Experimental Study on the Effects of Winglets on the Performance of Two Interacting Horizontal Axis Model Wind Turbines

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Abstract. The focus of this experimental study is to investigate the effects of winglets on the performance of two interacting similar horizontal axis model wind turbines. For this purpose, a downwind winglet is designed and manufactured to be attached to the blade tips of the upstream turbine. A set of wing extensions with the same length as the winglets is also produced to be compared to the winglets. Power and thrust coefficients of both turbines are measured with winglets as well as with wing extensions attached to the blade tips of the upstream turbine and are compared to the baseline case (rectangular tip without any tip devices). The model turbines are three bladed and have a rotor diameter of 0.94 m. The measurements are performed in two different wind tunnels (closed test section and open jet). For both sets of measurements, winglets have a noticeable increasing effect on the power coefficient of the individual turbine. There is an increase in the thrust coefficient as well. Measurements on the second turbine are done while it is positioned at downstream locations in line with the upstream turbine. Results show that it produces less power while operating in the wake of the upstream turbine with winglets. However, the overall power efficiency of two turbines can increase for the wingletted case. Moreover, results with wing extensions show that although upstream turbine produces more power with wing extensions attached, the power coefficient remains the same as the baseline case due to growth in rotor swept area and hence, it is less than the power coefficient of wingletted turbine.

Keywords: Winglet, Wind turbine, Wake interactions

1. Introduction
According to wind energy market forecasts, annual global installed capacity will grow up to 66.5 GW by the year 2019 which will lead to a global cumulative installed capacity of 666.1 GW [1]. Considering these numbers, it is certain that the future wind farms will consist of a higher number of wind turbines with higher power production capacities. On the other hand, there are always constraints on the rotor diameters of turbines [2]. To produce more power while maintaining the rotor diameter, wind turbines need to have higher power coefficients. One of the possible ways of maximizing the power coefficient, $C_p$, is adding winglets to the blade tips of the turbines. Similar to airplanes, winglets in wind turbines decrease the induced drag of the blade by reducing the downwash effect in the tip region[3]. However, winglets also add excess profile drag (form drag) to the blades and the outcome of these two effects is important regarding having a positive effect on the power production [4]. There
have been some computational and experimental studies on the effects of winglets and other types of tip devices on the performance of individual wind turbines [3,5–7]. Both positive and negative effects of winglets on the power coefficient of the turbines are reported. Regarding wind farm applications, any possible increase in the power coefficient of wingletted turbines will lead to excess thrust coefficient which can affect the power production of downstream turbines in the negative direction [8]. There are not many studies on the effects of these devices on the turbines operating downstream. Tobin et al. [9] experimentally investigated the effects of downwind winglets on the performance of two interacting model wind turbines with a rotor diameter of 0.12 m. Results for the wingletted turbine showed an increase in the power and thrust coefficient of 8.2% and 15.0%, respectively. Authors stated that a simple analytical treatment of obtained results showed a possible positive balance between the increasing power and thrust coefficients for a wind farm scale. The current study aims to investigate the effects of winglets attached to the blades of a model wind turbine on its performance as well as on the performance of a similar turbine operating downstream. The effect of a set of wing extensions with the same length as winglets is investigated as well.

2. Experimental facility

Two similar horizontal axis model wind turbines with a rotor diameter of 0.94 m are utilized for this study. The rotors are three bladed with non-linearly twisted and tapered blades that have an NREL S826 profile all along the span. Each model turbine is equipped with a torque meter with a measurement uncertainty equal to ±0.005 N.m, which is capable of measuring rotational speed. The turbines can operate at desired rotational speeds utilizing a computer controlled electric servomotors. Winglets for wind turbines are mainly considered in two categories, upwind and downwind. The blade bends toward its suction side for upwind winglet whereas it bends toward its pressure side for downwind configuration. Upwind winglets are expected to contract the wake while the downwind winglets are supposed to cause the wake to expand[5]. For the current study, a set of downwind winglets is designed and manufactured using 3D print technology. Winglet profile is selected as (PSU) 94-097. This airfoil is designed for use on winglets for low-speed airplanes which is also suitable for our turbines regarding Re number [10]. Cant, toe, twist and sweep angles are selected as 90°, 1°, -0.5° and 19°, respectively. These design variables are defined in Figure 1. The height of the winglet is selected as 6% of the rotor radius.

