage effect caused by the existence of the turbine itself.

Figure 9, also provide valuable insights about the wake patterns behind a turbine as it undergoes a pure heaving motion. The study of such behavior can be approached in two different ways: statically and dynamically. The static approach would only consider the frozen images of the oscillating turbine at specific heights, and investigates the wake profiles and compare them with the wake of a classical bottom fixed turbine. However, in the dynamic approach, one would take into account the continuous and periodic motion associated with the heaving motion within an acceptable vertical range. In reality, this kind of motion can induce fluctuations in the power output, thereby lowering the power quality of the floating offshore wind turbines. The periodic heave motion would also influence the dynamic loading associated with the floating wind turbines. The tendency of the floating turbine to go up or down (i.e., the hysteresis loop) to specific heights during the heave motion could have a significant impact on the wake patterns as well.

From the static point of view, the heave motion can either increase or decrease the hub (reference) height of the wind turbine. The turbine was set to heave within preselected (acceptable) limits (i.e., ±2 cm). The elevated/lowered turbine could be treated as the fixed turbine with increased/reduced hub height. Therefore, the typical wake pattern behind a wind turbine in pure heaving motion was found to be very similar to the wake of a classical bottom fixed turbine. The only difference observed is that the wake stream-wise velocity profile is shifted upwards at the upper location (see Figure (12d)), and it is shifted downwards at the
lower location (see Figure (15d)). The upward/downward shifts observed in the velocity profiles, can be clearly seen in both downstream locations of $x/D = 0.8$ and $x/D = 1.5$.

The elevated turbine (i.e., at the upper location) could experience higher wind speeds so that its power production is expected to be higher compared to the fixed turbine. The power production from the wind turbine is strongly linked with the velocity deficits observed in its wake. Therefore, as shown in Figure (12d), an upward shift on the velocity profile would indicate greater velocity deficits at the same height. The gap between velocity deficits was also found to be more pronounced towards the mid and tip sections (i.e., $0.2 < y/D < 0.5$) of the blade, since these sections are responsible for the power extraction from the incoming wind. However, as shown in Figure (15d), a downward shift would indicate less power extraction from the incoming wind, thereby causing smaller velocity deficits. This can be associated with the less power available in the wind, due to the fact that the heaving turbine is dropped (i.e., to the lower location), hence operating at a region of the boundary layer where wind speeds are significantly lower.

From the dynamic point of view, the continuous up and down movement of a wind turbine during the heave motion can significantly change the wake structure. As the oscillating turbine heaves within the preselected vertical limits, the frozen images of the moving turbine were also taken at the specific heights similar to the static case. However, as opposed to the static case, the oscillating turbine was either moving along the increasing vertical path (i.e., the turbine is moving upwards from -2 cm to +2 cm) or moving along the decreasing vertical path (i.e., the turbine is moving downwards from +2 cm to -2 cm) at that specific vertical position. Therefore, the oscillating wind turbine was put in a hysteresis loop, and the effects of the hysteresis on the wake dynamics were investigated.
When the oscillating turbine is moving upward to the upper location, its wake was found to deflect downwards; whereas its wake was found to deflect upwards as the turbine was moving downwards from the upper location. This effect (hysteresis) can be clearly seen from Figure (9b, 9c), Figure (12b, 12c) and Figure (15b, 15c). When the turbine is moving upward to the upper location, the difference between the velocity profiles (the vertical gap due to the upward shift), between the heaving turbine and the bottom fixed turbine was found to become narrow. This is an indication of the deflection of the wake towards the wake centerline (see Figure (12b)). However, this gap was found to become wider as the oscillating turbine was moving downwards from the upper location indicating the wake deflection towards the outer wake (see Figure (15c)). These effects would be the opposite in the case of the lower location (i.e., at -2 cm) since the vertical gap was formed due to the downward shift. Therefore, in this case, the gap was found to become wider when the oscillating turbine is moving upwards; whereas, it was found to become narrower when the floating turbine is moving downwards (see Figure (15b) and Figure (15c)).

The absolute dynamic effects induced by the continuous heaving motion were observed when the oscillating turbine is at the center (the neutral location). The wake profiles were found to shift upwards/downwards when the oscillating turbine is moving downwards/upwards (see Figure (9b) and Figure (9c)). The wake deflection due to the dynamic effects could be linked with the frequency of the heave motion. As the frequency of this up and down motion increases, these dynamic effects would be more pronounced; therefore, the wake deflections would play an important role in the wake development.

Figure (10, 13, and 16) show the pairwise (i.e., moving upwards and downwards) contour plots of the averaged normalized kinetic energy flux profiles in the wake of the oscillating turbine at different vertical positions. The vertical kinetic energy fluxes are very crucial for the
wake recovery as it entrains high momentum flow into the wake. As shown in Figure (10b, 10c, 13b, 13c, and 16b, 16c), negative values of kinetic fluxes were observed in the top tip (shear) layer of the floating turbine, and the areas covered by these negative fluxes were found to expand slowly as the wake flow advects downstream for the floating turbine. The negative valued kinetic energy fluxes could be used as an indicator of the flow entrained into the wake centerline. Therefore, the high momentum flow above the shear layer could mix with the wake flow characterized by greater velocity deficits, thereby accelerate the wake recovery. As a result, downstream turbines in wind farms/arrays could extract more energy from the disturbed flow. It has also been shown by Cal et.al. (2010) that the energy extracted from the turbines inside a wind farm is on the same order of magnitude with these turbulent kinetic energy fluxes.

Figure (10b, 10c, 13b, 13c, and 16b, 16c) also shows the effect of the hysteresis on the development of the kinetic energy fluxes for the floating turbine at predetermined vertical positions. The region with strong/negative fluxes, representing the wake shear (viscous) layer, was found to deflect downwards/upwards if the turbine is moving upwards/downwards. This is parallel to the previous findings on the relation between the wake deflection and the direction of the heave motion. Therefore, in case of a continuous heaving (up and down) motion of an oscillating wind turbine, shear layer expansion would occur in both vertical directions. This could enhance and promote strong mixing in the wake which leads to a faster wake recovery rate. Furthermore, the direction and the speed of the wake expansion strongly depend on the direction and the frequency of the heaving motion, respectively.

