Three-dimensional effects of trailing edge flap and winglet integrated on up-scale wind turbine blade

O S Motsamai¹ and P I Muiruri¹, ²

¹Department of Mechanical Engineering, Faculty of Engineering and Technology, University of Botswana, Private Bag 0061, Gaborone, Botswana.
E-mail: pmuiruri@jkuat.ac.ke

Abstract. Wind turbines must generate wind power cost-effectively for the wind power to remain viable and competitive among other renewable resources. The rotor diameter continues increasing in size to capture more energy to reduce the costs of wind power. However, the size of the rotor diameter is expected to reach limit due to restrictions related to the rotation of the entire blades, transport, and installation issues. This study, therefore, seeks to compare the effects of trailing edge flap and winglet embedded on the up-scale wind turbine blade. The investigated configurations are blade with winglet, blade with trailing edge flap and blade with a combination of the winglet and trailing edge flap. A straight blade of the NREL 5MW wind turbine was used as a benchmark to quantify effects of trailing edge flap and winglet. All simulations were performed using the ANSYS FLUENT. The steady pressure-based solver in absolute velocity formulation modelled the flow over the blade surfaces governed by Reynold-Averaged Navier-Stokes (RANS) equations closed with the $k - \omega$ SST turbulence model. Blades with trailing edge flap and combined trailing edge flap and winglet show similar effects in comparison of pressure coefficient at 0.32R, 0.60R and 0.92R. Blade with a winglet generates the highest aerodynamic torque, while blade with trailing edge flap decrease most of the flap-wise bending moment. The blade with combined trailing edge flap and winglet can serve as an alternative design for improving the wind turbine performance. That is, at the normal operating condition the trailing edge flap can be held at its neutral position whenever increment of the power is the primary target.

1. Introduction
Fossil fuel resources have been dominated sources of energy supplies globally for many years and still are dominating to date. Extensive use of these non-renewable energy resources has significantly caused pollution to the atmosphere, resulting in global warming across the world. The fossil fuel energy sources are also time-bound and may not last forever. Based on that facts, exploration of wind energy is gaining considerable attention because of its advantages such as; cost-effective, no emission causes little disruption to ecosystems, abundance and widely distributed worldwide, even though it occurs irregularly.

Wind turbines must generate wind power cost-effectively for the wind energy resources to remain viable and competitive among other renewable resources. The major unit of wind turbine are the tower and rotor. The tower rises the rotor to the required height above the ground to take advantage of high wind speed. The rotor comprising of the hub and the three blades are employed to capture the wind energy from the moving air and transforms it into mechanical energy at the hub [1]. Literature [2] revealed that installing few wind turbines with large rotor diameters is more cost-effective than installing many wind turbines of less diameter for a given site area.
As the rotor diameter increases in size, the structural loads correspondingly also grow due to an increase in gravity and aerodynamic loads. These loads are likely to cause non-desirable performance characteristics, premature damage of essential components or total damage if the loads exceed the ultimate limit. During the wind turbine's operation, the blades and tower are prone to bending stresses such as flap-wise stresses due to aerodynamic load and edgewise stresses due to gravitational load. The masses of the blades also increase by a cubic meter on increase of the blade span by one meter. As a result, increase in the size of the blades is likely to be restricted by other issues relating to rotation of the entire blades, transportation, installation and maintenance [3-5].

Rotating the entire blade is not ideal due to induced non-uniform aerodynamic loads across the blade span. Control systems are unable to respond rapidly due to the structural weight of the blades, which limits the speed of actuators. Excessive use of actuators leads to wear of pitch bearing and actuator resulting in unscheduled replacement and maintenance. Delivering large structures such as tower and blades to the area of installation encounters challenges concern use of public roads. The size and weight of the transport vehicle, the size of the blade’s chord and span length as well as tower are some of the constraints expected to restrict the further growth of the wind turbine size. The costs of installation and assembly also go up with an increase in the size of the tower due to the hiring of cranes and human resources.