The measurements are performed in two different wind tunnels. The first set of experiments is conducted at large scale closed loop wind tunnel of Norwegian University of Science and Technology (NTNU). This closed loop wind tunnel has a closed test section with a cross section of 2 m × 3 m that is 11 m long. The turbines are located in line with two different distances in between of 3 and 6 rotor diameters. Free stream velocity is set to 11.5 m/s at the inlet of test section for all measurements. The
average turbulent intensity is about 0.2%. Power and thrust measurements are performed on both upstream and downstream turbines while the upstream turbine is operating with and without winglets. Wind tunnel’s external balance system measures the thrust force. For each measurement point, Torque and thrust values are measured for 15 seconds with sampling rates of 40 kHz and 1 kHz, respectively. A 3D printed set of winglets from plastic material is used for this set of experiments. Figure (a) shows a picture of turbines located in the test section of NTNU wind tunnel. A view of the winglets attached to the turbine blades and the CAD model of the winglet are shown in Figure (b) and Figure (c), respectively. The second series of experiments are performed at Middle East Technical University, Center for Wind Energy (METUWIND). The same model turbines are located at the exit of METUWIND’s open jet wind tunnel with a jet exit diameter of 1.7 m. The distance in between turbines is set to 3 rotor diameters. The average turbulence intensity at the exit of the tunnel is about 2%. The measurements are performed at the jet exit velocity of 11.5 m/s.

For this set of experiments, a set of designed winglets and a set of wing extension are 3D printed from aluminum material. The length of wing extensions are equal to the height of winglets, and its profile is the same as the blades. Power measurements on both turbines are conducted while the upstream turbine is operating with winglets as well as with wing extensions attached to its blade tips, and the results are compared to the baseline case (no tip devices). Figure (a) shows a picture of the model turbines located at the exit of the open jet wind tunnel. A picture of the winglets attached to the upstream turbine’s blades can be seen in Figure (b). Figure (c) shows a picture of the upstream turbine with wing extensions attached. The wind turbine blockage ratios are 14.33% and 30.6% in NTNU closed loop and METUWIND open jet wind tunnels, respectively. The blockage ratio of the open jet tunnel is calculated for the jet exit. However, the turbine is located 0.5 D downstream where the jet

Figure 2. (a) Picture of turbines located in the test section, (b) Picture of the winglets attached to the blades of the first turbine, (c) CAD model of the winglet.

Figure 3. (a) Picture of model turbines located at the jet exit of the open jet wind tunnel, (b) Picture of the winglets attached to blade tips of the upstream turbine, (c) Picture of the wing extensions attached to blade tips of the upstream turbine.
flow expands freely. Hence, the actual blockage is lower than 30.6%. One should note that no blockage effect corrections are performed on the presenting results.

3. Results

Results from measurements at NTNU wind tunnel are presented in Figure 4 and Figure 5. Measurement results on the power and thrust coefficients of the upstream turbine with winglets compared to the non-wingletted case (referred as the baseline) are shown in Figure (a) and Figure (b), respectively. Attached winglets have a noticeable increasing effect on the power performance of the turbine for TSR values higher than 4. Measured thrust coefficient with winglets has similar behavior for the same TSR values. For the turbine running at TSR≈6, power and thrust coefficients increase about 4.2% and 6.5%, respectively. It should be noted that while the rotor is turning, the centrifugal force causes an outward deflection on the winglet tips (as the material for winglets used in NTNU wind tunnel is plastic). Therefore, the wingletted rotor is not turned higher than 1450 rpm (TSR≈6.25). The winglet outward deflection angle for TSR=6 (1350 rpm) is measured to be about 20° which causes a 4.4% increase in the rotor swept area. Power and thrust coefficients for the wingletted case calculated taking this growth in rotor swept area into consideration.

![Figure 4](image) Figure 4. Power (a) and thrust (b) coefficients variations with TSR measured for upstream turbine with and without winglets.