The static effects (due to the changes in the hub height of the oscillating turbine) of heaving motion were observed in Figure (10a, 10d, 13d, 16d), and comparisons could be made between the fixed turbine and the oscillating turbine. As shown in Figure (10d, 13d, 16d), the kinetic energy flux profiles were found to be pretty similar for all these cases. This might be attributed
to the narrow range (i.e., ±2 cm) of the heave motion where wind shear does not play a significant role.

As shown in Figure (11, 14, 17), the distribution pattern of the TKE production contours would seem quite similar to the kinetic energy flux contours shown in Figure (10, 13, and 16) It was observed from these figures that higher levels of TKE production, analogous to kinetic energy flux distribution, would occur at the top tip height and behind the nacelle. The maximum TKE production behind the nacelle of the oscillating turbine were found to be comparably higher than those observed at the top tip level. However, TKE production behind the nacelle were found to decay much faster (decays before x/D = 1.0) with increasing downstream distance.

The TKE production at the top tip level was observed to spread (i.e., more pronounced after x/D = 1.2) as the flow convects downstream. This spread (i.e., due to the shear layer expansion) can be clearly seen for all the cases. The hysteresis loop, shown in Figure (11b, 11c, 14b, 14c, 17b, 17c) as pairwise (i.e. moving upwards and downwards) for the specific heights of the oscillating wind turbine, was found to make no significant impacts on the magnitude ranges of TKE production. In addition, the wake deflection due to the hysteresis effects cannot be identified from the TKE production plots. This can be associated with the measurement plane extending only up to a downstream distance of x/D = 1.8 so that shear layer expansion was not fully visualized.

Figure (11a, 11d, 14d, 17d) also displays the static effects (i.e., due to the change in the hub height of the floating turbine) of the heave motion on TKE production profiles in comparison to the fixed turbine. Analogous to the kinetic energy flux profiles, TKE production profiles do not show significant differences (with slight fluctuations in the magnitude) for the fixed turbine and the floating turbine cases.
Figure 9: Normalized stream-wise velocity (U/Uhub) profiles in the wake of a bottom fixed turbine (a), the center location for a heaving turbine as it is moving upward (b), as it is moving downward (c), and the averaged of downward and upward motions (d).
Figure 10: Normalized Reynolds Shear Stress \( \frac{R_{uv}}{U_{hub}} \) and the Momentum Flux \( \frac{\partial U}{\partial y} \frac{R_{uv} \cdot D}{U_{hub}} \) plots in the wake of a bottom fixed turbine (a), and the center location of a heaving turbine as it is moving upward (b), as it is moving downward (c), and the averaged of downward and upward motions (d).
Figure 11: Normalized Turbulent Kinetic Energy \( \frac{T.K.E.}{U_{hub}} \) plots in the wake of a bottom fixed turbine (a), and the center location of a heaving turbine as it is moving upward (b), as it is moving downward (c), and the average of downward and upward motions (d).
Figure 12: Normalized stream-wise velocity (U/Uhub) profiles in the wake of a bottom fixed turbine (a), the upper location for a heaving turbine as it is moving upward (b), as it is moving downward (c), and the averaged of downward and upward motions (d).
Figure 13: Normalized Reynolds Shear Stress $\frac{R_{uv}}{U_{hub}^2}$ and the Momentum Flux $\frac{\partial U}{\partial y} \frac{R_{uw} \cdot D}{U_{hub}^3}$ plots in the wake of a bottom fixed turbine (a), and the upper location of a heaving turbine as it is moving upward (b), as it is moving downward (c), and the averaged of downward and upward motions (d).
Figure 14: Normalized Turbulent Kinetic Energy ($\frac{\text{T.K.E.}}{U_{\text{hub}}^2}$) plots in the wake of a bottom fixed turbine (a), and the upper location of a heaving turbine as it is moving upward (b), as it is moving downward (c), and the average of downward and upward motions (d).
Figure 15: Normalized stream-wise velocity ($U/U_{hub}$) profiles in the wake of a bottom fixed turbine (a), the lower location for a heaving turbine as it is moving upward (b), as it is moving downward (c), and the averaged of downward and upward motions (d).
Figure 16: Normalized Reynolds Shear Stress $\frac{R_{uv}}{U_{hub}^2}$ and the Momentum Flux $\frac{\partial U}{\partial y} \cdot \frac{R_{uv} \cdot D}{U_{hub}^3}$ plots in the wake of a bottom fixed turbine (a), and the lower location of a heaving turbine as it is moving upward (b), as it is moving downward (c), and the averaged of downward and upward motions (d).
Figure 17: Normalized Turbulent Kinetic Energy ($\frac{T.K.E.}{U_{hub}}$) plots in the wake of a bottom fixed turbine (a), and the lower location of a heaving turbine as it is moving upward (b), as it is moving downward (c), and the average of downward and upward motions (d).
CONCLUSION

A comprehensive experimental study was conducted to investigate the performance, loading and the near wake characteristics of a horizontal axis wind turbine subjected to heave motions. The results were then compared to those of a classical bottom fixed turbine. The current study was performed in a large-scale atmospheric boundary layer wind tunnel. The base of a 1:300 scaled model wind turbine was mounted on a translation stage. The translation stage was controlled to generate heave motions to simulate the dynamic surge motions experienced by floating offshore wind turbines. During the experiments, the velocity scaling method was chosen to maintain the similar velocity ratios (i.e., the ratios of the incoming airflow flow to that of turbine base motion) between the model and the prototype.

During the experiments, a high resolution digital particle image velocimetry (PIV) system was used to achieve flow field measurements to quantify the characteristics of the turbulent vortex flow in the near wake of the wind turbine model. Besides conducting “free run” PIV measurements to determine the ensemble-averaged statistics of the flow quantities such as mean velocity, Reynolds stress, and turbulence kinetic energy (TKE) distributions in the wake flow, “phase-locked” PIV measurements were also performed to elucidate further details about evolution of the unsteady vortex structures in the wake flow in relation to the position of the rotating turbine blades.