The use of winglets [6-9] and trailing edge flaps [10, 11] can improve the performance of the wind turbines without necessities of increasing their rotor diameter. A winglet is a load-carrying aerodynamic device that decreases the span-wise flow, diffuses and moves the tip vortex away from the rotor plane, hence decreases induced drag. On the other hand, trailing edge flap can be defined as a small lifting surface placed at the rearward portion of the blade profile, which alters the flow over the blade surface on pressure surface and suction surface by deflecting it interchangeably. The effects of the aforementioned aerodynamic devices on wind turbine operation have been investigated independently. For instance, rigid trailing edge flap, deformable trailing edge flap (DTEF) [4, 12-15] morphing trailing edge [16, 17] and winglet [6, 7, 9]. There is hardly study in the literature that compares the design of the rotor blades with either winglet, trailing edge flap or combination of both trailing edge flap and winglet.

This study compares the computational performance of the blades of different design configurations. This task is carried out by contrasting computational results performed through computational fluid dynamics (CFD) using ANSYS Fluent 19.1.

2. Methodology

2.1. Blades geometry
A conceptual up-scale NREL 5MW reference wind turbine [18] was used as the benchmark in the present study. Numerous researchers have also used a similar wind turbine for examining the aerodynamic behavior and aero-elastic models [4, 15]. ANSYS Design-Modeler utilized under the ANSYS Workbench platform was used to create and modify the geometry of the blade, while the ANSYS Fluent was utilized to resolve the current problem solution. Four sets of blade designs were established, which include; straight blade, blade with a winglet, blade with trailing edge flap, blade with a combination of both winglet and trailing edge flap. The winglet was inclined at 15° starting from 0.95R of the blade span, such that the rotor swept area remain unchanged. The trailing edge flap is located at 0.93R of the blade span, and it was extended towards root section with 0.20R span. The trailing edge flap has chord equal to 0.15c, which was deflected to suction direction with a deflection angle of 15°. The resultant geometry of the blades proposed in this study is shown in Figures 1-4.
2.2 Simulation domain

The present study considers only rotor blades for numerical modelling. The numerical computations were conducted using the real operating condition by modelling the flow over the wind turbine rotor at the rated wind speed of 11.4 m/s. A single blade was imposed in the simulation domain, and the two boundaries on the side of the domain were defined as a rotational periodic boundary condition because the three blades are spaced symmetrically with 120 degrees apart. The boundary conditions were specified at the domain’s boundaries shown in figure 5. The blade’s geometry was located 125 m away from inlet upstream and 300 m away from outlet downstream. The radius of the inlet is 120 m, whereas the radius of the outlet boundary is 270 m.
2.3 Meshing
The fluid computational domain was discretized into small unstructured mesh cells comprising of prismatic wedge mesh around the blade’s surface, and unstructured tetrahedrons cells at the rest part of the domain. First, the mesh matching conditions were imposed on the two periodic interfaces. Then, the blade surface mesh size was set to 0.05 m, which was determined from our previous study [19]. Fifteen inflation layers with a transition rate of 0.2 and growth rate of 1.1 were inserted around the blade surface, to attempt arresting the boundary conditions. The sphere influence mesh was defined around the blade, starting at the centroid point for a radius of 50 m and elements size of 1 m. The mesh size of the remaining part of the domain was specified to 3 m, whereas, the proximity and curvature sizing functions were specified at the global level to medium relevance. The resultant value of the non-dimensional wall $y^+$, which is calculated using Equation 1 was expected to be below 300 according to [20] at the fully turbulent region.

$$y^+ = \frac{u_\tau y}{v}$$ (1)

where $u_\tau$ denotes the friction velocity, $y$ is the distance from the wall, $v$ is kinematic viscosity and $y^+$ represents dimensionless distance measured from the blade surface (wall) to the viscous layer. The quality of the generated elements and nodes was examined based on skewness and orthogonal quality criteria.

