Effect of a winglet on the Power Augmentation of Straight Bladed Darrieus Wind Turbine

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Abstract. There has been an increased interest in enhancing the relatively low power coefficient of the Vertical axis wind turbine (VAWTs) for wider applications. Winglets are an effective solution for improving the aerodynamic performance in the aerospace field, and this paper numerically studies the aerodynamic effect of adding a winglet on the blade of a VAWT. The Computational Fluid Dynamics (CFD) base model is verified by experimental data from the available literature. The present work compares the effect of a winglet on the turbine performance of a VAWT. As a result, the power performance of the turbine with the appended winglets increases. The winglet assists in maintaining the pressure between the two sides of the blades. And, thus, weakens the tip vortex and improves the aerodynamic efficiency of the turbine blade.

1. Introduction
The wide deployment of Vertical Axis Wind Turbines (VAWTs) is hindered due to the lower power coefficients than the widespread Horizontal Axis Wind Turbines [1]. In VAWTS, the tip vortex dominates induced drag and reduces the power. The wingtip devices such as endplates, mie-vanes, winglets, among many other devices, are an effective solution to decrease the drag [2]. Among the wingtip devices, the winglet has better power improving ability [3]. Ahmed et al. [4] performed wind tunnel experiments and reported that winglets were able to increase the power performance of the manufactured VAWT by more than 10%. In a CFD study, Amato et al. [3] investigated different winglets on the performance of a single blade Darrieus VAWT. The blade with aerodynamic bulkhead was the most straightforward design and increased the performance directly. Also, two of the winglet designs were estimated to increase the power by 10% approximately, but the third winglet was reported to reduce rotor efficiency compared to the original blade. Recently, Lain et al. [5] numerically examined the effect of winglets on turbine performance with two different types of winglets and recorded higher improvement on use of a symmetric winglet design. However, the detailed analyses of the effect of individual key parameters used to define winglets on the aerodynamics of VAWTs are not readily available in the literature. The definitions of the key design parameters of a winglet are identical to those presented by Maughmer et al.[6], namely: (i) winglet height, (ii) cant angle, (iii) sweep angle, (iv) curvature radius, (v) toe angle, and, (vi) twist...
angle. These parameters have been proven to have an effect on the performance of HAWTs; thus, their impact on VAWTs will likely be advantageous. The present work is intended to study the effect of curvature radius on interference generated due to the sharp joint between the blade and winglets as well as on the performance of an H-type VAWT. Further understanding of the winglet parameters for an effective winglet design with enhanced power will be beneficial for the commercialization of VAWTs.

2. Base model

Figure 1 shows the base 3D model without any winglets. The model has three blades of airfoil cross-section NACA 0018 with a chord length \( c \) of 200mm. The turbine had a diameter of 800 mm and a height (blade span) of 800 mm per the model used in the experiment by Elkhoury et al. [7].

The VAWT blades rotate about the central shaft and thus, the resultant flow velocity is not constant as that of HAWTs. From Figure 2(a), we can understand that the flow velocity \( \mathbf{W} \) on the blade of a VAWT is a vector sum of freestream velocity \( \mathbf{V}_\infty \) and \( \mathbf{V}_r \) blade rotating speed (Equation 1). The azimuthal angle \( \theta \) defines the position of the blade during the rotation. Here, the resultant velocity depends on azimuthal angle \( \theta \) and the Tip Speed Ratio (TSR) \( \lambda \) (Equation 3). Then, the geometric angle of attack \( \alpha \) at a certain \( \theta \) can be defined by the Equation (4).

Figure 1. H-VAWT rotor model layout.

Figure 2. Vector diagram of flow velocities and forces on a VAWT blade: (a) flow velocities:
(b) blade forces

\[ W = V_\infty + V_i \]  

(1)

\[ V_i = \frac{\omega D}{2} \]  

(2)

\[ W = V \sqrt{1 + 2\lambda \cos \theta + \lambda^2} \]  

(3)

\[ \alpha = \tan \left( \frac{\sin \theta}{\lambda + \cos \theta} \right) \]  

(4)

During a complete revolution, the azimuthal angle changes, which in turn results in a large variation in the angle of attack between positive and negative values. These periodical values, therefore, affect load cycles and create large fatigue loads on the blades on VAWT. Also, while passing through downstream interaction between each blade of VAWT with its own wake, as well as the wake of other blades occurs. This interaction results in fluctuating aerodynamic forces on the blades. The directions of the lift and drag (L and D, respectively) forces with their normal (F_N) and tangential (F_T) components are presented in Figure 2(b). The mathematical relation between these forces can be defined as:

\[ L = F \cdot \cos(\alpha) + F \cdot \sin(\alpha) \]  