The results of the wake study reveal that the wake of a wind turbine subjected to heave motions, is highly dependent on which direction the turbine is oscillating. Furthermore, the velocity, frequency, and the range of oscillation also play an important role on the behavior and the wake pattern of the moving turbine. The wake of the oscillating turbine in heave motion, tends to accelerate as the turbine is moving upward, hence, reducing the power
extraction by the turbine. A decrease in Reynolds shear stress and the turbulent kinetic energy production was noted as the turbine was oscillating upward. However, as the turbine was moving downward, these effects reverse, and causes a deceleration in the wake of the moving turbine, hence increases the power production by the turbine, and increases the Reynolds shear stress and the turbulent kinetic energy. Averaging the wake results of both upward and downward motions of the turbine in heave motion produces results which are essentially the same as the wake of the bottom fixed turbine.

Both mean and the standard deviations of the power extracted by a small DC motor installed in the nacelle show great difference between the oscillating turbine and the bottom fixed turbine. The excessive fluctuations in the power output of the oscillating turbine is anticipated to greatly reduce the power quality of such oscillating turbines. The load measurements also show substantial amount of increase both in terms of mean and the fluctuating components for the oscillating turbine. Which consequently results in increased fatigue loads and decreased lifetime of the turbine and the associated floating components.

ACKNOWLEDGMENT

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CHAPTER 5

A STUDY OF THE PERFORMANCE, LOADING, AND THE NEAR WAKE CHARACTERISTICS OF A WIND TURBINE MODEL SUBJECTED TO COMBINED BASE MOTIONS

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Abstract: Installing wind turbines in deep water offshore environments is the future of wind energy. Although, there are many advantages with installing turbines in deep water, however, there are significant technological challenges associated with floating wind turbines in deep waters. The dynamic excitation of wind and waves can induce excessive motions along each of the 6 degrees of freedom (6-DOF) of the floating platforms. These motions will then be transferred to the turbine, and directly impact the loading, performance, and the wake characteristics of the floating wind turbines in an offshore environment.

In the present study, a brief study of loading, performance, and the near wake characteristics of a wind turbine model subjected to coupled base motions, which include a simultaneous movement of the turbine in surge, pitch, and heave motions. The full motion was calculated based on linear combinations of all uncoupled motions previously determined by the velocity ratio method. These experimental studies were performed in a large-scale atmospheric boundary layer wind tunnel with a scaled three-bladed Horizontal Axial Wind Turbine model placed in a turbulent boundary layer airflow with similar mean and turbulence characteristics as those over a typical offshore wind farm. The base of the 1:300 scaled model wind turbine was mounted on multiple translation and rotation stages. These stages can be controlled to generate all these motions to simulate the dynamics experienced by floating offshore wind turbines in the open seas.
A high resolution digital particle image velocimetry (PIV) system was used to achieve flow field measurements to quantify the characteristics of the turbulent vortex flow in the near wake of the wind turbine model. Besides conducting “free run” PIV measurements to determine the ensemble-averaged statistics of the flow quantities such as mean velocity, Reynolds stress, and turbulence kinetic energy (TKE) distributions in the wake flow, “phase-locked” PIV measurements were also performed to elucidate further details about evolution of the unsteady vortex structures in the wake flow in relation to the position of the rotating turbine blades. The effects of the coupled motions of the wind turbine base on the wake flow characteristics were examined in great details based on the PIV measurements. The performance of the scaled model wind turbine was measured using a small DC motor mounted in the nacelle assembly. A highly sensitive force/moment transducer was also mounted at the base of the turbine to measure the aerodynamic loading associated with the moving turbine. For better understanding of the effects of the full base motion on the Aerodynamics and Aeromechanics of wind turbines, the results were then compared to those of a traditional bottom fixed turbine.

**Results and Discussions**

The exact motions for the prototype turbine in full motion for the current study were determined using the previous numerical simulations results, and the linear combination of the most dominant uncoupled motions associated with a floating wind turbine. For the current study, the freestream velocity at the hub height of the scaled model turbine was set to 3.5 m/s. The turbine’s pitching frequency was 0.3 Hz, surge frequency of 0.2 Hz, and heave frequency of 0.32 Hz.
As previously described, a JR3 force-moment transducer was used in the present study that can provide the time-resolved measurements of all three component of the aerodynamic forces and moments about each axis. However, for the current study of the wind loads acting on turbine unit, static or dynamic, only the axial wind loads were considered, while other components of the loads can also be important factor in designing wind turbines and the floating platforms. Figure 1, gives the wind load measurement results in term of the instantaneous thrust coefficients for both the bottom fixed turbine and the moving turbine in pitch motion. As can be clearly seen from the time histories of the measured instantaneous thrust forces given in Figure 1, these loads are highly unsteady with their magnitudes fluctuating significantly as a function of time. The wind loads acting on the bottom fixed turbine in Figure 1(a), were found to be significantly different to the loads seen by the turbine in full motion 1(b). While the mean value of the wind loads acting on the turbine in full motion (i.e., \( CT = 0.4758 \)) is much higher than that of the bottom fixed turbine (i.e., \( CT = 0.3647 \)), the fluctuation amplitudes of the full motion were found to be significantly higher, which consequently increases the fatigue loads and ultimately reduces the life time of the moving turbine and the corresponding mooring lines of the floating platform which holds the turbine.

