An Experimental Investigation on the Control of Tip Vortices from Wind Turbine Blade

A thesis submitted in partial fulfillment of the
requirements for the degree of Master
of Science in Engineering

By

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2013
Wright State University

WRIGHT STATE UNIVERSITY

GRADUATE SCHOOL

May 2, 2013

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BY Zhe Ning ENTITLED An Experimental Investigation on the Control of Tip Vortices from
Wind Turbine Blade BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF Master of Science in Engineering.

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ABSTRACT

Ning,Zhe. M.S. Egr., Department of Mechanical and Materials Engineering, Wright State University, 2013. An Experimental Investigation on the Control of Tip Vortices from Wind Turbine Blade.

Wind turbine dynamics, wake effects and environmental impacts have been identified the most significant research topics needed for wind resource characterization and wind power generation. Among these issues, tip vortices generated from the blade tip have been recognized as a substantial resource for the turbulent wake flow as well as the aerodynamic noise emission from a wind turbine. An experimental study is conducted to characterize the evolution of the tip vortices downstream of a well-designed horizontal axis wind turbine (HAWT) model. In addition to measuring dynamic wind loads (both aerodynamic forces and moments) and power output from the wind turbine model, a Particle Image Velocimetry (PIV) system is used to make phase-locked flow field measurements to quantify the time-evolution of the tip vortices and turbulence flow structures in the wake of the wind turbine model. The objective of this study is to find an effective way to restrict the development of tip vortices and thus the consequential noise emission. By altering the blade tip design, unwanted tip vortices and vibration of the blade are suppressed considerably. The detailed flow field measurements are correlated with the wind load and power output measurements to elucidate the underlying physics associated with power generation and environmental impacts of wind turbines.

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ACKNOWLEDGEMENTS

First of all, I want to thank Dr. Zifeng Yang for all of his advice, help, funding, and time spend on my research work. Without these, I cannot finish my research and thesis. I am so happy to work under his direction. He taught me how to search information related to my research work, guided me to finish experiment. He was always there and helped me whenever or whatever I needed his help on my learning and research. Under his encouragement and suggestion, I had a lot of confidence to finish my work. I know how to study efficiently, and how to be a good researcher under his influence. I can bring all these skills into my future work and life.

Last but not least I would like to thank Scott Huang. Thanks for his time, help, and encouragement during my work. Every time when I had trouble with the experiment, he always helped me to find and solve problems. I really appreciate his time and help. Also, I would like to thank two senior design teams. I learned a lot of skills from them and I got more familiar with the experimental devices. Especially, the improvement of English is huge. At last, I would also like to thank my parents for their encouragement, understanding, and support. Especially, thanks Kuo Gai for her cooking and advice. She gave me a lot of hints over last one and half years. Sometimes, these hints saved me a lot times.

INTRODUCTION

Energy security and shortages have become a very popular topic in society. It is well known that fossil fuels have a lot of problems. They cause global warming, and environmental pollution. 85% of current primary energy driving global economies consists of the combustion of fossil fuels; and 56.6% of all anthropogenic greenhouse gases (GHG) come from the consumption of fossil fuels. From environmental friendly view, the environmental impacts and GHG emissions must be low for the energy services (Edenhofer et al., 2012). Therefore, people try to use renewable and environmentally friendly energy sources, such as, wind, solar, geothermal and biomass. Compared with all of the energy that is used by all the economies on Earth, the theoretical potential of renewable energy (RE) is much greater. Table 1 shows estimated annual fluxes of RE, annual primary energy supply, and a comparison between different RE sources and annual primary energy supply (Edenhofer et al., 2012). In 2008, the annual primary energy supply was 492 EJ/yr, of which 85% was derived from fossil fuels. Also, the total reserve of fossil fuels was 46700 EJ, which translates into a 112 year lifetime for the remaining fossil fuel reserve. Compared with fossil fuels, the annual flux of RE (including bioenergy, solar energy, geothermal energy, hydropower, ocean energy, and wind energy) is very high, 3,916,495 EJ/yr. Within these renewable energy sources, solar energy takes the first position with 3,900,000 EJ/yr; ocean energy and wind energy take second and third position with 7,400 EJ/yr and 6,000 EJ/yr respectively. Around the

world, more and more countries work on renewable energy. Siemens predicts that energy from renewable sources will account for 28 % of the global power mix in 2030 (Alfons Benzinger., 2010). That means renewable energy will be critical to maintain a sustainable future for the whole world.

As an important role within these renewable sources, wind energy has its advantages. First of all, the theoretical potential of wind energy is significant. As shown in table 1, the annual flux of wind is 6,000 EJ/yr, which is 12 times the 2008 primary energy supply. Secondly, wind power is one of the cleanest renewable energies available. Wind energy is a suitable alternative to fossil fuels because it is plentiful, widely distributed, and produces negligible amounts of greenhouse gas emissions during operation. Around 1 kg of carbon dioxide emission can be avoided with each kWh of electricity produced by wind energy (Wagner et al., 1996). Thirdly, the cost of wind energy is low. Although, the theoretical potential of wind energy is lower than solar energy and ocean energy, the levelized cost of electricity (LOCE) from wind is lower. The LOCE of wind energy, ocean energy, and solar energy are 20, 31, and 70 UScent₂₀₀₅/kWh respectively (Edenhofer et al., 2012). A target of 20% of US total electricity generation from wind power by 2030 has been announced by the U.S. Department of Energy (DoE). The target will lead to a great amount of manufacturing and installation of wind turbine, for example, around 150,000 large wind turbines (70m diameter) need to be built and installed by 2030 (Hu et al., 2011). With the increased need for renewable energy, the shortage of wind turbines will be more obvious.

Table 1 Renewable energy theoretical potential expressed as annual energy fluxes of EJ/yr compared to 2008 global primary energy supply.

Renewable source	Annual Flux (EJ/yr)	Ratio (Annual energy flux/ 2008 primary energy supply)	Total reserve
Bioenergy	1,548 ^c	3.1	—
Solar Energy	3,900,000 ^a	7,900	—
Geothermal Energy	1,400 ^c	2.8	—
Hydropower	147 ^a	0.30	—
Ocean Energy	7,400 ^a	15	—
Wind Energy	6,000 ^a	12	—
Annual Primary energy source	Annual Use 2008 (EJ/yr)	Lifetime of Proven Reserve (years)	Total Reserve (EJ)
Total Fossil	418 ^b	112	46,700
Total Uranium	10 ^b	100–350	1,000–3,500
Total RE	64 ^b	—	—
Primary Energy Supply	492 (2008) ^b	—	—

Sources: renewable energy sources and climate change mitigation, IPCC (Edenhofer et al., 2012)

Similar to other energy sources, wind energy also has its own limitations. The wake flow and aerodynamic noise are two main issues. Figure 1(a) is a real photo of a wind turbine farm in the ocean showing wake flow. Due to the moisture, the downstream wind turbine influenced by the first wind turbine can be clearly seen. Due to the wake effects the power losses can be up to 23% (Barthelmie, et al., 2009; Dahlberg & Thor, 2009). The power deficit can be found in figure 1(b). Fatigue loads can be increased up to 80% by wake interference on a downstream turbine (Sanderse, 2009).

