The effects of winglet on hawt blade and the optimum ratio between wing and winglet dimensions

Pradeep S Pillai\textsuperscript{1} and A R Harikumar

\textsuperscript{1}Department of Production Engineering, Government Engineering College Thrissur, Kerala, India
\textsuperscript{1}Email:pradeepspillai.sp@gmail.com

Abstract. Government wanted to make India a leading wind power nation. The government offers SOP to private investors to setup wind farms. But the wind flow patterns and the nature of the terrain are not always support to the installation of wind farms. Many stations have little wind to run their windmills. Even if power is generated, companies do not find it profitable to sell to the grid. Induced drag developed by tip vortices stands as a major reason for low power output. This study aims to find the changes in the power generation by wind mills after the addition of winglet to wind turbine blade and also to find an optimum ratio between the span of wing and winglet. The winglet helps to reduce the induced drag. A horizontal axis wind turbine (HWAT) with winglets is proposed. The selection of different airfoil shapes from NACA series was done and blade aerodynamics was simulated to investigate the flow structures and general aerodynamic coefficients are extracted using ANSYS software. A comparison of aerodynamic performance of different airfoil geometries is done to find a suitable airfoil shape based on L/D characteristics. 3D model analysis of blade from selected airfoil cross section, with and without winglet is carried out using ANSYS Fluent and the aerodynamic performance is compared to study the effectiveness of the winglet. It is found that the blade with winglet gives an L/D ratio of 13.8 compared to the one without winglet, 8.8, for a 3m wing span. The study then continued with the wing span of 5m and 7m. The study also extends to find an optimum ratio between wing and winglet.

1. Introduction
The increase in demand for power, results in huge need for renewable energy. Among various renewable energy sources, electricity from wind power grows to be the most essential. It is anticipated to help the global electricity by using greater than 20% through 2030. Wind power is converted into electricity using wind turbines. Madhu Nair \cite{2} discusses the potential of wind power, in Kerala, the need for it, challenges involved in harnessing. The wind energy harvesting potential of selected areas in Kerala is also compared. Mohammad et al. \cite{3} conducted a Feasibility study of wind turbine for low wind condition of Bangladesh. Darrieus vertical type three blade wind turbine has been chosen to investigate its performance in rural areas. Computational results of a CFD model for viscous free surface flow around NACA 0012 and NACA 0015. The results give a clear view about how much power can be extracted from this vertical type three blade Darrieus wind turbine. Ajayi et al. \cite{4} have done a research in the field of wind turbine rotor design. The study designed and analysed a new airfoil for use in a small horizontal axis wind turbine, it showed a better performance with good glide ratio over longer angle range, chord distribution and blade twist among other things. N. Manikandan and B. Stalin \cite{5} focused on increasing the reliability of wind turbines through the development of the airfoil structure and also to reduce the noise produced during the running period of the wind turbine.
blades. In this paper, Pro/E, software has been used to design blades effectively. NACA 63-215 airfoil profile is considered for analysis of wind turbine blade. Peter J. Schubel and Richard J. Crossley [6] presented a review of wind turbine design. A comprehensive look at blade design has shown that an efficient blade shape is defined by aerodynamic calculations based on chosen parameters and the performance of the selected airfoils. Mayurkumar Kevadiya et al. [10] did a study on designing the blade for regions of low wind power density and the NACA 4412 airfoil profile is considered and a CFD analysis is done at various angle of attack. Mina G. Mourad et al [11] studied the effect of winglet height (H) and toe angle (αw) on the turbine performance and the selected airfoil is SD8000, ANSYS 17.2 software is used.

The main factors which depend on the performance of a wind turbine are wind speed, turbine blade geometry and aerodynamic forces. The aerodynamic forces developed are resolved into lift (L) and drag (D) forces [1]. The ratio between the lift force and drag force is the measure of aerodynamic efficiency. The airflow around the wind turbine also creates blade tip vortices due to air pressure differences. The fast moving air mixed with slow speed air around turbine blade causes difference in air pressure. Generation of tip vortices inversely affect the aerodynamic efficiency of the wind turbine. The addition of winglet will reduce wing tip vortices and its associated induced drag. 3D blade structure is developed from the selected airfoil. Wind turbines overall performance is investigated by comparing the aerodynamic efficiencies of blades with and without winglet using ANSYS Fluent. The reduction in induced drag after the addition of winglet will result in improved aerodynamic efficiency of the blade. This study then expands to find the optimum ratio between the wing span and winglet span.

2. ANSYS Testing

2.1 Airfoil Selection

The airfoil identification is the primary step in designing a HWAT wind turbine blade. The general requirement for airfoil designs is high lift to drag ratio. Increasing the lift coefficient increases thrust, which would result reducing the drag coefficient, and increases higher aerodynamic efficiency [1]. Three airfoils were selected with the help of literature surveys from NACA series that suits the low wind conditions. The airfoil tools provide only the x and y coordinates. The curve point, coordinate points and the z coordinates are generated using MS Excel. These points are converted to import ready ANSYS 3D Design Modeler format with the aid of text document. The lift and drag calculation is carried out using Fluent.

![Figure 1. Plot between α and C_L / C_D](image-url)
The results of ANSYS 2D simulation show that, the NACA- 4412 is the best candidate based on the evaluation of the maximum aerodynamic efficiency. The curve indicates that L /D is maximum at angle of attack \( \alpha = 5^\circ \) and its coefficients values are \( C_L=1.0849, \ C_D=0.02241 \) and L/D = 48.3862 (figure 2). The lift to drag ratio (L/D) is the amount of lift generated by the blade compared to drag produced. L/D is the most important parameter affecting the aerodynamic performance. It is the direct measure of aerodynamic efficiency. It is determined by dividing the lift coefficient \( (C_L) \) by the coefficient of drag \( (C_D) \). It varies with changes in Angle of Attack (AOA).