Figure (a) shows the results of the downstream turbine’s power coefficient measurements located at 3 and 6 rotor diameters downstream of the first turbine while the upstream turbine is rotating at TSR=6 (design TSR) with and without winglets. Please note that in this study winglets are only attached to the first (upstream) turbine and the second (downstream) turbine is always operating without any tip devices. For both downstream locations, it is observed that the second turbine produces less power while operating downstream of the wingletted first turbine. Please note that the downstream turbine is exposed to less incoming kinetic energy while operating downstream of the wingletted turbine, so it is expected to have less power coefficient in the whole TSR range. Moreover, results show that the overall power efficiency of two turbines increases with winglets attached for both 3 and 6 diameters distances in between. Equation 1 defines the definition of overall efficiency (wind farm efficiency). Table 1 presents the quantitative comparison of the overall efficiency of two turbines.

\[
\eta_{overall} = \frac{C_{P1upstream} + C_{P2downstream}}{C_{P1\max(unobstructed)} + C_{P2\max(unobstructed)}}
\]
Table 1. The overall efficiency of two turbines.

| Distance in between Turbines | Overall efficiency |
|------------------------------|--------------------|
|                              | Upstream Turbine without Winglets | Upstream Turbine with Winglets |
| 3 rotor diameters             | 65.6%               | 66.7%               |
| 6 rotor diameters             | 69.9%               | 71.0%               |

Figure (b) shows the thrust coefficient for the second turbine at 3 rotor diameter downstream of the first turbine while the first (upstream) turbine is operating at TSR=6 with and without winglets. All coefficients are calculated according to free stream velocity equal to 11.5 m/s.

Figure 5. (a) Power coefficient for downstream turbine with 3 and 6 rotor diameters distance in between while the upstream turbine is operating at TSR=6 (rotor design TSR) with and without winglets. (b) Thrust coefficient for downstream turbine with 3 rotor diameter distance in between while the upstream turbine is operating at TSR=6 with and without winglets (all coefficients are calculated according to free stream velocity equal to 11.5 m/s).

The second series of experiments are conducted in METUWIND open jet wind tunnel. Figure  shows the comparison between power coefficient of the individual turbine at free stream velocity of 11.5 m/s measured at closed loop wind tunnel of NTNU and open jet wind tunnel of METUWIND. The results

Figure 6. Individual turbine baseline (no tip devices) power performance comparison between measurements at NTNU closed loop and METUWIND open jet wind tunnels.
are quite consistent however around design TSR region (TSR=6) the turbine have a slightly higher power coefficient at the closed loop wind tunnel. Different blockage ratios in two wind tunnels(14.33% in NTNU and 30.6% in METUWIND) as well as different incoming flow turbulence intensities(0.2% in NTNU and 2% in METUWIND) can be possible reasons. One should note that the blockage ratio for METUWIND open jet tunnel is calculated for the exit of the open jet. However, the turbine is located 0.5 D downstream of the jet exit where the jet flow expands freely. Hence, the actual blockage ratio for the open jet wind tunnel is lower, which can be a reason for less power production.

Figure 7 shows the power coefficient measurement results of the first turbine with winglets and wing extensions attached, compared to the baseline case (no tip devices). Please note that compared to the experiments at NTNU, this set of experiments are conducted utilizing winglets and wing extensions 3D printed from aluminum material, so it is possible to rotate the turbine at higher RPMs while the tip devices are attached. As shown in Figure (a), winglets have noticeable increasing effect on the power coefficient of the turbine around design TSR region (TSR=6) that is consistent with closed loop wind tunnel measurements. Figure (b) shows the effect of wing extension on the power coefficient of the turbine. The power coefficient seems to have similar values to the baseline case. However, there is a small shift in the corresponding TSR values. This can be due to change in TSR values caused by growth in radius because of wing extensions. Please note that for each case (baseline and wing extension), power coefficient values are normalized due to rotor swept areas, so it is clear that the turbine with wing extension produces more power compared to the turbine with no tip device (baseline).

Figure 7. Power coefficient measurement results of first turbine with winglets (a) and with wing extensions (b) attached compared to the baseline case (no tip devices).