Another problem with wind energy is the aerodynamics noise. The aerodynamic noise includes tip vortex formation noise, trailing edge noise, separation-stall noise, boundary layer vortex shedding noise, trailing edge bluntness vortex shedding noise, and noise due to the turbulent inflow, which are shown in figure 2. The first five types of noise are induced by the wind turbine itself. “The trailing edge noise is due to the interaction of the turbulent eddies generated in the boundary layer and the trailing edge of the airfoil. The turbulent eddies themselves are relatively weak sources, but their effect is

amplified when they are in the vicinity of a plate (in this case the trailing edge). Separation-stall noise occurs when the angle of attack is too large and flow separation results. In such cases the separation-stall noise dominates the other noise sources. At the tip of the blade a vortex is formed due to the pressure difference on the pressure and suction sides. The pressure fluctuations due to the presence of this vortex result in tip vortex formation noise. The boundary layer vortex shedding noise occurs when boundary layer instabilities develop along the airfoil. Such instabilities might lead to separation and the appearance of Tollmien Schlichting waves. Trailing edge bluntness vortex shedding noise appears when the thickness of the trailing edge exceeds a critical limit, dependent on the Reynolds number and the shape of the airfoil” (Wei Tong, 2010). Figure 3 shows the noise distribution from one wind turbine. At the beginning, the noise can be up to 105 dB, which is similar to the noise of a lawnmower. 400 m away from the wind turbine, the noise reduces to 40 dB, which is similar to the sound from a refrigerator. One thing that should be mentioned is that as the sound generation power increases 10 times, the sound level will increase 10 dB. That means the number of wind turbines located in a given area has a direct effect on the sound generation. When a wind farm which contains many wind turbines is located near a residential area, the sound level is high, and this can be recognized as a serious sound pollution problem. Due to the unbearable low-frequency noise, people who lived near a wind farm are susceptible to headaches, ear pain, nausea, blurred vision, anxiety, memory loss, and an overall unsettledness. Because of the wind turbine noise pollution, some residences abandoned their home which is close to a wind farm and moved to another location.

Figure 1 (a) Wake flow visualization. Data Source: Rev Horn offshore wind farm in Denmark. (b) Power deficit. Source: Modeling and measurements of wakes in large wind farms (Barthelmie, et al., 2009).

Figure 2 Noise generation mechanisms for an airfoil. Source: Wind power generation and wind turbine design (Wei Tong, 2010).

Figure 3 Noise distribution.

Source : < <http://www.gereports.com/how-loud-is-a-wind-turbine/> >

Wind turbine dynamics, wake effects and environmental impacts have been identified as the most significant research topics needed for wind resource characterization and wind power generation (Schreck et al., 2008). While a great deal of research effort has been drawn into the optimization of blade design (Fuglsang, 1998; Somers, 2005; Wang et al., 2010), the turbulent wake downstream of the wind turbine cannot be avoided. The unsteady wake creates a velocity deficit and highly turbulent flow, which results in energy drop and flow induced vibration respectively. The airfoil wake vortex shedding induces periodic loading on the structure, which results in unwanted structural vibration. Vibration of the blades adversely affects both energy output, rotor operation and the fatigue life time.

Figure 4 Near wake and far wake of a wind turbine.
Sources: Aerodynamics of wind turbine wakes (B. Sanderse. 2009)

The wake of a wind turbine is typically divided into a near and a far wake, which is clearly shown in figure 4. The near wake is referred to the region from the turbine to approximately one rotor diameter downstream. In the near wake, the presence of the rotor is apparent by the number of blades, blade aerodynamics such as attached or stalled flows, 3-D effects and tip vortices. The far wake is the region beyond the near wake, where the actual rotor shape is less important. The main attentions for far wake flows are usually drawn in wake models, wake interference, turbulence models, and topographical effects (Vermeer, 2003). Therefore, the study of the far wake is important for the turbine site optimization in wind farm design. Compared with the far wake, the near wake has more relationship with the wind turbine blade. Therefore, the study of the near wake is very important for blade design and optimization. A significant feature in the near wake of a wind turbine is the helical tip vortices induced by the rotating blades, which is shown in figure 5.

Figure 5 Helical tip vortex visualization.

Source : <<http://www.caebridge.com/wind-turbine-blade-design-optimization>>

Figure 6 Formation of tip vortex.

Figure 6 shows the formation of the tip vortex. The blue arrows represent the air flow. At the tip, the pressure differences between the suction side and the pressure side result in a cross flow over the side edge of the tip which is responsible for the formation of a tip vortex. The tip vortex generated from the blade tip has been recognized as a substantial resource for the turbulent wake flow, as well as the aerodynamic noise emission from a wind turbine (Wagner et al., 1996). On one hand, the formation of the tip vortices will turn into a turbulent flow downstream of a wind turbine; on the other hand,

tip vortices interact with edges and emit aerodynamic noise which accounts for most of the noise generation from a wind turbine. While the exact mechanisms of blade tip noise generation have not been fully understood, tip vortex noise is assumed to be mainly influenced by the convection speed of the vortex and its spanwise extent (Brooks et al., 1989). However, it can be expected that the location of the vortex core, the strength of the vortex, the Reynolds number and blade load distribution have an influence as well (Wagner et al., 1996). Surprisingly, very few studies can be found in the literature to provide strategies for the reduction of tip vortices. Arakawa et al. (2005) conducted a numerical study on the noise reduction of a wind turbine blade tip. A decrease of the sound level in the high frequency domain is observed for the ogee type tip shape. Brooks and Marcolini (1989) experimentally investigated tip vortex noise formation for a rectangular planform and rounded tip for stationary blades. They found that for the stationary blade tip vortex noise is less important to the overall broadband self-noise spectrum than boundary layer and trailing edge noise. However, they mentioned that this will not necessarily be so for rotor systems, because of the tip's relative higher velocities compared to the inboard regions of the blade and the tip loading which should be high as well. The problem of tip noise deserves attention as the physical mechanisms for the generation of tip noise are incompletely understood. Therefore, the present study focuses on the characteristics of the formation and convection of tip vortices, and further the reduction of the tip vortices through modification of the blade tip.

Compared to traditional point-wise flow measurement techniques, such as hot-wire anemometry, hot-film anemometry and Laser Doppler Velocimetry, used to conduct flow velocity measurements at a limited number of points (Alfredsson et al., 1979; Tsutsumi &

Matsumya, 1987; Ebert & Wood, 1997 & 2001; Vermeer, 2001; Medici & Alfredsson, 2006; and Chamorro and Porte'-Agel, 2009), advanced flow diagnostic techniques, such as particle image velocimetry (PIV) or Stereo PIV has a unique advantage in temporally synchronized and spatially-resolved flow field measurements. This enables us to elucidate the underlying physics and improve our understanding about turbulent wake flow characteristics and transient behavior of the helical tip vortices in wakes of wind turbines. Very few experimental studies can be found in the literature to provide whole-field measurements to quantify the transient behavior of the helical tip vortices in the wakes of wind turbines. Whale et al. (2000) carried out an investigation on the tip vortices generated by an untwisted two-bladed rotor in a water tank by using a PIV system. Based on the comparison of the PIV measurements with the numerical simulation results using a rotor vortex lattice method, they suggested that the fundamental behavior of the helical tip vortices would be almost insensitive to the blade chord Reynolds number as long as the similarity of the tip-speed-ratio (TSR) of the wind turbine is observed. Grant and Parkin (2000) employed a digital PIV system to conduct flow field measurements at the downstream of a two-bladed wind turbine model in a low-speed wind tunnel. More recently, Massouh & Dobrev (2007) conducted a wind tunnel study to characterize the wake flow downstream of a small wind turbine model based on the phaselocked PIV and hotwire measurements. The evolution of the helical tip vortices downstream side of a wind turbine was revealed from the measured results. While useful information has been uncovered by those previous studies, no one has conducted a study on modifications to reduce the tip vortex. Strategies for control of the tip vortices have not been fully explored and are highly desirable.