2.4 Boundary conditions
Inlet-velocity boundary conditions at the inlet and inlet-top were defined with uniform velocity equivalent to the wind speed of 11.4 m/s imposed to (0, 0, -1) direction. Gauge pressure of zero Pascal was set at the outlet for outlet-pressure boundary condition. The respective turbulent intensity and viscosity ratio was retained as software default values of 5% and 10% respectively, which was determined to cover a wide range of flow according to [20]. A non-slip wall boundary condition was specified at the blade surface. The fluid domain frame was imposed to rotate with an angular speed of 12.1 rpm, whereas periodic boundary conditions were defined on the two sides of the fluid domain. The properties of the fluid (air) consist of the density $\rho = 1.225 kg/m^3$ and viscosity of $1.82 \times 10^{-5} kg \cdot s/m$

2.5 Numerical set-up
A single moving reference frame (SMRF) approach was used to account for the rotational effects of the turbine blade. A small cluster was created by connecting four desktop computers, whereby, the three-dimensional double precision parallel version was set in the ANSYS FLUENT. The mesh was partitioned automatically into sixteen equal portions by use of a METIS algorithm, which means that each computer solves the Reynolds-Average Navier-Stoke (RANS) equations using four cores. The steady pressure-based solver with absolute velocity formulation was used to model the flow over the blade surface. In order to solve Reynold tensor stress, $K - \omega$ SST turbulence model was used to close the open RANS equations.

A SIMPLE algorithm scheme has been employed to solve pressure-velocity coupling in a segregated manner. A spatial discretization scheme utilizing the Least Squares Cell-Based gradient was also used to discretize the pressure at second-order. Both momentum and turbulent kinetic energy were discretized through the second-order upwind scheme. The solution convergence was monitored through residual tolerance and axial force which were expected to drop below $10^{-6}$. The solution was initialized using hybrid initialization method. All CFD calculations were specified to solve RANS equations iteratively in 8000 iterations.

3. Results and discussions

3.1 Check for simulation
All simulations were deemed to have correctly solved the models when all residual tolerance show a consistent trend and have dropped below the order of $10^{-5}$ apart from turbulent kinetic energy (k) tolerance. At the same time, the axial force monitors converge after about 4000 iterations. The resultant mass balance was less than 0.1%. Validation of the initial straight blade model was carried out by comparing the computed mechanical power of the straight blade model performed at the rated wind speed of 11.4 m/s to rated mechanical power adopted from literature [18, 21]. Mechanical power is the product of obtainable aerodynamic torque (Mz) multiplied by the angular rotation speed of the blade ($\Omega = 12.1$ rpm), and the results are given in table 1.

| Author          | Simulation code | Mechanical power ($10^6$), Watts |
|-----------------|-----------------|----------------------------------|
| Jonkman et al.  | FAST 2          | 5.297                            |
| Zhoa et al.     | OpenFoam        | 5.290                            |
| Present (k−ω SST) | ANSYS Fluent   | 5.313                            |

Even though direct matching was not expected, the results show good agreement as depicted in Table 1. After validation, the CFD models of other blades configurations were performed and compared to the straight blade model.

### 3.2 Computational results

Obtainable axial force (Fz), aerodynamic torque (Mz) and flap-wise bending load (My) were compared to the results of a straight baseline blade as given in Table 2.

| Blade configurations | Fz ($\times 10^3$) | Mz ($\times 10^6$) | My , ($\times 10^6$) |
|----------------------|-------------------|-------------------|---------------------|
| Baseline             | 230               | 1.44              | 9.18                |
| B-W                  | 246               | 1.57              | 10.28               |
| B-F                  | 208               | 1.33              | 8.10                |
| B-F-W                | 210               | 1.33              | 8.17                |

Application of trailing edge flap and winglet devices alter pressure distribution on the blade surface resulting in a decrease of axial force (thrust force). Winglet causes an increase in aerodynamic torque and the corresponding flap-wise bending load. Trailing edge flap of 15% Chord when is deflected at 15o to suction surface causes a decrease in both aerodynamic torque and flap-wise bending load.

### 3.3 Pressure Distribution

Obtainable aerodynamic torque and flap-wise bending load depend on pressure distribution per unit length. Figures 6-9 illustrate pressure distributions on both suction and pressure surfaces.
The maximum negative pressure occurs near the leading edge on the suction surface at the tip region, and the highest positive pressure takes place at the leading edge on the pressure surface near the tip region. Correspondingly, the highest aerodynamic force exists near the tip region. To get a clear insight into how the winglet and trailing edge flap devices affect the pressure distribution on the blade surfaces, we compare the pressure coefficient at different span-wise chords. For the blade with winglet and trailing edge flap, the region with the highest negative pressure on the suction side occurs near the tip at the leading edge.

