An Experimental Investigation on Dynamic Wind Loads Acting on a Wind Turbine Model in Atmospheric Boundary Layer Winds

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An experimental study was conducted to investigate the dynamic wind loads acting on a wind turbine model sited in atmospheric boundary layer winds. The experimental studies are conducted in a large-scale Aerodynamic/Atmospheric Boundary Layer (AABL) Wind Tunnel available at Iowa State University. A three-blade Horizontal Axial Wind Turbine (HAWT) model was placed in atmospheric boundary layer winds with different mean and turbulence characteristics to simulate the situations in onshore and offshore wind farms. In addition to measuring dynamic wind loads (both forces and moments) acting on the HAWT model, a high-resolution Particle Image Velocity (PIV) system is used to conduct detailed flow field measurements to quantify the characteristics of the turbulent vortex flow in the near wake of the wind turbine model. The detailed flow field measurements were correlated with the dynamic wind loads measurements to elucidate underlying physics in order to gain further insight into the characteristics of the dynamic wind loads for for better durability of the wind turbines in atmospheric boundary layer (ABL) winds.

Nomenclature

\( R \) = radius of the wind turbine rotor
\( H \) = hub height of the wind turbine
\( U_{Hub} \) = inflow velocity at hub height of wind turbine
\( C_T \) = thrust coefficient
\( C_{M_y} \) = bending moment coefficient along y direction
\( \Omega \) = turbine angular velocity
\( \lambda \) = tip speed ratio
\( \theta \) = phase angle of the wind turbine blades
\( \rho \) = air density

I. Introduction

The mechanical design of a wind turbine structure involves the fatigue loading as well as extreme loading, which are fairly difficult to characterize because they are of variable amplitude with the intensity of the variations depending on the environmental wind climate. In order to conduct the effective dynamic wind loads analyses, the factors affecting dynamic loads acting on wind turbine must be comprehensively considered. These factors include wake induced effects, terrain characteristics, as well as atmospheric boundary layer wind characteristics such as wind shear, thermal stability and flow turbulence. For example, today’s wind turbines operate under many different terrain conditions, ranging from rather flat sites with low turbulence to complex terrain with quite high turbulence. However, it is often not known how the wind turbine performs with these conditions.

In reality, the wind turbine loading time series are usually obtained from prototype measurements. These measurements are carried out with the chosen test sites often feature with benign climatic conditions. Since the flow conditions are difficult to control for onsite tests, the measured dynamic loads of prototypes can not necessarily reflect the underlying physics associated with fatigue loads analyses. Thus, it is difficult to use such measurements data to predict the fatigue loads in the series at a particular site properly. In addition to the full-scale field measurements, different approaches in numerical modeling have been implemented in order to predict the dynamic response of the wind turbines. Moriarty et al. (2004) generated multiple samples of loading data under various wind conditions.

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conditions by using the stochastic turbulence simulator coupled with the aeroelastic code. Furthermore, in the study of Lee et al. (2012), the atmospheric and wake turbulence impacts on wind turbines are investigated by using a two-way coupled aeroelastic tool with LES. However, there is still space for using present developed simulation to accurately predict the dynamic loads acting on wind turbine under different conditions. One challenge associated with the development of these numerical modeling are the fewer quantitative experimental and field measurement data to verify the numerical simulation results.

Nowadays, wind tunnel facilities have been widely used for wind turbine studies due to their capabilities to produce well-controlled flow environments. Recently, Hu et al. (2012) conducted an experimental study on a wind turbine model and found that the instantaneous wind loads acting on the model wind turbine are highly unsteady with their magnitude fluctuating randomly, which could be 2~3 times higher compared with the time-averaged values. The quantitative measurement results of wind tunnel study with well-controlled flow conditions not only can be used as the database for numerical simulation validation and verifications, but also can be used for elucidating the underlying physics to explore the optimal design paradigms for better turbine durability.