Figure shows the measured power coefficient for the downstream turbine with 3 rotor diameters distance in between while the upstream turbine is operating at TSR=6 (rotor design TSR) without any tip devices, with winglets, and with wing extensions. Please note that all coefficients are normalized according to free stream velocity equal to 11.5 m/s. It is depicted that similar to what is observed in the first set of experiments, the downstream turbine has less power coefficient while operating in the wake of wingletted upstream turbine compared to the case in which upstream turbine has no tip devices (baseline). For the case that the first turbine has wing extensions, the highest drop is observed in downstream turbine’s power performance. The upstream turbine with wing extensions, extracts more power from the incoming flow. Hence, the velocity deficit in its wake region is higher, and there is less energy left to the downstream turbine.
Table 2 presents the actual power production of the upstream turbine and downstream turbine for all three cases. The upstream turbine’s power production increases about 3% while the winglets are attached compared to the baseline case. By attaching the wing extensions to the upstream turbine, its power production increases about 16%. However, this is due to increase in its rotor swept area by the same ratio (power coefficient remains the same as the baseline). Increase in the total power production of two turbines for the cases of winglets and wing extensions compared to the baseline case are about 1% and 9%, respectively. From these results, it seems that using wing extensions are more beneficial compared to winglets. However, there are always restrictions on increasing the turbines’ rotor radius.

|                     | Power Production (watts) |
|---------------------|--------------------------|
| Upstream turbine    |                          |
| without any tip devices | 214.1                |
| Upstream Turbine    |                          |
| with Winglets       | 219.76                   |
| Upstream Turbine    |                          |
| with Wing Extensions| 250.74                   |
| Downstream turbine  |                          |
|                      | 63.07                    |
| Downstream Turbine  |                          |
|                      | 60.46                    |
| Total               |                          |
|                      | 277.17                   |
|                      | 280.22                   |
|                      | 303.9                    |

4. Conclusions
The focus of this experimental study is to investigate the effects of winglets on the performance of two interacting similar horizontal axis model wind turbines. For this purpose, a downwind winglet is designed and manufactured to be attached to the blade tips of the upstream turbine. A set of wing extensions with the same length as the winglets is also manufactured. Performances of both turbines are studied with winglets as well as with wing extensions attached to the blade tips of the upstream turbine and are compared to the baseline case (rectangular tip without any tip device). The measurements are performed in two different wind tunnels. The first set of experiments is conducted at large scale closed loop wind tunnel of Norwegian University of Science and Technology (NTNU). Power and thrust measurements are carried out on both upstream and downstream turbines while the upstream turbine is operating with and without winglets. For the wingletted turbine running at the rotor design TSR value (TSR=6), power coefficient increases noticeably compared to the non-wingletted case. By attaching the winglets, the thrust coefficient increases as expected. Measurements on the second turbine are done while it is positioned at two downstream locations with separation distances of 3 and 6 rotor diameters from the upstream turbine. For both locations of the downstream
turbine, results show that it produces less power while operating in the wake of the upstream turbine with winglets. However, the overall power efficiency of two turbines increases for the case with winglets for both 3 and 6 diameters distances in between. The second series of experiments are performed at Middle East Technical University, Center for Wind Energy (METUWIND). The same model turbines are located at the exit of an open jet wind tunnel. Power measurements on both turbines are conducted while the upstream turbine is operating with winglets as well as wing extensions attached to its blade tips. The results are compared to the baseline case (Rectangular tip without winglets and wing extensions). Measurements show that connecting winglets to the upstream turbine increases its power coefficient relative to the baseline case. Results with wing extensions indicate that although upstream turbine produces more power with wing extensions attached, the power coefficient remains the same as the baseline case and hence, it is less than wingletted turbine. Second turbine is positioned 3 rotor diameter downstream of the first turbine. Two turbine measurements show that wing extensions attached to the upstream turbine has the maximum decreasing effect on the second turbines performance. Finally, it is important to note that in wind farms, having two turbines exactly in line with each other is rarely occurring (only for a small region of wind directions), which further motivates the use of winglets.

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