In the present work, an experimental study is conducted to characterize the turbulent flow structures and the evolution of the helical tip vortices in the wake of a horizontal axis wind turbine (HAWT) model placed in a low speed wind tunnel. In addition to measuring dynamic wind loads (both aerodynamic forces and moments) and power output from the wind turbine model, a particle image velocimetry (PIV) system is used to make phaselocked flow field measurements to quantify the time-evolution of the wake vortex and turbulence flow structures downstream of the wind turbine model. The objective of this study is to find an effective way to restrict the development of tip vortices and the consequential noise emission. By altering the blade tip design, unwanted tip vortices and vibrations of the blades is suppressed considerably. Detailed flow measurements at several cross sections of the blade are also conducted to illuminate the mechanism of vorticity reduction. These measurements are correlated with the wind load and power output measurements to elucidate the underlying physics associated with power generation and environmental impacts from wind turbines.

EXPERIMENTAL SETUP AND MODEL DESIGN

2.1 Low-speed wind tunnel

The experiments were conducted in a low-speed, open-circuit wind tunnel that has a maximum velocity of 40 m/s located in the Department of Mechanical and Materials Engineering at Wright State University. The tunnel has an optically transparent test section of 2 ft $\times$ 2 ft (i.e., 610 mm $\times$ 610 mm) in cross section. The tunnel has a 10:1 contraction section upstream of the test section with honeycombs and screen structures installed ahead of the contraction section to provide uniform, low-turbulence incoming flow into the test section. The turbulence intensity in the center of the test section was found to be about 1.0% of the incoming flow measured by using a hotwire manometer. There is a control box used to control the motor speed and thus the rotation speed of fan installed at the end of the wind tunnel. The wind speed was set to 6 m/s and 7 m/s for the present study, which corresponds to 7.71 Hz and 8.77 Hz of the rotation frequency.

2.2 Experimental setup for dynamic wind load and flow field measurements

In the present study, a steel rod was used as the tower to support the nacelle and rotor blades of the wind turbine model. Through a hole in the bottom of the wind tunnel, the tower was connected to a highly-sensitivity force-moment sensor (JR3, model 30E12A-I40) in order to measure the dynamic wind load (both force and moment) acting on the wind turbine model. The JR3 load cell is composed of foil strain gage bridges, which are capable of measuring the forces on three orthogonal axes, and the moment (torque) about each axis. The precision of the force-moment sensor cell for force measurements is

$\pm 0.25\%$ of the full range (40 N). In the present study, the thrust coefficient (i.e., aerodynamic force coefficients along the X –direction, as shown in Figure 8) and bending moment coefficient (i.e., the moment coefficient along Z-direction, as shown in Figure 8) of the wind turbine model were calculated by using the expressions of $C_T = T / \frac{1}{2} \rho U_0^2 \pi R^2$, and $C_{M_Z} = M_Z / \frac{1}{2} \rho U_0^2 \pi R^2 H$ where ρ is the air density, U_0 is the mean flow velocity at the hub height, H . During the experiments, the wind loads were acquired for 60 seconds at the sample rate of 1,000 Hz for each tested case.

Figure 7 PIV principal

In addition to the wind load measurements, a high-resolution digital Particle Image Velocimetry (PIV) system was used to achieve detailed flow field measurements to quantify the characteristics of the turbulent wake flow, the transient behavior of the unsteady tip vortices at the downstream of the wind turbine model, and the flow field around several cross sections of the blade. PIV is a particle tracking technology, which is an important way to study detailed flow field structure. The principal of the PIV

technology is based on image processing. As shown in figure 7, the big rectangle shows the whole flow field taken from the camera, and the two small rectangles represent the same small area used to calculate velocity at different time t and t' . The blue points and circles represent the location of same particles at time t and t' . Using the position of the particles and the delay time between time t and t' , the average velocity for this small area can be calculated. Figure 8 shows the schematic of the PIV system used in the present study. For the PIV measurements, the flow was seeded with $1\text{ }\mu\text{m}$ water based smoke droplets by using a fog generator. Illumination was provided by a double-pulsed Nd:YAG laser (NewWave Gemini 120) adjusted on the second harmonic and emitting two pulses of 120 mJ at the wavelength of 532 nm. The laser beam was shaped to a sheet by a set of mirrors with spherical and cylindrical lenses. The laser sheet is parallel to the side wall of the wind tunnel and vertical to the ground. The thickness of the laser sheet in the measurement region was about 1.5 mm. The time interval between two laser pulses is set to $100\text{ }\mu\text{s}$. A high resolution 12-bit CCD camera (Pixelfly, CookeCorp) was used for PIV image acquisition with the axis of the camera perpendicular to the laser sheet. The CCD camera and the double-pulsed Nd:YAG lasers were connected to a workstation (host computer) via a Digital Delay Generator (Berkeley Nucleonics, Model 565), which controlled the timing of the laser illumination and the image acquisition. During the experiments, “free-run” PIV measurements were conducted at first in order to determine the ensemble-averaged wake flow statistics (e.g., mean velocity, turbulence intensity, Reynolds Stress, and turbulence kinetic energy) at the downstream of the wind turbine model. It should be noted that the data acquisition rate for the “free-run” PIV measurements was pre-selected at a frequency that is not a harmonic frequency of the

rotational frequency of the rotor blades in order to ensure a meaningful determination of the ensemble-averaged flow quantities.

Figure 8 Experimental Setup for the dynamic wind load and flow field measurements

Phased-locked PIV measurements were also conducted to elucidate more details about the time evolution of the helical tip vortices in relation to the position of the rotating rotor blades. In order to achieve the phase-locked PIV measurements, as shown in Figure 8, a digital tachometer was used to detect the position of a thin reflective tape on the hub as a reference. The tachometer would generate a pulsed signal as the tape on the hub pass the detecting laser. The pulsed signal with appropriate time delay through a Digital Delay Generator (DDG) was sent out to trigger the digital PIV system for the phased-locked PIV measurements. By adding different time delays between the input signal from the tachometer and the TTL signal output from the DDG to trigger the digital PIV system, the phased-locked PIV measurements at different rotation phase angles of the pre-marked rotor blade (i.e., with respect to different rotating positions of the pre-

marked rotor blade) can be accomplished. At each pre-selected phase angle, 266 frames of the instantaneous PIV measurements were used to calculate the phase-averaged flow velocity distribution in the wake of the wind turbine model.

In the present study, instantaneous PIV velocity vectors were obtained by a frame to frame cross-correlation technique involving successive frames of patterns of particle images in an interrogation window of 32X32 pixels. An effective overlap of 50% of the interrogation windows was employed in PIV image processing. After the instantaneous velocity vectors (u_i, v_i) were determined, the vorticity (ω_z) can be derived based on the equation $\omega_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$. The distributions of the ensemble-averaged flow quantities such as the mean velocity (u_p, v_p) , turbulent velocity fluctuations (uu_p, vv_p) , normalized Reynolds Stress $(RS = \overline{uu_p vv_p} / U_{in}^2)$, and normalized turbulence kinetic energy $(\chi k k = \frac{1}{2}(\overline{uu_p^2} + \overline{vv_p^2}) / U_{in}^2)$ were obtained from a cinema sequence of about 300 frames of the instantaneous PIV measurements. The measurement uncertainty level for the velocity vectors is estimated to be within 2% and 5% for the turbulent velocity fluctuations, Reynolds Stress, and turbulent kinetic energy calculations.

2.3 Wind turbine model

The prototype wind turbine model used for the present study was comprised of three airfoils categorized by the National Renewable Energy Laboratory (NREL) as “quiet”. As shown in Figure 9, the rotor radius R of the wind turbine model was 125 mm, and the height of the turbine nacelle H was 220 mm above the wind tunnel floor. Setting the scale

ratio at 1:24, the test model represented a full scale wind turbine with a rotor diameter of about 3 m and a tower height of about 5.3 m.