The present wind tunnel study investigates the behavior of dynamic wind loads acting on the wind turbine model under different simulated ABL wind conditions. Moreover, the contributions of wind turbine components to the dynamic wind loads acting on model wind turbine were also revealed along with the effects of different blade phase angles for a stationary wind turbine in the event of shut down.

II. Experimental Setup

The experiments were conducted in a large-scale Aerodynamic/Atmospheric Boundary layer (AABL) Wind Tunnel located at the Aerospace Engineering Department of Iowa State University. The AABL wind tunnel is a closed circuit wind tunnel with a test section of 20m long, 2.4m wide and 2.3m high. In the present study, two types of ABL wind corresponding to different terrains were simulated by adjusting the triangular spires at the beginning of the test section and the wooden blocks covered on the wind tunnel floor, as shown in Figure 1. The boundary layer growth of the simulated ABL wind under zero pressure gradient condition was achieved by adjusting the ceiling profile of the test section of the wind tunnel.

It is suggested that the velocity profile of an ABL wind over an open terrain can usually be fitted well by using a power function. The different power-law exponents represent the different types of open terrain. Figure 2 shows the measured normalized stream-wise mean velocity and turbulence intensity profiles at the centerline of wind tunnel where the model wind turbine was located. As shown in Figure 2(a), the power-law exponent for the first type of ABL wind is about 0.11, which can be used to represent the offshore (open sea) terrain according to ASCE standard (2005). The corresponding turbulence intensity shown in Figure 2(b) is about 9.5% at hub height ($z/H=1$), which is similar to ABL wind turbulence character over open sea based on the onsite measurements of Hansen et al. (2012) at Horns Rev offshore wind farm. For the second type of ABL wind, the power-law exponent in Figure 2(c) is about 0.16, which represents the onshore wind farm sited over terrain of open country with low scrub or scattered trees. Figure 2(d) shows the turbulence intensity as a function of the height above the floor of the AABL wind tunnel. It can be seen clearly that the turbulence intensity is in fairly good agreement with the standard turbulence intensity profile of an ABL wind over an open terrain as suggested by Architectural Institute of Japan (AIJ, 1996).

![Atmospheric Boundary Layer Wind](image_url)
Figure 2. Characteristics of simulated ABL wind (a) offshore, stream-wise mean velocity; (b) offshore, turbulence intensity; (c) onshore, stream-wise mean velocity; (d) onshore, turbulence intensity

The wind turbine model used for the present study represents the most widely used three-blade horizontal axis wind turbines (HAWT). The rotor radius of the wind turbine model is 127 mm and the height of the turbine nacelle is 225 mm above the wind tunnel floor. With the scale ratio of 1:350, the test model would represent a wind turbine in a wind farm with the rotor diameter about 90 m and tower height about 80 m. The blade of tested model was generated based on the ERS-100 prototype of wind turbine blade developed by TPI. Furthermore, in order to analyze the dynamic wind loads acting on different components of wind turbine, the tested model can be separated into three parts: tower, nacelle and rotor. In the present study, the angular velocity of the turbine blades was adjusted by applying different electric loads to the small DC generator installed inside the turbine nacelle. The turbine angular velocity ($\Omega$) can change from 0 to 2200 rpm and the corresponding tip speed ratio of the tested model ($\lambda = \Omega (2\pi/60) R/U_{\text{hub}}$, where $R$ is the radius of the rotor, $U_{\text{hub}}$ is the oncoming flow velocity at the hub height, $H$) is in the range from 0 to 6.0. The optimum tip speed ratio, which corresponds to maximum power coefficient of the wind turbine model, is around $\lambda = 4.6$.

In order to measure the dynamic wind loads acting on the wind turbine, a high-sensitivity force transducer (JR3, model 30E12A-I40) with transducer full scale of 40 N and accuracy of ±0.25% was connected to the underneath of the installed wind turbine. In the present study, the dynamic wind loads including thrust coefficient (i.e., the force coefficient along stream-wise direction) and bending moment coefficient (i.e., the moment coefficient along span-wise direction) were given and calculated by using the expressions of $C_T = T/(0.5 \rho U_{\text{hub}}^2 \pi R^2)$ and $C_M = M_y/(0.5 \rho U_{\text{hub}}^2 \pi R^2 H)$, where $\rho$ is the air density. For each tested case, the wind load data were acquired for 120 seconds at a sample rate of 1000 Hz.