Figure 2 corresponds to the power spectral density of the measured instantaneous thrust forces acting on both model wind turbines (i.e. bottom fixed turbine and the oscillating turbine in full motion) through a Fast Fourier Transform (FFT) analysis procedure. In the case of the bottom fixed turbine (i.e. red color), a dominant peak at \( f_0 = 17 \) Hz can be identified which corresponds to the rotational speed of the turbines rotor blades at the optimum tip-speed-ratio of 4.5. The rotational frequency of \( f_0 = 17 \) Hz based on FFT analysis of the dynamic wind load measurements was found to agree very well with the independently measured rotational speed of the turbine blades by using a tachometer. However, in the case of the oscillating
turbine in full motion, multiple dominant frequencies are observed. As the turbine was oscillating with a very low frequencies in different directions, the power spectra plot clearly shows these motions with dominant frequencies of around 0.3 Hz. As the turbine was oscillating in full motion, the relative velocity seen by the rotor and the effective angle of attack of the blades significantly change, contributing to significant fluctuations in the rotational frequency of the rotor are apparent in the power spectra plot.

Figure 1: Measurement results of dynamic thrust force acting on the model wind turbine. Left (5a): bottom fixed turbine. Right (5b): turbine in full motion.

Figure 2: Comparison between the power spectra of the thrust forces of the bottom fixed turbine and the oscillating turbine in full motion.
Figure 3, shows the normalized power output of the bottom fixed turbine and the turbine in full motion. As can be seen in Figure 3, there is little difference between the mean power extractions by the two turbines. However, as can clearly be seen in Figure 4, the fluctuations in the power extraction of the turbine in full motion is substantially higher than those of the bottom fixed turbine. It is important to note that these fluctuations will significantly impact the quality of power generated by such oscillating turbines.

Figure 3: Performance comparison between the bottom-fixed turbine and the turbine in full motion.

Figure 4: Time history of the voltage measurements of the bottom fixed turbine (left) and the turbine in full motion (right).
The flow field \((x/D < 1.8)\) measurement in the wake of the turbine in full motion was also carried out by using a high-resolution PIV system, and the wake results obtained at the center location were then compared to those of a classical bottom-fixed turbine.

The measurement plane was composed of two fields with an overlap of 15mm length, and two CCD cameras were used to acquire images from these fields. Two fields were then merged in Tecplot to acquire the image in the measurement plane. Finally, ensemble averaged flow quantities, such as mean flow velocity, Reynolds stresses and Turbulence Kinetic energy, were analyzed.

Figure 5, shows the two pairs of contour plots accompanied by their extracted data (at \(x/D = 0.8\) and \(x/D=1.7\)) of the PIV measurements of the averaged stream-wise velocity component \(U\), normalized by the relative velocity experienced by the rotor at the hub height, for a classical bottom fixed turbine (a), the turbine in full motion at the center location.

As can be seen in Figure 5, there is clear evidence of the deficit in the velocity in the wake of both; the bottom fixed turbine and the turbine in full motion. This deficit is the result of energy extraction by the turbine itself. Double peaks are observed and understood as characteristic of the near wake profiles \((X/D <1)\). But as we go farther down in the wake \((X/D >1)\), the double peaks die out and become just a single peak. This single peak eventually dies out in approximately 15~20 diameter downstream of the turbine, where the flow gains its fullest momentum and becomes the undisturbed flow again. There is some overshoot at the top region of the profiles in the near wake regions which suggests that the flow is accelerating at near top-tip of the blade, and also could be an evidence of the blockage effect caused by the existence of the turbine itself.

Unlike the previous chapters, due to the complexity of motion, the PIV results could not be distinguished between which direction the turbine was oscillating. Therefore, as can be
observed in Figure 5b, there is little difference between the wake characteristics of the moving turbine and the bottom fixed turbine.

Figure 5: Normalized stream-wise velocity (U/Uhub) profiles in the wake of a bottom fixed turbine (a), the center location for a turbine in full motion (b).

Figure 6 and 7, shows the Reynolds shear stress ($\tau = \frac{-u'v'}{U_{hub}^2}$) and the turbulent kinetic energy ($T.K.E. = \frac{1}{2} \left[ u'^2 + v'^2 \right] / U_{hub}^2$). The Reynolds shear stress deals with the transport of momentum from high energy flow above the rotor to the lower energy area of the wake region. T.K.E. is the kinetic energy per unit mass associated with the eddies in the turbulent flows. T.K.E. deals with the diffusivity effect which is responsible for enhanced mixing. By studying both the Reynolds shear stress and the T.K.E., one can determine on how fast the wake is recovering. As can be seen in Figure 6 and 7, there are relatively higher amount of Reynolds shear stress, and T.K.E. associated with the turbine in full motion in comparison to the bottom fixed turbine. This is an indication of faster wake recovery in the case of floating turbine.
Figure 6: Normalized Reynolds Shear Stress ($\frac{R_{uv}}{U_{hub}}$) plots in the wake of a bottom fixed turbine (a), and the center location of a turbine in full motion (b).

Figure 7: Normalized Turbulent Kinetic Energy ($\frac{T_K E}{U_{hub}}$) plots in the wake of a bottom fixed turbine (a), and the turbine in full motion.
AN EXPERIMENTAL INVESTIGATION ON THE PERFORMANCE, LOADING, AND THE NEAR WAKE CHARACTERISTICS OF A DARRIEUS VERTICAL AXIS WIND TURBINE

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Abstract: The wake flow field \((x/D < 2.5)\) measurements behind a two-bladed Darrieus type VAWT were carried out by using a high-resolution PIV system, and the results obtained at two different horizontal \((x-y)\) planes, at the equator height \((H/2)\) and above the equator height \((3H/4)\), for four different tip speed ratios \((\lambda = 2, 2.5, 3 \text{ and } 3.5)\) of the VAWT were then evaluated and compared. The wake of the VAWT is found to be significantly different to that of the HAWT’s. At lower tip-speed-ratio (i.e. TSR 2) the wake tends to be very asymmetric and skewed with relatively higher amount of momentum in the wake in comparison to higher tip-speed ratios (i.e. 3 or 3.5). As tip-speed ratio increases, there is a tendency in flow stagnation in the wake and eventually flow reversal would occur at higher tip-speed-ratios. The wake dynamics (i.e., the instabilities inherent in VAWT) behind the VAWTs would lead to a much faster wake recovery in comparison to the HAWTs.