Figure 10 compares pressure coefficient (Cp) on inboard region at 0.32R chord. Figure 11 illustrates a comparison of pressure coefficient (Cp) in the mid-span region at 0.60R chord, while Figure 12 shows pressure coefficient (Cp) comparison on the outboard region at 0.92R chord.
Figure 10. Comparison of pressure coefficient (Cp) at 0.32R chord for different blade configurations

Figure 11. Comparison of pressure coefficient (Cp) at 0.60R chord for different blade configurations

Figure 12. Comparison of pressure coefficient (Cp) at 0.92R chord for different blade configurations

The effects of trailing edge flap deflected on the suction side are clearly shown by pressure coefficient probed at 0.92R chord in Figure 12. Inclining winglet upward the same as a trailing edge flap cause an increase of the negative pressure acting on the pressure surface. From the observation, winglet causes a significant pressure difference near the tip region. Application of trailing edge flap to suction side causes the pressure acting in that region of application to increase on suction, but decrease pressure acting on the pressure side. The blade shows this observation with a trailing edge flap and also a blade with both trailing edge flap and winglet.

Figure 13 illustrates a comparison of the pressure coefficient along the blade span, estimated at 0.25c measured from the leading edge. As it is seen from the figure, the pressure difference reduces in the region where the trailing edge flap is applied, while winglet increases the pressure difference near the tip of the blade.

Figure 13. Comparison of pressure coefficient distribution along the blade span at 0.25 Chord
As it is seen from the figure, the pressure difference reduces in the region where the trailing edge flap is applied, while winglet increases the pressure difference near the tip of the blade.

3.4 Visualization of the vortex in wake structure

The vortices are flow regions with positive second-invariant of velocity ($\nabla u$), given that the $Q > 0$. As a result, the flow in the motion moved from the region of positive pressure around the tip chord and at the trailing edge of the blade to the region of negative pressure region. The region of vorticity occurs as a vortex when the local rate of rotation is larger than the rate of strain. In the present study, resultants vortices contours are solved at the rated wind speed of 11.4 m/s for the rotor rotating at 12.1 rpm. Figures 14 to 17 show iso-surface-vorticity contour of the respective blades when the blade is rotating to the top position.

The figures display the formation of the wake vortices at the tip of the blade and are rotating downstream in spiral nature and seemed to expand outward. In addition, a large number of high magnitude vortices are formed at the top blade tip. Significant structures are visualized for other blades apart from the blade with a winglet.

4. Conclusion and recommendation

The study investigated three-dimensional effects of trailing edge flap and winglet integrated on wind turbine blade using ANSYS FLUENT. Validation results in a good agreement with a difference of 0.30% and 0.43% of works performed using FAST 2 and Open Foam codes respectively. By using the same mesh topology and boundary conditions for all the blades, the computational results for the straight blade with a trailing edge flap, blade with a winglet and blade with a combination of trailing edge flap
and winglet were compared to results obtained for a straight baseline blade. Blade with a winglet produces the highest increase in the aerodynamic torque by 9.0% and corresponding flap-wise bending load by 12.0%. The aerodynamic torque reduces upon application of trailing edge flap deflected to the suction side. Blade with trailing edge flap records drop in aerodynamic torque by 7.6% and the corresponding flap-wise bending load by 11.8%. Aerodynamic torque and flap-wise bending load were reduced by 7.6% and 11.0% respectively for the blade with a combination of trailing edge flap and winglet. Application of trailing edge flap and winglet shows an effect on pressure coefficient distribution at different span-wise locations and also along 0.25c span-wise. The vortex with high magnitude prevails at the tip section of the blades. From computational results, the blade with a combination of trailing edge flap and winglet could be used as an alternative to enhance power production as well as reduce the excess aerodynamic load. That is if the trailing edge is held at its neutral position, the blade produces the highest aerodynamic torque but compromise power generation when it is applied, though, the blade enjoys a reduction in flap-wise bending load. The study also recommends further investigation for the wind speed below and above rated wind speed.