(5)

\[ D = F \cdot \sin(\alpha) - F \cdot \cos(\alpha) \]  

(6)

3. Winglet design

Figure 3 describes the parameters that define the geometry of the proposed winglets. The winglet is generated by sweeping the airfoil along the arc and its tangent line. The curvature radius (R) and radian angle (Ω) are equal to the radius and radian of the arc. C_tip is the chord length of the airfoil at the tip of the winglet, and L_tip is the length of the tangent. The airfoil section throughout the winglet is maintained to be the same as that of the blade’s airfoil (NACA 0018) with varying chord length(c). The current study investigates the effects of the curvature radius of the winglet. Based on the research by [8], only winglets bent towards the upstream side have been analyzed as such winglets have better power production.

In this study, five different winglet designs have been computed. The first winglet design consists of a straight winglet with a cant and sweep angles of 75°, the profile’s chord at the winglet tip is
0.5c(C_tip=100 mm), and the winglet height is 5% of the total blade span (h = 40 mm). Three more models with cant angle 75° and different curvature radii are designed. The resulting design matrix is given in Table 1.

| Model | Base model | W1 | W2 | W3 |
|-------|------------|----|----|----|
| Curvature radius (% winglet height) \((R)\) | 0 | 100% | 50% | 12.5% |
| Length of the tangent \((L_{tip})\) | 0 | 0 | 20 mm | 35 mm |

### Table 1. The adopted curvature radius of all models.

#### 4. Methodology

Figure 3(a) illustrates the 3D computational domain of the selected H-type VAWT. The computational domain can be divided into a stationary rectangular outer zone and a cylindrical rotating inner zone. The width of the outer zone is ten times the rotor diameter, while its height is three times the blade span, as shown. For the inner zone, its diameter is impact times the rotor diameter, and its height is 1.5 times the blade span. Inlet and outlet boundary conditions were placed respectively five rotor diameters upwind and 15 rotor diameters downwind of the rotor. The six sides of the outer zone are set as inlet velocity, pressure outlet, and four slip wall condition, as shown in Figure 4(a). The blade surfaces are assigned the non-slip wall condition, and an interface is set on the contact surface of the two sub-domains.

![Figure 4. Mesh setup of computational domain: (a) 3D topology; (b) grids around the blade](image)

The mesh setup is completed in commercial CFD solver STAR-CCM+. Figure 4(b) shows the grids of the computational domain around the turbine blade at mid-plane. The mesh topology consists of unstructured trimmed cells with varied sizes in different zones. The mesh employs prismatic boundary layer cells on the surface of the blades. The prismatic boundary layer consists of 25 0.01 m thick layers with a growth ratio of 1.25 applying the ‘all-\(y^+\)wall treatment.’ The current study employs standard SST \(k-\omega\) turbulence model, which is a hybrid treatment method combining, standard \(k-\varepsilon\) model and standard \(k-\omega\) model. This model is wildly adopted in many CFD studies as it is adaptable to both coarse and fine grids by being able to switch between the two standard turbulence models depending on the zones. All the parameters of the settings mentioned above are kept constant for automatic meshing for each generated model.
5. Validation of the CFD study
In this section, the power coefficient of the simulations is validated with the experimental data for fixed-pitch NACA0018 airfoil for freestream velocity values of 8 m/s of the VAWT by Elkhoury et al. [7]. Figure 4 presents the validation at various TSRs for the velocity of 8 m/s. As observed in Figure 5, the simulation accurately replicates the shape of the experimental curve.