Introduction

With the increasing popularity of using wind as a renewable source of energy and the rapid development of onshore wind farms in the U.S., a saturation in the development of onshore wind energy in many good wind potential areas of the country is inevitable. Therefore, in order to continue with the increase in the wind generation capacity and to achieve the 20% goal by 2030, set by the U.S. Department of Energy, there is a need for offshore wind energy development in this country. The United States is especially fortunate to be surrounded by vast
waters on both sides of the nation. This provides a unique opportunity for offshore wind farm developments in this country. There is over 4000 GW of wind potential within 50 nautical miles of the U.S. coastlines (Musial et al, 2010), which is approximately four times the current U.S. power generation capacity.

By the end of 2013, there were 69 offshore wind farms operating in 11 European countries, yielding over 6.5 GW of electricity. All of these wind farms are located in shallow waters with depths less than 20 meters where the turbines are fixed to the sea floor (Corbetta G., 2014). Unlike the shallow European waters, the U.S. waters are, on the other hand, mostly deep (with the exception of a few regions in the East Coast and the Gulf of Mexico). Therefore, offshore wind farm development in the U.S. will most likely be based on the floating concept.

However, stability becomes a major problem with any floating structures and especially the Horizontal Axis Wind Turbines (HAWTs), since there Center of Gravity (CG) is located at a much higher location in relation to their Center of Buoyancy (CB) point of the structure. However, due to lower center of gravity, lesser mechanical complexity, and more cost effectiveness in stronger wind potential areas, the Vertical Axis Wind Turbines (VAWTs) can be a good alternative for floating offshore applications.

Although, the aerodynamics and aeromechanics of the Vertical Axis Wind turbines (VAWTs) have been studied in the past three decades, however due to rapid technological advancements and specifically with the recent popularity of laser diagnostics technique methods, the aerodynamics of VAWTs are being reevaluated for better understanding and improvements of VAWTs designs.

This paper presents the results of an experimental study performed on performance and the near wake of two-blades Darrieus VAWT subjected to different tip-speed-ratios for gaining a better understanding of the aeromechanics of such turbines.
Experimental Setup

The present experimental study is performed at the large-scale Aerodynamic/Atmospheric Boundary Layer (AABL) wind and gust tunnel located in the Department of Aerospace Engineering at Iowa State University. The AABL wind tunnel is a closed-circuit wind tunnel with a boundary-layer test section 20 m long, 2.4 m wide and 2.3 m high, optically transparent side walls, and with a capacity of generating a maximum wind speed of 40 m/s in the test section. Arrays of chains were laid-out on the wind tunnel’s floor on the upstream side of the wind turbine model in order to match the flow to that of offshore environment. The boundary layer growth of the simulated ABL wind under almost zero pressure gradient condition was achieved by adjusting the ceiling height of the test section of the wind tunnel. The oncoming boundary layer wind velocity profile was fitted by using Equation 1, where $z_{ref}$ is a reference height (equatorial height) and $U_{ref}$ is the wind speed at the reference height which is 5.2m/s. The power law exponent $'\alpha'$ is associated with the local terrain roughness. The power law exponent in Equation 1 was found to be $\alpha = 0.18$. For the current experimental study, a longitudinal turbulence intensity of 18% at the reference height of the model turbine was chosen.

$$\frac{U}{U_{ref}} = \left(\frac{z}{z_{ref}}\right)^\alpha$$  \hspace{1cm} (1)

Figure 1 shows, a 1:125 geometrically scaled model vertical axis wind turbine (HAWT) of height $H=400$ mm (excluding the base height $h=70$mm) representing Sandia’s 50m tall VAWT in full scale, with a constant airfoil NACA 0018 with a chord length of 50mm across the entire blade. The corresponding chord based Reynolds number was determined to be 18600. The equatorial diameter ($D$) is 270mm, and the swept area which is proportional to the square of the equatorial diameter ($D$) is $0.0715 \text{ m}^2$. The blockage ratio was determined to be 1.3%.
A 2-D Particle Image Velocimetry (PIV) technique was used (as shown in Figure 2) to capture whole-field information of the wake of both the bottom fixed turbine and the turbine with the surge motion. The coordinate system indicating three velocity components is also shown in Figure 2. The flow was seeded with 1-5 μm oil droplets and the laser system used for illumination of the seeding particles was a double-pulsed Nd:YAG laser (Ever Green big sky laser series) emitting two 200 mJ laser pulses at a wavelength of 532 nm and with a repetition rate of 1 Hz. For a better accuracy in results, the laser sheet thickness was adjusted to be around 1 mm. Two high-resolution (2048×2048 pixels) charge-coupled device (CCD) cameras with axis perpendicular to the laser sheet was used for PIV image acquisition. The CCD camera and the double-pulsed Nd:YAG lasers were connected to a workstation via a digital delay generator that controlled the timing of both the laser illumination and the image acquisition.

Instantaneous PIV velocity vectors were obtained using a frame-to-frame cross correlation technique involving successive frames of patterns of particle images in an interrogation window with 32×32 pixels and an effective overlap of 50% to satisfy the Nyquist criterion. The ensemble averaged flow quantities such as mean velocity, turbulent-velocity fluctuations, normalized turbulent kinetic energy, and Reynolds shear stress distributions were obtained from approximately 1000 frames of instantaneous PIV measurements. The measurement...
uncertainty level for the velocity vectors was estimated to be within 2.0\%, and that of the
turbulent velocity fluctuations and turbulent kinetics energy was about 5.0\%.

![Figure 2: PIV set-up](image)

**Results and Discussions**

The wake flow field (x/D < 2.5) measurements behind a Darrieus type vertical axis wind
turbine (VAWT) were carried out by using a high-resolution PIV system, and the results
obtained at two different horizontal (x-y) planes, at the equator height (H/2) and above the
equator height (3H/4), for different tip speed ratios (\(\lambda = 2, 2.5, 3\) and 3.5) of the vertical axis
wind turbine (VAWT) were then evaluated and compared.