Figure 9 A schematic model of the wind turbine model

Figure 10 A schematic model of the wind turbine blade

The blade model design is shown in figure 10. The 0% dash line represents the center of the hub. Other percentage numbers represent the different sections along the radius. The rotor blades had chord lengths of 4.5 mm at the tip, 13.6 mm at the midsection, and 28 mm at the root (28% of radius). The chord lengths were intentionally doubled compared to the NPS-100 prototype in order to ensure good geometrical accuracy of the small blades. The airfoil cross-sections of the blade were chosen from the S83X family (Somers, 2005), which are shown in figure 11. The S835 root airfoil was used between

28% and 56% radius, the S833 primary airfoil was used between 60% and 84% radius, and the S834 tip airfoil was used at 90% radius. A small electricity generator was installed inside the nacelle of the wind turbine model, which produced electricity as it was driven by the rotating blades. The primary design parameters of the wind turbine are listed in Table 2.

One thing that should be mentioned is the 5° tilt angle, which is widely used in commercial wind turbines to maintain a clearance gap between the tower and the wind turbine rotors. The optimal angles of attack (AOA) for each airfoil cross-section were determined using “AirfoilPrepv2p2,” an Excel macro provided by the NREL in which different parameters can be entered, such as the wind speed, rotor radius and 2D airfoil data. In figure 12(a), the vertical red dash line represents the rotating disk of the wind turbine. The tilt red dash line is the chord line of the airfoil. The incoming wind speed, wind turbine rotating speed, and total speed are represented by V_0 , V_r , and V_{total} , respectively. The AOA α is the angle between chord line of airfoil and V_{total} . The twist angle β is the angle between the chord line and rotating disk. The macro then calculates a plot displaying the coefficient of lift versus the AOA, from which an optimal AOA can be determined. The optimal AOA's are summarized in Table 3.

Figure 12(b) shows the planform of the twist of the blade, where the smallest airfoil represents the blade tip and largest airfoil represents the blade root. The blade twists from 21° at root to 0° at tip. The twist angle at each cross-section was calculated using the optimal AOA's and a tip speed ratio (TSR) of 5.0. This value for the TSR was chosen because it most accurately represents the TSR achieved by commercial wind turbines (i.e., TSR between 4 to 6). Based on a TSR of 5.0, the sum of the AOA and twist angle at

each cross section can be easily calculated. These values were calculated to be 11° , 22° , and 34° for tip, primary, and root, respectively. Subtracting the optimal AOA from these values, the twist angles for tip, primary, and root are, 5° , 15° , and 26° respectively. Initially, the hub was designed with a 5° pitch angle, which altered the twist angle of the blade ranged from 21° at root to 0° at tip. This was done to maintain the overall twist angles of 5° and 26° previously mentioned. Finally, the pitch angle of the blade on the hub is 2 degree, which is determined from a TSR comparison of pitch angles 2° , 3° , 5° , and 6° as shown in figure 13. The 2 degree pitch angle can provide the best TSR.

Figure 11 NREL's S83X family

(a)

(b)

Figure 12 a) Angle of Attack and b) Planform of twist angles

Figure 13 Tip-speed-ratio versus wind speed for different pitch angles

Table 2 The primary design parameters of the wing turbine model

Parameter	R	H	d_{rod}	$d_{naccele}$	α (tilt angle)	a
Dimension(mm)	125	220	20	20	5°	100

Table 3 Optimal Angle of Attack for different sections of the blade

Section	Root	Primary	Tip
Optimal of AOA	8°	7°	6°

2.4 Wind turbine tip shapes model

In the present study, 7 different wind turbine tip shapes (flat end plates, curved end plate, airfoil shape end plate, positive winglet, negative winglet and ogee tip shape) were incorporated into the original wind turbine model design. Figure 14 shows all 7 different wind turbine tip shapes. The blue arrows shown in the figure represent the incoming air flow; the red arrows represent the blade rotating direction. The lengths in tangential and chordwise widths of the small flat end plate and big flat end plate are 6.75 mm X 4.5 mm (one tip chord length) and 11.25 mm X 9 mm (two tip chord lengths) respectively, both

having a thickness of 1 mm. The curved end plate was designed to fit the rotating pathline of the tip after noting that the tip rotating pathline was a circle with a 125 mm rotating radius. The plate curved from the leading edge to the trailing edge of the tip with a 125 mm curve radius. The length and width of the curved end plate were 6.75 mm and 4.5 mm, respectively, having 1mm thickness. In order to reduce the blunt body effect, the NACA001234 airfoil shape was integrated into the design of the airfoil shape end plate. The chord length and width were 4.7 mm and 6.75 mm, respectively. The use of positive and negative winglets was inspired by the use of winglets on aircraft to increase the lift. The NACA0012 airfoil shape with a 5.7 mm chord length was used to design the positive and negative winglets. In consideration of the tip strength, a 3.375 mm radius fillet was added into the two winglet designs. An ogee shape tip is widely used in helicopters to decrease the noise; therefore, the ogee shape was examined in the present study for comparison. The coordinates of the tip planform for ogee shape tip are given in four pieces A, B, C, and D as shown in Figure 15.

Figure 14 Seven different tip shapes, (a) Flat end plate (6.75X4.5 mm) and (11.25X9 mm) (b) Curved end plate (c) Airfoil shape end plate (d) Negative winglet (e) Positive winglet (f) Ogee shape

Figure 15 Ogee shape design

RESULTS AND DISCUSSIONS

3.1 Rotation and power testing results

Figure 16 TSR testing

During the experiment, wind turbine blades with 8 different tip shapes were used to study the tip speed ratio (TSR) in a uniform flow with the free stream velocity of 6 m/s and 7 m/s. The rotation speed was measured using a tachometer as shown in figure 16, which is a laser reflection based revolution counter. The TSR is calculated from equation $\lambda = \frac{\Omega R}{U_{\infty}}$, where Ω is the angular rotating speed, R is the radius of the wind turbine model blades, and U_{∞} is the free stream velocity at the hub height.

Varying the wind speed between 6 m/s and 7 m/s, the TSR varied from 3.7 to 4.51 for all eight turbines. The TSR fell out of the desired range of 4-6 for the wind turbine model merely with the big flat end plate (9X11.25 mm). The range of 4-6 is recognized as the

appropriate TSR of a typical three-blade HAWT in a wind farm. It should be noted that the near wake characteristics would be similar if the wind turbines have similar TSR (Medici and Alfredsson, 2006). As shown in Figure 17, the TSRs of the original blade (without tip modification) were 4.23 and 4.42 at wind speed of 6 m/s and 7 m/s respectively. The turbine blade with large size flat end plate shows the worst TSR 3.73 and 3.93 at 6 m/s and 7 m/s wind speed respectively, which indicates that the flat end plate induces a drastic reduction of the driven force for rotation. But a smaller size of the flat end plate has a very limited effect on the aerodynamic force, which results in a little reduction of the TSR. The curved end plate with the same size as the small flat end plate can be treated as a chopped piece of a circle end plate. Unfortunately, this trial produces a relatively low TSR, although shrouded a wing turbine has been proven to generate higher output power (Ohya & Karasudani, 2010). The reason for this discrepancy is that the chopped piece of the shroud is in rotation instead of staying static. This difference will change the aerodynamic force acting on the turbine blade dramatically. In order to improve the aerodynamic performance of the end plate, an airfoil shape end plate was proposed in the present study. However, the airfoil shape does not provide a better TSR compared to the small flat end plate at 6 m/s, but provides a decent TSR at 7 m/s.

After all trials using end plates, winglet ideas were grabbed from the wing design of aircraft. Compared to the original blade the wind turbine with a positive winglet tip has almost the same TSR. A negative winglet tip produces a comparable TSR at 6 m/s but produces a relatively low TSR at 7 m/s. Surprisingly, the ogee type tip shape yielded the highest TSR, 4.39 and 4.51 at wind speeds of 6 m/s and 7 m/s respectively. This interesting finding was attributed to the fact that a loss of moment of inertia, due to the

chop of material near the tip for the ogee shape, has a considerable effect on the rational speed of the rotor; although the aerodynamic force driving the rotation reduced a bit due to less acting area on the blade.