A high-resolution Particle Image Velocimetry (PIV) system was used in the present study to conduct detailed flow field measurements in a vertical plane through the rotation axis of the wind turbine model. The flow was seeded with ~1 $\mu$m oil droplets by using a droplet generator. Illumination was provided by a double-pulsed laser (Evergreen) adjusted on the second harmonic and emitting two pulses of 200 mJ at the wavelength of 532 nm. The thickness of the laser sheet in the measurement region was about 1.5 mm. A high-resolution 12-bit CCD camera...
(PCO1600, CookeCorp) was used for 2D PIV image acquisition with the axis of the camera perpendicular to the laser sheet. In addition, a Digital Delay Generator (Berkeley Nucleonics, Model 565) was used to control the timing of the laser illumination and the camera image acquisition. The phased-locked PIV measurements were conducted to elucidate the details about the evolution of the vortex structure in relation to the position of the rotating turbine blades.

III. Results and Discussion

3.1 Dynamic Wind Loads Acting on Different Components of Wind Turbine Model

In the present study, the tested model is designed to be separated into three parts: tower, nacelle and rotor. Figure 3(a) shows the mean thrust force and bending moment acting on different components of the wind turbine model. The rotating case corresponds to the wind turbine model operating at optimum tip speed ratio of $\lambda=4.6$. The results for the stationary case refer to the wind loads acting on tested model when the rotor of wind turbine does not rotate. At first, it can be seen that without rotor, the wind loads acting on both tower and nacelle together contribute only around 10% of the overall wind loads corresponding to the wind turbine rotating at optimum tip speed ratio. In addition, since the wind speed in ABL wind increases continuously with the height, the region corresponding to the rotor of wind turbine would experience much higher wind speeds, and thereby results in the portion of wind loads acting on rotor much greater compared to the wind turbine located in the uniform oncoming flow. As shown in Figure 3(a), around 90% of the wind loads acting on wind turbine under operating comes from the rotating rotor. These quantitative results highlight the importance of the mechanical design for the connecting parts between rotor and nacelle. Secondly, the rotor is located in the upper region of wind turbine, which can increase the length of the arm of bending moment. Therefore, it can be seen clearly that the increase of bending moment is more evident than that of the thrust force after the rotor was added to the nacelle. Thirdly, it is well known that the wind turbine will be controlled to stop running if the wind speeds go beyond the “cut-off” speed. However, as shown in Figure 3(a), the wind loads acting on stationary wind turbine can achieve 40% compared to the rotating case. Thus, the wind loads acting on wind turbine under extreme wind conditions still need to be considered even the rotor of wind turbine does not rotate.

![Figure 3. Comparison of dynamics wind loads acting on different components of wind turbine](image-url)

(a) mean wind loads; (b) fatigue wind loads

While the mean wind loads were traditionally used for the mechanical design of the wind turbines, the wind loads fluctuations, which highly associated with fatigue lifetime of wind turbine, are studied extensively in recent years for optimal wind turbine design. In the present study, the standard deviations of the measured wind loads are used to represent the fatigue loads acting on the wind turbine. As shown in Figure 3(b), the fatigue loads acting on both tower and nacelle together are less than 10% of the overall dynamic wind loads corresponding to the rotating case. More than 90% of fatigue loads come from the rotating rotor, which is even higher than the proportion in mean wind loads. Moreover, the fatigue loads acting on the stationary wind turbine constitute 20% of the overall fatigue loads although the contribution of the stationary wind turbine to the overall mean wind loads was found to be around 40%. It clearly indicate that the motion of rotor contribute most of the fatigue loads acting on wind turbine.
3.2 Dynamic Wind Loads Acting on Stationary Wind Turbine with Different Blade Phase Angle

As mentioned above, the mean wind loads acting on the stationary wind turbine can reach 40% compared to the wind turbine rotating at optimal tip speed ratio. Thus, it is important to reduce the dynamic wind loads acting on stationary wind turbine under the extreme wind conditions such as blast or gale. Figure 4 shows the dynamic wind loads acting on the stationary wind turbine with different phase angles of the turbine blades. In the present study, phase angle was defined as the angle between the vertical plane passing through the rotation axis of the wind turbine model and the position of a pre-marked rotor blade.