The measurement plane was composed of two fields with an overlap of 15 mm length, and
two CCD cameras were used to acquire images from these fields. Two fields were then merged
in Tecplot to acquire the image in the measurement plane. Finally, ensemble averaged flow
quantities, such as mean stream-wise flow velocity, Reynolds shear stresses and Turbulence
Kinetic energy, were analyzed. In addition, the vorticity calculations from PIV measurements
were used to understand the evolution of the vorticity field in the VAWT wake.

Figure 4 shows the contours of ensemble-averaged stream-wise velocity in a horizontal plane
at the equator height (H/2) and above the equator height (3H/4), respectively. All velocities are
normalized with the freestream velocity at the equator height of the turbine, and x and y axes
are normalized with the rotor diameter. The plots are shown for different tip speed ratios (\(\lambda =
2, 2.5, 3\) and 3.5). In addition, the wind flows from left to right in the given plots.
As VAWT rotates in the counter clockwise direction, it extracts the energy available in the wind flow, leaving a region with greater velocity deficits in its wake. As shown in the streamwise velocity contours in Figure 4, greater momentum deficits can still be observed within the range of measurements (2.5 diameters downstream of the VAWT). However, the effects of VAWT wake can be noticeable even after downstream distances as large as 10 rotor diameters (Shamsoddin et al., 2014). Therefore, the full VAWT wake dynamics with complete wake recovery are not fully captured due to the limited range of measurements. Nevertheless, when we go further downstream of the VAWT, the signs of the wake recovery can be observed. As the wake recovery is associated with the high momentum flow entrained from above, the onset of the wake recovery becomes more evident in the horizontal plane above the equator height (3H/4). In addition, the region with greater velocity deficits is observed to shrink tighter spanwise in a horizontal plane away from the equator of the turbine due to the unique shape (i.e., its diameter reduces away from its equator) of the VAWT.

Different tip speed ratios are found to significantly affect the wake flow dynamics of VAWTs. As shown in Figure 4, as VAWTs rotate faster with respect to the incoming wind flow (i.e., increasing the tip speed ratio of VAWT), the blue region with greater velocity deficits is observed to expand in span-wise (y) direction; whereas it is observed to shrink in stream-wise (x) direction. Therefore, at lower tip-speed-ratios (i.e. TSR 2) the wake tends to be very asymmetric and skewed with relatively higher amount of momentum in the wake in comparison to higher tip-speed ratios (i.e. 3 or 3.5). As tip-speed ratio increases, there is a tendency for the flow to stagnate in the wake of the VAWT and eventually flow reversal would occur at higher tip-speed-ratios. The wake asymmetry behind the VAWT was also stated by Tescione et al. (2014) and Shamsoddin et al. (2014). Figure 4, show the extracted data from the streamwise velocity contours shown in Figure 4. These plots are extracted at the center line
(location 0) of the wake for all tip-speed-ratios and at tow heights \((Z= 1/2H \text{ and } 3H/4)\) and they provide valuable information on the wake recovery of a VAWT. As VAWT rotates in counter clockwise direction, the stream-wise velocity component of the blade velocity in the positive \(y\) axis is in the opposite direction with the inflow wind; whereas the stream-wise velocity component of the blade velocity in the negative \(y\) axis is in the same direction with the inflow wind. The wake symmetry is observed to be broken towards the positive \(y\) axis on the horizontal plane, and the wake is much stronger in that region. The asymmetry due to the unbalanced blade forces in the windward (positive \(y\)) and leeward (negative \(y\)) side of the VAWT leads to the skewness in the velocity profiles with more pronounced wake expansion and velocity deficit towards the windward side. These effects due to the wake asymmetry can be seen at all tip speed ratio cases, and they are more evident at the upper half of the equator \((3H/4)\). However, blade velocity depends on the rotor radius, and rotor radius reduces away from the equator thereby reducing the induced flow velocity. Since the blade forces are dependent on the relative velocity at the blades, velocity deficits observed on the horizontal plane would be lesser away from the equator of the VAWT. Therefore, velocity deficits are found to be comparably weaker above the equator height \((3H/4)\). Thus, the wake starts to recover earlier with the high momentum flow entrained from above. It is also a well-known fact that wake recovery is strongly dependent on the turbulence levels in the flow; therefore, it would be insightful to investigate the generated turbulence in the VAWT wake.

The turbine power output measurements were achieved by measuring the voltage outputs of the small DC generator (Kysan, FF-050S-07330) installed at the bottom of the wind turbine, below the wind tunnel floor. During the experiments, the voltage outputs of the DC generator was acquired through an A/D board plugged into a host computer at a data sampling rate of 1
kHz for two minutes. Figure 5, shows the normalized power coefficient extracted by VAWT at different rotational frequencies. As the rotational frequency of the turbine increases, the tip-speed-ratio increases, resulting in higher energy extraction from the flow. These power measurement results are quite consistent with the wake results shown in Figure 4.

![Figure 3. Extracted mean streamwise velocity, U/Ueq, taken at the center location of the wake (location 0 in the contour plots) at the equator height (H/2 – on the left) and above the equator height (3H/4 – on the right).](image)

![Figure 5. Normalized (with respect to maximum power extracted) power coefficients of the VAWT at different TSRs.](image)

Both static and dynamic wind loads were also measured using two identical high-sensitivity force-moment sensors (JR3, model 30E12A-I40) that were installed on top and the bottom of the turbine. The precision of the force-moment sensor cell for force measurements
is ±0.25% of the full range (40 N). While the force-moment sensors mounted at the top and bottom of the turbine tower can provide time-resolved measurements of all three components of the aerodynamic forces and the moment (torque) about each axis, only the measured thrust coefficient, $C_{Fx}$, are given in the present study. The thrust coefficient (along the streamwise velocity direction) is defined by using $C_{Fx} = \frac{Fx}{\frac{1}{2} \rho U^2 \pi R^2}$ where $\rho$ is the air density, $U$ is the mean flow velocity at the equator height. The wind load data was acquired for five minutes at a sampling rate of 1,000 Hz for each tested case. Table 1, provides the results of wind load measurements on the model turbine at different tip-speed-ratios.