Figure 17 TSR versus wind speed for various blade tip shapes at 6m/s and 7m/s wind speed

Figure 18 Electric circuit of the power measurement

The electric circuit for the power measurement is shown in figure 18. An adjustable resistance was connected to the generator. By adjusting the outside resistance the maximum power output can be achieved. The power is calculated from equation $P = \frac{v^2}{R}$, and the calculation of the power coefficient is using equation $C_p = \frac{P}{\frac{1}{2}\rho AV^3}$, where ρ is the density of the air, A is the wind turbine blade swept area, and V is the speed of the wind.

The result of the power coefficient of the wind turbine model at 6 m/s and 7 m/s wind speeds for blades with different tip shapes are shown in Figure 19. The power coefficient is drastically low (less than 1%) compared with real wind turbines (above 35%) working in wind farms. The low C_p was to be expected due to the scale-down effect and the low efficiency of the generator (off the shelf for toys) used in the present study. The lowest C_p values achieved were 0.49% and 0.46% with the large flat end plate (9 mmX11.25 mm) tip blade which agree with the finding in the TSR test. The C_p values ranged from approximately 0.60% to 0.70% for all other wind turbine blade designs with different tip shapes. The C_p values for the original blade were 0.68% and 0.64% at 6 m/s and 7 m/s free stream wind speeds, respectively. Compared with the original blade, the wind turbines with positive winglets had approximately the same C_p value, and the ogee type tip wind turbine increased the power coefficient by approximately 6% at 6 m/s and 7 m/s of wind speeds. As explained previously, this is mainly due to the change of moment of inertia. If the assumption is made that the rotating momentum is a constant, the rotating speed will increase when the moment of inertia ($I = \sum_{i=1}^N m_i R_i^2$) decreases. In the ogee shape case, the moment of inertia was significantly reduced due to the cut near the tip, where the radius reaches a maximum value. Although the rotating momentum reduced by the order of R due to the loss of the aerodynamic force, the moment of inertia reduced by

the order of R^2 , which implies that the ogee shape case would generate the best TSR and power coefficient. Taking both the TSR and power coefficient results into consideration, the ogee shape tip wind turbine blade model achieves the best performance. Positive winglet and negative winglet wind turbine blade models achieve fairly equal power output and TSR compared with the original blade.

Figure 19 Power coefficient versus wind speed for various blade shapes at 6m/s and 7m/s wind speed

3.2 Dynamic wind load measurement results

In an effort to provide a comprehensive understanding the effect of the modification of the blade tips, the dynamic wind loads of wind turbines with different tips were investigated at different tip speed ratios. During the experiments, the rotational speed of the wind turbine blades was adjusted by applying different electric loads to the small electricity generator mounted inside the turbine nacelle while the incoming free stream wind speed was kept constant. Power output coefficient as a function of the tip-speed-

ratio of a wind turbine have been intensively reported in previous studies (Boeing 1982; Jain 2007), very little can be found in the literature about the variations of the wind loads (e.g., aerodynamic thrust and bending moment) acting on wind turbine as a function of the tip-speed-ratio, even though wind load data are very critical for the mechanical design of wind turbines operating in the field. Figure 20 presents the measured mean thrust coefficient, C_T , and bending moment coefficient, C_{Mz} , of the wind turbine model as a function of the TSR for 8 different types of blade tips at a free stream wind speed of 6 m/s. All the symbols shown in Figure 20 represent experimental data, and all the lines represent the power law curve fit. It can be observed clearly that the measurement data can be represented reasonably well by the power function. The profiles of C_T and C_{Mz} were found to follow a similar trend as the tip-speed-ratio of the wind turbine model increases. As shown in the figure, C_T and C_{Mz} were found to increase gradually as the TSR increased; they reached their peak values at a certain TSR, then began to decrease with increasing TSR. The peak values of thrust and bending moment coefficients are observed at a TSR of 2.8 for the original and the large flat end plate (9X11.25 mm), 3.0 for the small flat end plate (4.5X6.75 mm) and approximately 3.3 for the other five cases. As mentioned above, the free run TSR of the 8 different types of the wind turbine blades at 6m/s free stream wind speed are within the range of 4.0 to 4.5. The C_T of the airfoil shape end plate and big flat end plate (9X11.25 mm) tip types wind turbine blades are similar as the original wind turbine blade. The C_T of other wind turbine blades is higher than the original wind turbine blade at the same TSR. The C_{Mz} of the airfoil shape end plate is very close to the original blade. The C_{Mz} of other wind turbine blades are higher compared with the original wind turbine blade at the same TSR. The variation of the C_T

and C_{Mz} values is caused by the different tip shapes which restrict the wind speed at the tip of wind turbine blades. Also, as the whole blade rotor is tilted backward 5° , the end plates and winglets have 5° difference with the incoming airflow because they are vertical to the blade itself. Thus, a component of force from the end plate or winglet was added to the thrust.

(a) Time-average thrust coefficient (b) Time-average bending moment coefficient
Figure 20 Variations of the time-average wind loads as a function of tip-speed-ratio

(a) Time-average thrust coefficient (b) Time-average bending moment coefficient
Figure 21 Time-average wind loads at 6m/s wind speed for a free run

Figure 21 (a) and (b) present C_T and C_{Mz} of the wind turbine model without any control on the TSR at a free stream wind speed of $U_0 = 6$ m/s. The C_T and C_{Mz} results of the original wind turbine blades are shown in the figure as black square symbols.

Compared with the original case, the thrust coefficient C_T and bending moment coefficient C_{Mz} of the wind turbine model with airfoil shape end plates increased by 3% and 5% respectively. The curved end plate tip wind turbine generated an increase of 13% for C_T and 19% for C_{Mz} while other 5 cases produced an increase of 7-9% for C_T and 7-9% for C_{Mz} . It should be noted that only the effect of the tip modification was taken into account for the results shown in Figure 21. With the same incoming wind speed, a change in TSR was observed for different blade tips.

3.3 PIV measurement results

3.3.1 “Free-run” PIV measurement results

As described previously, a high-resolution PIV system was used to measure the flow field in the vertical plane pass through the rotational axis of the wind turbine. Typical “free-run” PIV measurement results for the original turbine blade at a free stream wind speed of 7 m/s was presented in figure 22. In figure 22(a) as shown in the dashed line box, five tip vortex structures as a queue were clearly revealed downstream of the turbine blade. Due to the centrifugal force, the tip vortices diffuse outward, which can be seen clearly from the time average vorticity contour shown in Figure 22(c). The pathline of the tip vortex street has been revealed in terms of a concentrated vorticity region downstream of the tip. Within the flow field, behind the turbine nacelle, a flow separation zone was formed due to the blunt body effect.

Figure 22(b) and (d) show the instantaneous and ensemble-averaged PIV measurement results in terms of mean velocity and vectors respectively. The flow speed reduction can be observed in the contour plot, which means part of the kinetic energy in the incoming flow is harvested by the wind turbine and thus converted to electric power

through rotation of the generator inside of the nacelle. The normalized turbulent kinetic energy (TKE) distribution is presented in Figure 22(d). TKE is a significant indicator of the turbulence level. The high TKE levels were found downstream of the nacelle and along the tip vortices shedding path in the wake of the wind turbine model. The shedding vortices from the blade tip and nacelle are the two main resources for the turbulent flow in the wake. Also, along the tip vortices shedding path and downstream of the nacelle in the wake, the normalized Reynolds stress (RS) was found to be high. A high Reynolds stress can promote vertical transport of kinetic energy in the wake (Cal et al, 2010). That means the RS can drive the high velocity wind from the surroundings to the inboard. Therefore, the velocity reduction in the wake of a wind turbine can be recovered faster.