The mean wind load variations with the phase angle can be seen clearly in Figure 4(a). The mean wind loads decrease with the phase angle, attain a minimum value at phase angle $\theta=60^\circ$ and then increase with further increase in the phase angle. The fact that one of the blades is right in front of the tower at the phase angle of $\theta=60^\circ$, thereby significantly decreasing the wind loads acting on the tower. Moreover, the top tip height reached by the wind turbine blades is lowest at phase angle $\theta=60^\circ$ so that the rotor experiences lower wind speeds in ABL wind compared to other phase angles. Thus, minimum mean wind loads were found to appear at the phase angle of $\theta=60^\circ$.

As shown in Figure 4(a), the mean thrust and bending moment coefficients at the phase angle of $\theta=60^\circ$ were calculated as $C_T=0.165$ and $C_M=0.177$, respectively. Both of the thrust and bending moment at $\theta=60^\circ$ were found to be around 15% less than the maximum loads appeared at the phase angle of $\theta=0^\circ$. Therefore, the mean wind loads acting on the stationary wind turbine could be reduced by adjusting the turbine blade to an appropriate circumferential position. Furthermore, it can be seen from Figure 4(b) that the variation of fatigue loads with the phase angle follow the same trend with the mean wind loads variations. The minimum fatigue loads were also found to occur at the phase angle of $\theta=60^\circ$, which were 10% less than the fatigue loads at the phase angle of $\theta=0^\circ$.

![Figure 4. Dynamics wind loads acting on stationary wind turbine with different blade phase angles](image)

3.3 Dynamic Wind Loads Acting on a Wind Turbine Sited in Different ABL Winds

In the present study, two types of ABL wind were simulated to represent the oncoming flow corresponding to the offshore and onshore wind environments with hub height velocity, $U_{hub}$, equal to 4.9 m/s and 4.5 m/s, respectively. The time history of dynamic thrust force acting on the wind turbine sited in the offshore and onshore wind environment are shown in Figure 5(a), 5(b). The instantaneous wind loads acting on the wind turbine model were found to be highly unsteady with their magnitudes fluctuating significantly as a function of time. The time-averaged values were also plotted in the graphs as the dashed lines for comparison. The measurement results in Figure 5 reveal clearly that the instantaneous wind loads acting on a wind turbine operating in a turbulent ABL wind could be significant compared with the time-averaged values. In addition, as shown clearly in Figure 5(a) and 5(b), the magnitudes of the instantaneous thrust force acting on the model wind turbine sited in onshore wind environment were found to be more significant than that acting on the wind turbine model sited in offshore wind environment.

Figure 5(c) and 5(d) show the histograms of the measured dynamic thrust acting on the wind turbine model. While the instantaneous wind loads acting on the wind turbine model were found to be highly unsteady with their magnitude fluctuating randomly, the histograms of the measured thrust coefficients were found to be fitted reasonably well by using Gaussian functions for both offshore and onshore wind environments, which confirm that
it is reasonable to use the standard deviation of wind loads to estimate the fatigue loads acting on wind turbine even though sited in turbulence ABL winds. While the standard deviation of the thrust coefficient acting on wind turbine sited in offshore wind environment was found to be 0.144, the standard deviation of the thrust coefficient corresponding to the wind turbine sited in onshore wind environment was 0.232. This evident difference is mainly due to the high turbulence intensity levels of the ABL wind corresponding to onshore wind environment. The quantitative measurement results highlight the importance of taking the ambient turbulence intensity levels of the ABL winds into account for the fatigue loading analysis of the wind turbines in the mechanical design.