As can be seen in Table 1, as the tip-speed-ratio increases, the mean thrust load acting on the turbine also increases. Although the mean wind loads are important for designing wind turbines, however, the unsteadiness effects also become important to consider mostly because of the influence these type of loads have on fatigue lifetime of the wind turbines operating in turbulent ABL winds. Also it is a well-known that vertical axis wind turbine suffer from fatigue loading because at-least one of the blades is always operating in the wake of the other blades, hence impacting the life time of the blades significantly.

<table>
<thead>
<tr>
<th>T.S.R.</th>
<th>Thrust (axial) loading coefficient ($C_{Fx}$)</th>
<th>$\sigma(C_{Fx})$</th>
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<tr>
<td>2.0</td>
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<td>0.23</td>
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<tr>
<td>2.5</td>
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</tr>
<tr>
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<td>0.31</td>
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Table 1. Static and dynamic wind loads acting on a VAWT at different TSRs.

Figure 6 shows the contours of ensemble-averaged Turbulence Kinetic Energy (TKE) in a horizontal plane at the equator height (H/2) and above the equator height (3H/4), respectively. The TKE distribution plots in Figure 6 show distinct characteristics in the span-wise and
stream-wise directions. As can be seen from the contours given in Figure 6, TKE levels are very low in the vicinity of the turbine and also in the near wake. TKE levels are found to gradually increase as we go downstream. However, this increase in TKE levels is observed to extend and shrink at the same time further downstream of the VAWT (i.e., more pronounced towards the wake centerline), leaving tail-like contours on the horizontal plane at the equator height (H/2). As the tip speed ratio of VAWT increases, TKE enhancement in the tail-like contours can easily be distinguished. However, in the case of the horizontal plane above the equator height (3H/4), TKE level at the wake centerline (i.e., Y/D =0.0) is observed to reach maximum at shorter downstream distances without leaving any traces of tail-like contours. The span-wise variation of TKE shows significant enhancement in TKE levels on the edges of the wake due to the unsteady vortex shedding from the blades. The shear (viscous) layer formed by the shedding vortices is observed to expand as we go further downstream. The strong mixing in the viscous layer would lead to effective momentum transfer into the wake center, thereby increasing the wake recovery rate. The shear layer is also observed to expand and reach the wake centerline much faster as the tip speed ratio of the VAWT increases. As tip speed ratio increases, the blade may interact with its own wake together with the other blade’s wake several times (i.e., blade-wake interaction) which leads to a faster transition to the full rotor wake where blade wakes are no longer noticeable (Tescione et al., 2014). This quick transition might provide better wake recovery rates for VAWTs.

Figure 7 shows the contours of ensemble-averaged Reynolds shear stress (Ruv) in a horizontal plane at the equator height (H/2) and above the equator height (3H/4), respectively. As can be seen from the contours given in Figure 7, higher levels of Reynolds shear stress occur on the edges of the wake analogous to TKE distribution. Reynolds shear stress can be used as an indicative of the momentum transfer into the wake. Therefore, the sign change is only
associated with the change in the direction of the momentum transfer; where in case of positive
(i.e., shown in red contours) Reynolds shear stress, the momentum transfer is in the –y direction
and in case of negative (i.e., shown in blue contours) Reynolds shear stress, the momentum
transfer is in the +y direction. Therefore, Reynolds shear stress is a very crucial parameter for
the wake recovery since it entrains high momentum flow into the wake. As tip speed ratio
increases, the instabilities mainly caused by blade-wake interaction become more evident
increases the extent of the mixing region which results in the expansion of the high TKE and
Reynolds shear stress region. In addition, the region with absolute higher Reynolds shear stress
is observed to be comparably narrower for the horizontal plane above the equator height (3H/4)
in comparison to that at the equator height (H/2). This can be attributed to the decrease in the
local tip speed ratio due to the reduction in the diameter of the VAWT when we go away from
the equator of the VAWT where the maximum rotational speed (RΩ) is observed.

Figure 8a and Figure 8b show the contours of the vorticity in a horizontal plane at the equator
height (H/2) and above the equator height (3H/4), respectively. The phase locked vorticity
contours behind the VAWT are given at a blade phase angle of 0°. As shown in Figure 8a and
Figure 8b, the wake flow behind the VAWT is utterly dominated by the evolution of the
unsteady vortex structures released from the trailing edge of each blade. However, the shedding
of the concentrated vortices would be highly turbulent with the blade-wake interactions and
ambient turbulence, thereby inducing instabilities in the wake flow which promotes rapid
dissipation/breakdown of the vortex structures. The dissipation/breakdown of the vortex
structures will result in significant enhancement in TKE and Reynolds shear stress levels on
the edges of the wake. All these instabilities for the VAWT wake might lead to faster wake
recovery rates.
Figure 4. Contours of the normalized mean streamwise velocity, \( U/U_{eq} \), in a horizontal plane at the equator height (\( H/2 \) – on the left) and above the equator height (\( 3H/4 \) – on the right)
Figure 6. Contours of the turbulence kinetic energy (TKE) in a horizontal plane at the equator height (H/2 – on the left) and above the equator height (3H/4 – on the right)
Figure 7. Contours of the Reynolds shear stress ($R_{uv}$) in a horizontal plane at the equator height (H/2 – on the left) and above the equator height (3H/4 – on the right).
Conclusions

An experimental study was performed to analyze the effects of four different tip-speed-ratios (\(\lambda = 2, 2.5, 3,\) and 3.5) on the aerodynamics and aeromechanics of a two-bladed Darrieus vertical axis wind turbine. The wake flow field (\(x/D < 2.5\)) measurements were carried out by using a high-resolution PIV system, and the results obtained at two different horizontal (x-y) planes, at the equator height (H/2) and above the equator height (3H/4). The wake of the VAWT is found to be significantly different to that of the HAWT’s. At lower tip-speed-ratio (i.e. TSR 2) the wake tends to be very asymmetric and skewed with relatively higher amount of momentum in the wake in comparison to higher tip-speed ratios (i.e. 3 or 3.5). As tip-speed ratio increases, there is a tendency in flow stagnation in the wake and eventually flow reversal
would occur at higher tip-speed-ratios. The wake dynamics (i.e., the instabilities inherent in VAWT) behind the VAWTs would lead to a much faster wake recovery in comparison to the HAWTs. With an increase in tip-speed ratio both the power measurement and the thrust loading acting on the turbine increases.