Figure 22 Free run PIV measurement results at a free stream wind speed of $U=7$ m/s

3.3.2 Phase-lock PIV measurement results

In order to study the unsteady wake vortex structures quantitatively and clearly, “Phase-locked” PIV measurements were used to achieve the flow characteristics in the wake flow. The phase angle was defined as the angle between position of a pre-marked wind turbine blade and the vertical measurement plane. In this study, the flow characteristics in the wake flow were obtained at several phase angles which change from 0° to 345° with 15° as the step size.

3.3.3 Flow characteristics in the wake flow

The visualization of the flow by putting intense smoke at the phase angle of 0° and 60° for the original blade and blade with flat end plate respectively are presented in Figure 23(a) and (b). From the visualization, one can observe the “wave-shaped” flow structures downstream of the wind turbine model, which corresponds to the shedding of tip vortices and the trace of the invasion effect of the turbine blade. The “wave-shaped” flow structures can be also found in other phase angles for the 8 different cases. A similar flow feature was also reported by Hu et al. (2011). The velocity distribution of the “phase-locked” PIV measurement results of the original wind turbine model at a free stream velocity of $U_0=6$ m/s are shown in Figure 24. Figure 24(a) shows the velocity distribution at a phase angle of 0° which corresponds to the position where the pre-marked blade is just crossing the measurement plane. Several strip shape low-speed regions can be observed downstream of the turbine. Each of these regions represents a cut-in by the blade. As the phase angle increases, the blade rotates out of the measurement plane as shown in Figure 24 (b) for a phase angle of 45° . The newly generated wake sheds from the next blade. As the wake keeps moving downstream, the strip shape of the low speed region becomes tilted because of the velocity gradient in the flow. After around one radius distance, the wake starts to mix with the surrounding flow, thus the low speed region becomes less distinct as shown in Figure 24 (c) and (d). The wake due to the existence of the nacelle generates a big low speed region, which recovers slowly compared with the blade wake.

Figure 23 Visualization of the wake flow

Figure 24 Velocity distribution of the “Phase-locked” PIV measurement results of the original wind turbine at 6m/s wind speed, Phase angle: (a) 0°, (b) 45°, (c) 90°, (d) 135°

Figure 25 shows the velocity distribution at 0°, 45°, 90°, and 135° phase angle of the original wind turbine at 7 m/s wind speed. In this figure, the strip shape low-speed

regions and flow features as described before can be observed downstream of the wind turbine. However, the strip shape low-speed regions at 7 m/s are not obvious compared with them at 6 m/s. The reason is that the velocity difference between strip-shape low-speed regions and the surrounding region of 7 m/s is not as that of 6 m/s.

Figure 25 Velocity distribution of the “Phase-locked” PIV measurement results of the original wind turbine at 7m/s wind speed, Phase angle: (a) 0°, (b) 45°, (c) 90°, (d) 135°

The similar flow feature also can be observed downstream of the turbine with other tip shapes. Velocity distribution results for different tips at wind speeds of 6 m/s and 7 m/s are shown in figure 26 and 27 respectively. It should be noted that velocity distributions of the “Phase-locked” PIV measurement results are only presented at phase angles of 0° and 90° as the characteristic representatives of the flow feature. The strip-

shape low speed regions are different case by case, because the different tip shape has different influence on the airflow flow passing the wind turbine.

g)

h)

i)

j)

k)

l)

Figure 26 Velocity distribution of the “Phase-locked” PIV measurement results at phase angles of 0° and 90° for many tip shapes at wind speed of $U_0=6$ m/s, Tip shape: (a), (b) big flat end plate; (c), (d) small flat end plate; (e), (f) curved end plate; (g), (h) airfoil shape end plate; (i), (j) positive winglet; (k), (l) negative winglet; (m), (n) ogee shape

e)

f)

g)

h)

i)

j)

Figure 27 Velocity distribution of the “Phase-locked” PIV measurement results at phases angle of 0° and 90° for many tip shapes at a wind speed of $U_0=7$ m/s, Tip shape: (a), (b) big flat end plate; (c), (d) small flat end plate; (e), (f) curved end plate; (g), (h) airfoil shape end plate; (i), (j) positive winglet; (k), (l) negative winglet; (m), (n) ogee shape

The vorticity distribution of the “Phase-locked” PIV measurement results of the original blade at 6 m/s wind speed are shown in Figure 28. As mentioned previously in “free-run” PIV measurement results, a typical feature of the weak flow, tip vortex can be visualized more clearly. The number 1, 2, and 3 in the figure represent the tip vortex generated by the 1st, 2nd, and 3rd blades of the wind turbine model, which can be clearly seen in the 3-D reconstruction results in figure 29. The tip vortex induced by the tip of the wind turbine blade model can be clearly captured in the figure 28(a) through (d). Besides the tip vortices, both positive and negative vorticity regions induced by the whole blade

formed below the tip vortices as shown in figure 28 (a) through (d). The non-uniform vorticity distribution in this region is attributed to fact that the non-uniform cross section airfoils were used to construct the wind turbine blade. It should be noted that, the vorticity due to cross section transition on the blade is weak, and thus it could be eliminated by improving the blade design. The tip vortices decay relatively slow compared to the blade wake. Also, from the “phase-locked” PIV measurement results, the unsteady vortex structures at the roots of the rotating blades are clearly shown, which were also reported by Massouh and Dobrev (2007). The large Karman vortex street generated by the incoming flow passing the nacelle was also presented in the plots. However, it should be pointed out that these vortices dissipate faster compared to the tip vortices.

Figure 29 shows a 3-D view of the tip vortex structure for the original turbine blade at $U_0=6$ m/s. Hu et al. (2011) suggested that due to the PIV measurement results can only obtain a plane view of the multifaceted 3-D wake vortex flow within the vertical measurement plane, a 3-D view of the wake vortex structure reconstruction is highly desirable to understand underlying physics in wake flow. In this figure, three track lines are interpolated into the plot to show trajectories of tip vortices induced by blade 1, blade 2 and blade 3. Tip vortex trajectories were calculated based on tracking the centers of the tip vortices at different phase angles. They clearly show the helical traces of the tip vortices which move to downstream with a reversed rotational direction with respect to the wind turbine. The helical tip vortex tube was visualized using smoke in previous studies as well (Anderson et al, 1982).

Figure 28 Vorticity distribution of the “Phase-locked” PIV measurement results at free stream wind speed $U_0=6$ m/s

Figure 29 3-D view of the tip vortex structure

3.3.4 Vorticity distribution of the same blade models at different phase angle

The vorticity distribution of the original blade model at different phase angles at a wind speed of 6 m/s is shown in figure 30. Through (a) to (h), the phase angle increases from 0° to 315° with a 45° step size. The numbers added into the graphs are the maximum absolutely value of the vorticity at the center of the same vortices generated from blade 1, which can serve as the index of the strength of the tip vortices. With the increase of the phase angle the value of the vorticity reduces and the tip vortices move downstream can be clearly seen. Similar features were also found for other wind turbine models and different wind speeds.

Figure 30 Vorticity distribution of the original blade at different phase angle at 6 m/s wind speed, Phase angle: (a) 0deg, (b) 45deg, (c) 90deg, (d) 135deg, (e) 180deg, (f) 225deg, (g) 270deg, (h) 315deg

3.3.5 Comparison of vorticity for the blade model at different wind speeds

Figure 31 shows the vorticity distribution of the “Phase-locked” PIV measurement results at 0° , 105° , and 210° phase angles of the original blade at different wind speeds, Figure 27 (a), (c), and (e) show the tip vortices of original wind turbine at 7 m/s wind speed, and figure 27 (b), (d), and (f) show the tip vortices of the original wind turbine at 6m/s wind speed. The numbers added into the graphs are the maximum absolute value of the vorticity at the center of the same vortices generated from blade 1. The vorticity of the vortices for the current and previous rotation cycles are 0.26 and 0.124 respectively in figure 31(a). As expected, with the increase of wind speed, the

strength of the tip vortices increased, which is mainly due to the increased velocity gradient near the tip.