6. Results
6.1 Aerodynamic forces
Here, the forces (tangential and normal) required for calculating the lift ($C_L$) and drag ($C_D$) coefficients were computed from simulations. The coefficients were defined by following appropriate expression [9] rather than standard aerodynamic definitions:

$$C_L = \frac{L}{0.5\rho W^2 A}$$  \hspace{1cm} (7)

$$C_D = \frac{D}{0.5\rho W^2 A}$$  \hspace{1cm} (8)

The study of lift and drag coefficients provide an idea of overall efficiency, and higher values of these coefficients for various values of $\alpha$ would likely enhance the performance of VAWTs [10]. Figure 6(a) and (b) demonstrate the dynamic $C_L$ and $C_D$ versus $\alpha$ for models with varying curvature radii during the last revolution. In the upstream region ($0^\circ \leq \alpha \leq 90^\circ$) of Figure 6(a), the $C_L$ increases while the increase in $C_D$ for the same region is minor, as seen in Figure 6(b). While in the downstream region ($90^\circ \leq \alpha \leq 0^\circ$), it can be observed that the lift coefficient is distinctly reduced while the drag coefficient does not differ. In the upstream region of all the figures ($0^\circ \leq \alpha \leq 90^\circ$), the $C_L$ increases while the increase in $C_D$ for the same region is minor. This implies that the rise in the lift (without a change in drag) produces a tangential force increment and, therefore, higher torque. While in the downstream region ($-90^\circ \leq \alpha \leq 0^\circ$), it can be observed that the lift coefficient is distinctly reduced while the drag coefficient does not differ. So, it is evident from the observation that a decrease in the lift reduces torque generated. It is clear that the curvature radius does affect the lift and drag coefficient, though minutely. On the other hand, the winglet model WM_R12.5% provides a greater lift to drag ratio and, thus, is the optimum curvature radius for the present study.
6.2 Instantaneous pressure distribution

Figure 7 showed that the pressure difference was greatest for the Blade 1 positioned at azimuthal angle 90°. Figure 7 illustrates the pressure distribution on a single blade, blade 1, at azimuthal angle 90° for the base model and winglet model R12.5% over the entire blade surface. The figure shows both the blades have negative pressure at the suction side. In the base model, at the leading edge, a negative pressure of an approximate value of 750 Pa appears, increasing to 0 approximately at the trailing edge. Similarly, on the suction side of the winglet blade, maximum negative pressure of 1000 Pa is observed at the leading edge that increases to 0 at the trailing edge. For both models at the same angle, the change in pressure on the pressure side is relatively smaller, with positive values ranging from 0 to 100 Pa. For the base model (left side), the maximum positive pressure is found near the middle section at the trailing edge and while the other three edges have negative values. For the winglet model (right side), the maximum positive pressure of value 100 Pa can be observed in most parts.

6.3 Velocity field analysis

Figure 8 compares the flow field characteristics of the base model and optimum winglet model, W3 when the azimuthal angle is 90°. In Fig. 7(a), the near-tip of the reference blade of the base model, streamlines easily transfer from the pressure side to the suction side, which results in the smaller
pressure difference between the two sides of the blade. Whereas, in Fig. 8(b) the winglet separates both sides of the blade, obstructing parts of the streamlines to cross the blade tip. This improves the efficiency of the blade by utilizing the pressure difference to generate thrust and thus enhance the power-generating ability of the surface near the blade tip. The figure also presents the flow field on the XZ mid-plane for both models when the azimuthal angle is 90°. The wind originates from the left, so the reference blades on the left (blade 1), are on the downwind section of the turbine. From the figure, it can be seen the downwind blade has the highest approaching velocity at the mid-plane.

![Flow field characteristics](image)

**Figure 8.** Flow field characteristics: (a) base model; (b) W3 model.

7. Conclusions
This paper numerically investigated the effect of the curvature radius of winglets on an H-type VAWT performance. A comparative study was performed to converge to an effective winglet shape that can provide maximum aerodynamic performance when compared to the nonwinglet VAWT. The research shows for the given model at a TSR = 1.0, a there is a direct relationship between the curvature radius and power performance of a winglet. The study concludes the aerodynamic performance of a winglet increases when the curvature radius decreases. The winglet model with the least radius curvature decreases the magnitude of the vortex shedding by increasing the pressure difference between two sides of the blade and therefore improves power performance.
8. References

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Acknowledgments

The financial supports from the National Natural Science Foundation of China (Nos. 51879160, 11772193 and 51679139), Innovation Program of Shanghai Municipal Education Commission (No. 2019-01-07-00-02-E00066), Shanghai Natural Science Foundation (No. 18ZR1418000), and Project of Thousand Youth Talents are acknowledged gratefully. This research is also sponsored in part by Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning (Nos. ZXDF010037, ZXDF010040), Program for Intergovernmental International S&T Cooperation Projects of Shanghai Municipality (No.18290710600), and State Key Laboratory of Ocean Engineering (No. GKZD010075).