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**References**


Floating offshore wind turbines are the future of wind energy. The United States is especially fortunate to be surrounded by vast yet deep waters on both sides of the nation. This provides a unique opportunity for offshore floating wind farm developments in this country. But, so far, no major progress has been made in developing any offshore floating wind farms. This is mainly due to lack of experience and knowledge needed to overcome the obstacles faced by wind turbine manufacturers. One of these obstacles is the uncertainty associated with the performance, loading and sitting of such floating turbines. With only few numerical simulation studies being done to understand the coupled behavior of floating offshore wind turbines, there is a need for a comprehensive experimental study to validate the numerical results and perhaps to improve our current understanding of the floating offshore wind turbines’ performance and aerodynamics, which can potentially lead to more accurate load and performance predictions and design improvements.
In order to understand, and fully explore the Aerodynamics and aeromechanics of floating wind turbine, a comprehensive experimental study was performed on the performance, loading, and the near wake characteristics of a wind turbine model subjected to uncoupled and coupled base motions: surge, pitch, and heave. The results were then compared to that of a classical bottom fixed turbine. These studies were performed under the condition of normal sea condition and therefore, no extreme scenarios were evaluated in this study. A high resolution PIV system was used for detailed near wake flow field measurements (free-run) so as to quantify the near wake turbulent flow structures. The results of the wake study however, shows strong dependency on which direction the turbine is oscillating. Furthermore, the velocity, frequency, and the range of oscillation also play an important role on the behavior and the wake pattern of the moving turbine. The wake of the oscillating turbine in surge and pitch motion, tends to accelerate as the turbine is moving with the flow, hence, reducing the power extraction by the turbine. A decrease in Reynolds shear stress and the turbulent kinetic energy production was noted as the turbine was oscillating with the flow. However, as the turbine was moving into the flow, these effects reverse, and causes a deceleration in the wake of the moving turbine, hence increases the power production by the turbine, and increases the Reynolds shear stress and the turbulent kinetic energy. Averaging the wake results of both forward and backward motions of the turbine in surge and pitch motions produces results which are essentially the same as the wake of the bottom fixed turbine.

Although, the mean power measured by a small DC motor installed in the nacelle shows little difference between the oscillating turbine and the bottom fixed turbine, but the excessive fluctuations in the power output of the oscillating turbine is anticipated to greatly reduce the power quality of such oscillating turbines. The load measurements also show substantial amount of increase both in terms of mean and the fluctuating components for the oscillating
turbine. Which consequently results in increased fatigue loads and decreased lifetime of the turbine and the associated floating components.

The static and dynamic effects of the heaving motion on the mean and turbulent quantities were investigated. The wake development behind the oscillating turbine in pure heave motion was found to be altered by the direction of the heave motion (hysteresis effect). The wake of the oscillating turbine in heave motion, tends to accelerate as the turbine is moving upward, hence, reducing the power extraction by the turbine. A decrease in Reynolds shear stress and the turbulent kinetic energy production was noted as the turbine was oscillating upward. However, as the turbine was moving downward, these effects reverse, and causes a deceleration in the wake of the moving turbine, hence increases the power production by the turbine, and increases the Reynolds shear stress and the turbulent kinetic energy. Averaging the wake results of both upward and downward motions of the turbine in heave motion produces results which are essentially the same as the wake of the bottom fixed turbine.

Both mean and the standard deviations of the power extracted by a small DC motor installed in the nacelle show great difference between the oscillating turbine and the bottom fixed turbine. The excessive fluctuations in the power output of the oscillating turbine is anticipated to greatly reduce the power quality of such oscillating turbines. The load measurements also show substantial amount of increase both in terms of mean and the fluctuating components for the oscillating turbine. Which consequently results in increased fatigue loads and decreased lifetime of the turbine and the associated floating components.

The combination of the all the three dominant degrees of freedom (i.e. surge, pitch, and heave) associated with a floating wind turbine results in a non-linear combination of the results of the uncoupled motions. Although both mean and standard deviation of the power and load measurements of the combined motions show significant difference between the bottom fixed
turbine and the turbine in full motion, but due to complexity of the motion, it becomes difficult to analyze the flow based on which direction the turbine is oscillating and hence, the results of the wake study become very similar to that of a bottom fixed turbine.

Finally, an experimental study was performed to analyze the effects of four different tip-speed-ratios ($\lambda = 2, 2.5, 3,$ and $3.5$) on the aerodynamics and aeromechanics of a two-bladed Darrieus vertical axis wind turbine. The wake flow field ($x/D < 2.5$) measurements were carried out by using a high-resolution PIV system, and the results obtained at two different horizontal ($x$-$y$) planes, at the equator height ($H/2$) and above the equator height ($3H/4$), for four different. The wake of the VAWT is found to be significantly different to that of the HAWT’s. At lower tip-speed-ratio (i.e. TSR 2) the wake tends to be very asymmetric and skewed with relatively higher amount of momentum in the wake in comparison to higher tip-speed ratios (i.e. 3 or 3.5). As tip-speed ratio increases, there is a tendency in flow stagnation in the wake and eventually flow reversal would occur at higher tip-speed-ratios. The wake dynamics (i.e., the instabilities inherent in VAWT) behind the VAWTs would lead to a much faster wake recovery in comparison to the HAWTs. With an increase in tip-speed ratio both the power measurement and the thrust loading acting on the turbine increases.