Figure 31 Vorticity distribution of the “Phase-locked” PIV measurement results at 0°, 105°, and 210 ° phase angle of original blade at different wind speed (a) original at 7 m/s , (b) original at 6m/s, (c) positive winglet at 6m/s, (d) positive winglet at 7m/s, (e) ogee shape at 7m/s, (f) ogee shape at 6m/s

Similar feature can also be found for the other 7 cases, which are shown in figure 32. Figure 32 (a), (c), (e), (g), (i), (k), and (m) are the vorticity distributions of the other cases at 105° phase angle at 6 m/s wind speed, and Figure 32 (b), (d), (f), (h), (j), (l), and (n) are the vorticity distribution of the other cases at 105° phase angle at 7 m/s wind speed.

g)

h)

i)

j)

k)

l)

Figure 32 Vorticity distribution of the “Phase-locked” PIV measurement results at 105° phase angle of other wind turbine blades at different wind speeds, Tip shape: (a), (b) big flat end plate; (c), (d) small flat end plate; (e), (f) curved end plate; (g), (h) airfoil shape end plate; (i), (j) positive winglet; (k), (l) negative winglet; (m), (n) ogee shape

3.3.6 Comparison of the characteristics of wake flow using different tips at the same phase-angle

In the present study, the comparisons of the characteristics of the wake flow using different tip shapes on wind turbine blade models are studied at free stream wind speeds of $U_0=6$ m/s and $U_0=7$ m/s. Figure 33 shows the “phase-locked” PIV measurement results at 60° phase angle for all 8 different blade tips at the free stream wind speed of $U_0=6$ m/s. As mentioned above, the vortices generated from the tip, cross sections of the transition part along the blade, the root, and the nacelle can be viewed clearly in figure 33 (a) through (h). Compared to the original blade, the vorticity caused by the whole blade for the turbine blade with the large flat end plate (4.5X6.75), small flat end plate (9X11.25), curved end plate, and airfoil shape end plate present a larger value. This is mainly due to the addition of the flat plate tip, which restricts the air flow around the tip of the blade. The numbers added in this figure are the absolute value of the maximum vorticity of the

center of the tip vortices generated by the first blade, and they indicate the strength of the vortices.

As show in figure 33 (a), the vorticity values of the tip vortices generated by blade 1 from the current cycle and previous cycle are 0.187 and 0.117 respectively. Compared to the original blade, the blade with the large flat end plate (9X11.25), negative winglet, and ogee shape have larger vorticity of tip vortices; the blade with the small flat end plate (4.5X6.75) has the same vorticity; and other blades with curved end plate, airfoil shape end plate and positive winglets have lower value of vorticity. For the blade with airfoil shape end plate, the vorticity of the tip vortices reduces a lot however the inboard vortices located a little below the tip vortices increases drastically. Similar vortices were also observed for the blade with the small flat end plate, large end plate and curved end plate. Looking through all cases, tip vorticity for the blade with positive winglet reduced up to 14.5% compared with the original blade, at the meanwhile, the vorticity due to the whole blade maintain a relative low value. The blade with ogee shape tip produces low vorticity in the wake of the whole turbine blade although vorticity of the tip vortex increased.

Figure 33 Vorticity distribution of the “phase-locked” PIV measurement results at a phase angle of 60° for 8 different tip shapes with $U=6$ m/s. Tip shape: (a) original, (b) Flat end plate (4.5×6.75 mm), (c) Flat end plate (9×11.25 mm), (d) Curved end plate, (e) Airfoil shape end plate, (f) Positive winglet, (g) Negative winglet, (h) Ogee shape tip

The main reason for the differences of the inboard wake of the blade is attributed to variation of the angle of attack (AOA). In figure 34, the vertical red dash line represents the rotating disk of the wind turbine. The tilted red dash line is the chord line

of airfoil. The incoming wind speed, wind turbine rotating speed, and total speed are represented by V_0 , V_r , and V_{total} . The AOA is the angle between chord line of the airfoil and V_{total} . As mentioned previously, the TSR of the wind turbine varied with different tip shapes. Therefore, the angle of attack at different cross sections of the blade changes correspondingly. The schematic of the angle of attack for all eight blades at different radius with a wind speed of 6 m/s is shown in figure 29. The AOA is 8.5° , 8.5° , and 7.9° at 75% of the radius for the original, positive winglet, and ogee shape tip respectively, which are shown in figure 34 (a), (b), and (c). The AOA at 50% of the radius for the blade of original, positive winglet, and ogee shape tip is 9.3° , 9.3° , and 8.5° respectively as show in figure 34 (d), (e), (f). Compared with the original blade, AOA for the positive winglet is the same, but smaller for the ogee tip. The decrease of the AOA for the ogee shaped blade definitely produces the weaker wake flow, i.e. less turbulence and lower vorticity, downstream of the blade, which agrees with the observation from the vorticity distribution as shown in figure 33.

Figure 34 Schematic of the angle of attack at 75% radius: (a) original blade, (b) positive winglet, (c) ogee shape; at 50% radius: (d) original blade, (e) positive winglet, (f) ogee shape

Figure 35 shows the “phase-locked” PIV measurement results at a phase angle of 180° for all 8 different blade tips at the free stream wind speed of $U_0 = 6$ m/s. As mentioned before, with the increased phase angle the tip vorticity value was reduced for all 8 cases. The comparison results of the 180° phase angle are a little bit different than the results at 60° . The blades with negative winglet and ogee shape still have higher vorticity of the tip vortices compared with the original one; and blades with a curved end plate, an airfoil shape end plate and positive winglets still have lower vorticity of the tip vortices compared with the original blade. However, the vorticity value of the blade with small flat end plate has a lower value compared with the original blade, and the big flat end plate do not provide larger values of vorticity, in contrast, it has a lower value compare with the original blade.

Figure 35 Vorticity distribution of the “phase-locked” PIV measurement results at phase angle of 180° for 8 different tip shapes with $U_0=6$ m/s. Tip shape: (a) original, (b) Flat end plate (4.5×6.75 mm), (c) Flat end plate (9×11.25 mm), (d) Curved end plate, (e) Airfoil shape end plate, (f) Positive winglet, (g) Negative winglet, (h) Ogee shape tip

The “phase-locked” PIV measurement results at 300° phase angle for all 8 different blade tips at free stream wind speed of $U_0=6$ m/s are shown in figure 36. Comparing

these 8 cases, some interesting insights can be obtained combined with the comparison results at a 180° phase angle.

From comparison results at 60° , 180° , and 300° phase angles at 6 m/s wind speed, it can be found that the negative winglet and ogee shape tip wind turbines always have larger values compared with the original blade; that means these two tip shapes increase tip vorticity at a wind speed of 6 m/s. The airfoil shape end plate, curved end plate, and positive winglet produce lower vorticity compared with original blade; that means these three tip shapes restrict tip vortices at a 6 m/s wind speed. The small flat end plate and big flat end plate generate higher vorticity values than the original blade at the beginning, however, the decay of the vorticity is faster than the original blade at 6m/s. The detailed decay rate comparison will be discussed later.

Figure 36 Vorticity distribution of the “phase-locked” PIV measurement results at phase angle of 300° for 8 different tip shapes with $U_0=6$ m/s. Tip shape: (a) original, (b) flat end plate (4.5×6.75 mm), (c) flat end plate (9×11.25 mm), (d) curved end plate, (e) airfoil shape end plate, (f) positive winglet, (g) negative winglet, and (h) ogee shape tip

Figure 37 shows vorticity distribution at the phase angle of 60° for all 8 different blade tips at a free stream wind speed of $U_0=7$ m/s. The vorticity values of tip vortices

from the same blade at different downstream position are 0.24 and 0.13 respectively for the original blade. Compared with the original case, the wind turbine blades with big flat end plates, small flat end plates, negative winglets and ogee shape tips produce larger values of vorticity. The curved end plate, airfoil shape end plate, and positive winglet tip wind turbine blades produce lower vorticity of the tip vortices.