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References
[1] Vermeer L, Sorensen J N and Crespo A 2003 Wind turbine wake aerodynamics Progress in Aerospace Sciences 39 467-510,
[2] Wiser R, Hand M, Seel J and Paulos B 2016 Reducing Wind Energy Costs through Increased Turbine Size: Is the Sky the Limit? In: Lawrence Berkeley National Laboratory, https://emp.lbl.gov/sites/all/files/scaling_turbines.pdf
[3] Chen Z and Stol K 2014 An assessment of the effectiveness of individual pitch control on upscaled wind turbines. In: Journal of Physics: Conference Series: IOP Publishing) p 012045
[4] Lackner M A and van Kuik G 2010 A comparison of smart rotor control approaches using trailing edge flaps and individual pitch control Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology 13 117-34,
[5] Tjiu W, Marnoto T, Mat S, Ruslan M H and Sopian K 2015 Darrieus vertical axis wind turbine for power generation II: Challenges in HAWT and the opportunity of multi-megawatt Darrieus VAWT development Renewable Energy 75 560-71,
[6] Elfarra M A, Sezer Uzol N and Akmandor I S 2015 Investigations on blade tip tilting for HAWT rotor blades using CFD International journal of green energy 12 125-38,
[7] Gupta A and Amano R 2012 CFD analysis of wind turbine blade with winglets. In: ASME 2012 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, (Chicago, Illinois, USA: American Society of Mechanical Engineers) pp 843-9
[8] Lawton S and Crawford C 2014 Investigation and optimization of blade tip winglets using an implicit free wake vortex method. In: Journal of Physics: Conference Series: IOP Publishing) p 012033
[9] Zhou C, Hodson H, Tibbott I and Stokes M 2013 Effects of winglet geometry on the aerodynamic performance of tip leakage flow in a turbine cascade Journal of Turbomachinery 135 051009,
[10] Daynes S and Weaver P M 2012 A morphing trailing edge device for a wind turbine Journal of Intelligent Material Systems and Structures 23 691-701,
[11] Lachenal X, Daynes S and Weaver P M 2013 Review of morphing concepts and materials for wind turbine blade applications Wind energy 16 283-307,
Barlas T, Van der Veen G and Van Kuik G 2012 Model predictive control for wind turbines with distributed active flaps: incorporating inflow signals and actuator constraints Wind Energy 15 757-71.

Barlas T K and Madsen H A 2011 Influence of actuator dynamics on the load reduction potential of wind turbines with distributed controllable rubber trailing edge flaps (CRTEF). In: 22nd International Conference on Adaptive Structures and Technologies (Corfu, Greece).

Yu W, Zhang M M and Xu J Z 2012 Effect of smart rotor control using a deformable trailing edge flap on load reduction under normal and extreme turbulence Energies 5 3608-26,

Zhang M, Tan B and Xu J 2015 Parameter study of sizing and placement of deformable trailing edge flap on blade fatigue load reduction Renewable Energy 77 217-26,

Barbarino S and Bilgen O 2011 Rafic m. Ajaj, Michael I. Friswell, Daniel J. Inman. "A Review of Morphing Aircraft. Journal of Intelligent Material Systems and Structures 22

Pechlivanoglou G, Wagner J, Nayeri C and Paschereit C 2010 Active aerodynamic control of wind turbine blades with high deflection flexible flaps. In: 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, (Orlando, Florida , USA) p 644.

Jonkman J, Butterfield S, Musial W and Scott G 2009 Definition of a 5-MW reference wind turbine for offshore system development. National Renewable Energy Lab.(NREL), Golden, CO (United States))

Muiruri P I, Motsamai O S and Ndeda R 2019 A comparative study of RANS-based turbulence models for an upscale wind turbine blade SN Applied Sciences 1 1-15

FLUENT 2017 ANSYS Fluent Theory Guide. ANSYS, Inc.) https://www.scribd.com/document/375085140/ANSYS-Fluent-Theory-Guide Access Date: 20 May 2019

Zhao W, Cheng P and Wan D 2014 Numerical computation of aerodynamic performances of NREL offshore 5-MW baseline wind turbine. In: The Eleventh ISOPE Pacific/Asia Offshore Mechanics Symposium, (Shanghai, China: International Society of Offshore and Polar Engineers)