Figure 5. Measured wind loads acting on the wind turbine model (a) time history of $C_T$, offshore; (b) time history of $C_T$, onshore; (c) histogram of $C_T$, offshore; (d) histogram of $C_T$, onshore; (e) power spectrum of $C_T$, offshore; (f) power spectrum of $C_T$, onshore
Figure 5(e), 5(f) shows the power spectrum of the measured aerodynamic thrust obtained through a fast Fourier transform (FFT) analysis procedure. A dominant peak at $f_0 = 28\,\text{Hz}$ can be identified clearly in the spectrum plots shown in Figure 5(e), which corresponds to the rotational speed of the rotor blades of the wind turbine model at the tip speed ratio of $\lambda = 4.6$. The rotational frequency of $f_0 = 28\,\text{Hz}$ based on the FFT analysis of the wind load measurements was found to agree well with the independently measured rotational speed of the rotor blades by using a tachometer. Other peaks, which represent the harmonic frequencies of the rotational frequency of the turbine rotor blades, $f_0$, can also be identified clearly from the power spectrum plots. However, as shown in Figure 5(f), there is no dominating peak in the spectrum as shown in Figure 5(f). The rotational speed of the rotor blades fluctuate in a wide frequency region (i.e. $23\,\text{Hz} < f_0 < 30\,\text{Hz}$). Obviously, the wind loads acting on the wind turbine would change significantly with the rotational speed of wind turbine blades accelerating or decelerating randomly in a wide range.

In the present study, the turbulent vortex flow structures in the near wake of the wind turbine model was also measured to further understand the underlying physics associated with the dynamic wind loads. Figure 6 shows the typical out-of-plane vorticity distribution in the near wake of the wind turbine model by using phase-locked PIV measurements. The effects of the different ABL winds on the evolution of the unsteady vortex flow structures in the wake of the wind turbine model were revealed clearly from the comparison of the PIV measurement results. It can be seen clearly from Figure 6(a) that the tip vortices induced by the three turbine blades aligned themselves well behind the tips of the turbine blades with identical spacing to form a moving tip vortex array in the wake. In addition, a series of vortices shedding periodically from the roots of the rotating turbine blades can also be found clearly in the wake. However, as shown in Figure 6(b), the intensity of vortex shedding from the turbine blades become much weaker compared to the vortex shown in Figure 6(a). Moreover, the concentrated vortex structures were found to break down completely in the region after the second tip vortex. In fact, these significant differences between Figure 6(a) and 6(b) can be attributed to two aspects. First, as mentioned before, the rotational speed of the wind turbine blades was found to fluctuate in a wide frequency range for the wind turbine sited in the onshore wind environment, which would highly introduce the vortex instability and restrict the formation of concentrated vortex. Secondly, the high ambient turbulence levels in ABL wind corresponding to onshore wind environment would significantly enhances the mixing of flow momentum in the wake, which could distinctly accelerate the breakdown of the vortex structures with the wake moving downstream.

Figure 6. The evolution of the vortex structures in the near wake of the wind turbine model
(a). offshore wind environment; (b). onshore wind environment

IV. Conclusion

In summary, an experimental study was conducted to analyze the dynamic wind loads acting on a horizontal axial wind turbine model placed in atmospheric boundary layer winds. Firstly, the mean wind loads as well as the fatigue loads acting on different components of wind turbine model were revealed in the present study. Secondly, it was indicated that the wind loads acting on stationary wind turbine would change with the phase angle of the turbine blades. The maximum variation could achieve 15% for mean wind loads and 10% for fatigue loads. Finally, the behaviors of dynamic wind loads were found to be highly dependent on the environmental wind climate. The discrepancy of dynamic wind loads acting on wind turbine sited in offshore and onshore wind environments were

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exposed by correlating wind loads measurement with high-resolution particle image velocimetry measurement in order to improve our understanding associated with the optimal mechanical design of the wind turbine.

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