Figure 37 Vorticity distribution of the “phase-locked” PIV measurement results at phase angle of 60° for 8 different tip shapes with $U_0=7$ m/s. Tip shape: (a) original, (b) flat end plate (4.5×6.75 mm), (c) flat end plate (9×11.25 mm), (d) curved end plate, (e) airfoil shape end plate, (f) positive winglet, (g) negative winglet, and (h) ogee shape tip

Figure 38 shows the vorticity distribution at a phase angle of 180° for all 8 different blade tips at a free stream wind speed of $U_0=7$ m/s. Compared with the original blade, the wind turbine blades with big flat end plate, small flat end plate, negative winglet and ogee shape have larger values of vorticity; the curved end plate and positive winglet tip wind turbine blade produce lower vorticity; the airfoil shape end plate produces a similar value of vorticity.

Figure 38 Vorticity distribution of the “phase-locked” PIV measurement results at phase angle of 180° for 8 different tip shapes with $U_0=7$ m/s. Tip shape: (a) original, (b) flat end plate (4.5×6.75 mm), (c) flat end plate (9×11.25 mm), (d) curved end plate, (e) airfoil shape end plate, (f) positive winglet, (g) negative winglet, and (h) ogee shape tip

Figure 39 shows vorticity distribution at phase angle of 300° for all 8 different blade tips at the free stream wind speed $U_0=7$ m/s. Compared with original case, the same conclusions can be obtained as with the results at 60° phase angle.

The conclusion of comparison results at 60° , 180° , and 300° phase angles at 7 m/s wind speed are the same. Compared with the original blade at the wind speed of 7 m/s, wind turbines with the big flat end plate, small flat end plate, negative winglet, and ogee shape tip produces higher vorticity of the tip vortices, and the curved end plate, airfoil shape end plate, and positive winglet tip installed on wind turbine blade reduce the strength of tip vortices.

Figure 39 Vorticity distribution of the “Phase-locked” PIV measurement results at phase angle of 300° for 8 different tip shapes with $U_0=7$ m/s. Tip shape: (a) original, (b) flat end plate (4.5×6.75 mm), (c) flat end plate (9×11.25 mm), (d) curved end plate, (e) airfoil shape end plate, (f) positive winglet, (g) negative winglet, and (h) ogee shape tip

3.3.7 Decay of the tip vortices

Another point worth considering is that the decay rate of the tip vortices, which plays an important role in the transition process to turbulence. Figure 40 shows the vorticity value at different distances downstream of the wind turbine with a power curve fitting the data. The measurement results of the tip vortices of the original blade at a free stream wind speed of $U_0=6$ m/s are represented by the blue circle points in the figure, which were achieved by tracking the maximum vorticity value of the tip vortices from the

“phase-locked” PIV measurements at different phase angles of the same blade 1. As the tip vortices move downstream, the strength of them reduces rapidly. The red line represents the power law curve fit. It can be seen clearly that the measurement data can be represented by the power function.

Figure 40 The tip vortices decay with respect to distance in flow direction

For the purpose of comparing the effect of different tips on the decay characteristics, the decay profiles of the tip vortices for different tips at the free stream wind speed, $U_0 = 6$ m/s and $U_0 = 7$ m/s are plotted in figure 41. Compared to the original blade, the lower value of vorticity along the decay curve is found for the blade with the curved end plate, the airfoil shape end plate, the small flat end plate and the positive winglet at the free stream wind speed of 6 m/s; and the blade with curved end plate, positive winglet, and airfoil shape end plate at 7 m/s free stream wind speed. These findings agree with the previous analysis on tip vortices. Considering the decay result of all the cases at 6 m/s and 7 m/s, the wind turbine model with curved end plate, airfoil shape end plate, and positive winglet reduce the vorticity compared with the original blade. For the airfoil shape end plate tip shape, although it starts with a low value of the vorticity, the decay

rate for it presents a slow trend as shown in Figure 41(a) and (b) after 60mm downstream of the turbine (almost half the blade radius). The vorticity value for the blade with the airfoil shape end plate wind turbine blade model was found to be greater than the positive winglet wind turbine model after 120 mm and 70 mm in x-direction at a wind speed of 6 m/s and 7 m/s, respectively. The wind turbine model with curved end plate, it generates similar vorticity values as the positive winglet model; however, it reduces almost 10% of the power output compared with the positive winglet blade model. Therefore, considering the TSR, power coefficient, wind load and decay of the tip vortices results together, the best case should be the wind turbine blade model with positive winglet tip shape, which produces the comparable power output and reduces the tip vortices drastically compared with the original wind turbine blade model. While the ogee shape tip wind turbine model increases the power output, it also increases the strength of tip vortices. As for the blade with curved end plate it fairly reduces the tip vortices; however it also reduces the power output dramatically.

Figure 41 The decay of the tip vortices for the wind turbine model with different tips

CONCLUSIONS

In conclusion, a comprehensive experimental study was conducted on the effect of tip modifications on the power output, dynamic wind load and the formation and evolution of tip vortices downstream of the wind turbine model. In addition to power measurements using a circuit and force measurements using a highly sensitive six-component load cell, a high resolution PIV system was employed to conduct flow measurements of detailed flow characteristics in the near wake through both “free run” and “phase-locked” measurements. Eight different tip modifications were tested, including original, small flat end plate, big flat end plate, curved end plate, airfoil shaped end plate, positive winglet, negative winglet and ogee shape tip. The power output and wind load data are analyzed correlating with the quantitative flow field measurements.

The measurement results of the rotation, power test and the dynamic wind load reveal that the ogee tip wind turbine blade model has an increase of around 4% of the TSR and 6% of the power output that provides the best performance among all turbines tested in the present study. The wind turbine model with the positive winglet tip and the negative winglet maintains the TSR and power output compared with the original wind turbine model. The worst power output was observed for the wind turbine with the large flat end plate and curved end plate. Wind turbine models with other tip modifications produce a slight reduction of the power output. From the force measurements, it has been found that all wind turbines with tip modifications experience a higher value of thrust and bending

moment coefficient with varied tip speed rotation. It indicates that the tip modifications either enhance the flow in the rotor volume or reduce the moment of inertia, which results in a higher thrust and bending moment coefficient.

The maps of the tip vortices generated from the blade, root, and nacelle are achieved from the PIV measurement results. The absolute value and distribution of vorticity shed from the tip and whole blade varied with different tip modifications. It has been found that wind turbine models with curved end plate, airfoil shape end plate and positive winglet produce weaker tip vortices, while the airfoil shape end plate produces a stronger wake from the blade below the tip vortices.

Considering the power coefficient, wind load and decay of the tip vortices results together, the best case would be the wind turbine blade model with positive winglet tip shape; this produces a comparable power output and reduces the tip vortices drastically compared with the original wind turbine blade model.

FUTURE WORK

Currently, a comprehensive experimental study of the effect of tip modifications are studied on the power output, dynamic wind load and the formation and evolution of tip vortices downstream of the wind turbine model. As mentioned before, tip vortices interact with edges and emit aerodynamic noise which accounts for the most part of noise generation from a wind turbine. An experimental test on the noise will be studied. As the tip shape varies, the different feature of the tip will also be added into the wing turbine blade design. In the future, the feature inspired by an owl's wing will be considered to be an important idea for noise reduction, because the owl is recognized as the most silent flyer. The leading edge and trailing edge serrations and the down hair type of surface will be added into the blade design, and also surface grooves will be added on to the blade design.

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