2.2 Aerodynamic efficiency of 3D blade

2.2.1 Blade without winglet. The 3D modelling of NACA 4412 is done using design modeler. Wing span is taken as 3m. The angle of attack is found efficient at 5\(^\circ\) of angle.

![Figure 2. 3D modelling of blade](image1)
![Figure 3. Domain creation](image2)
Domain generation is one of the crucial step in analyzing 3D blade because the domain represents same atmosphere of the identified site for the wind farm. According to theory, the domain should be designed as 10 times the size as that of the wing span because for an external flow problem, the flow domain should be as large as possible. To run a simulation on an airfoil, the boundaries should be placed at a sizable distance so that it does not see the effect of wall and can apply far-field boundary condition on the model. In this project, wing span is designed with 3m, hence the domain is 30m. Meshing is an important factor in the analysis of any wing, mesh size influence the result. All three mesh qualities were tried and by using the fine meshing the results are found to be more appropriate (Figure 5).

K-epsilon turbulence model is used, it is the most common model used in Computational Fluid Dynamics (CFD) to simulate mean flow characteristics for turbulent flow conditions. It is a two-equation model that gives a general description of turbulence by means of two transport equations. K-epsilon model predicts wall far from the boundaries (wall). The SST model is also used. The aerodynamic efficiency of 3D blade design from NACA 4412 airfoil profile is found as 8.8429.

| ID | Parameter Name | Value | Unit |
|----|----------------|-------|------|
| 1  | A0 | AoA | 4 | degree |
| 8  | P2 | lift | 11.427 | N |
| 9  | P3 | drag | 1.0337 | N |
| 10 | P4 | CL | 1.0576 | N |
| 11 | P5 | CD | 0.11959 | N |
| 12 | P6 | CL/CD | 8.8429 | |

Figure 4. Meshing

Figure 5. Aerodynamic efficiency of blade
2.2.2 Blade with winglet. Winglet (WL) is a small device added to blade tip and it can be constructed from the same airfoil used in the blade or other airfoil. The WL geometry diverges the blade tip vortices away from turbine blades and reduces induced drag. This experiment focuses on the aerodynamic efficiency of blade after adding winglet. The optimum winglet height \( H \) and cant angle is also determined.

![Figure 6. Blade designed with winglet](image_url)

Blade with winglet is designed and analysed using ANSYS design modeller. The cant angle from 1° to 90° and winglet span from 0.1m to 1.5m is tested with its aerodynamic efficiency to determine the optimum values.

![Figure 7. Meshing](image_url)
The aerodynamic forces are resolved into lift and drag along y and x direction respectively. Using ANSYS the values of lift force (figure 9) and drag force (figure 10) were calculated.

**Figure 8. Lift Calculation**

**Figure 9. Drag calculation**

### 2.3 Optimum cant angle

The best cant angle that gives the optimum aerodynamic efficiency is found as $50^\circ$ (Table 1) after the trails run in ANSYS Fluent from $0^\circ$ to $90^\circ$. 
Table 1. Cant angle

| Winglet Angle | Lift N | Drag N | CL N | CD N | CL/CD |
|---------------|-------|-------|------|------|-------|
| 10            | 10.2871 | 0.8513 | 0.9521 | 0.0788 | 12.0845 |
| 20            | 11.4205 | 0.9941 | 1.057 | 0.092 | 11.4887 |
| 30            | 11.9539 | 1.0974 | 1.1064 | 0.1016 | 10.893 |
| 40            | 12.6874 | 1.2321 | 1.1743 | 0.114 | 10.2972 |
| 45            | 12.9657 | 1.1306 | 1.2 | 0.1046 | 11.4682 |
| 48            | 14.2208 | 1.0181 | 1.3162 | 0.0942 | 13.9681 |
| 49            | 12.9002 | 1.1271 | 1.194 | 0.1043 | 11.4452 |
| 50            | 13.139 | 0.939 | 1.2161 | 0.0869 | 13.9925 |
| 55            | 14.2613 | 1.0235 | 0.0947 | 1.3199 | 13.9345 |
| 60            | 14.0923 | 1.0213 | 0.0945 | 1.3043 | 13.7987 |
| 65            | 14.3715 | 1.3301 | 1.0612 | 0.0982 | 13.5426 |
| 70            | 13.5424 | 1.0965 | 1.2534 | 0.1015 | 12.351 |
| 80            | 14.4939 | 1.8314 | 1.3415 | 0.1695 | 7.9141 |
| 90            | 14.9455 | 2.0422 | 1.3833 | 0.189 | 7.3183 |

2.4 Optimum winglet span

The optimum winglet span is found at 0.8m with L/D value 13.84. (Table 2). An increase in the aerodynamic efficiency can be seen after the winglet addition.

Table 2. Winglet span for 3m Wing

| Winglet m | Wing m | Drag N | Lift N | C_D | C_L | C_L/C_D | Wing : Winglet |
|-----------|--------|--------|--------|-----|-----|---------|----------------|
| 0.1       | 3      | 1.148  | 14.9102 | 0.1063 | 1.38 | 12.9876 | 30              |
| 0.2       | 3      | 1.1533 | 15.1579 | 0.1067 | 1.4029 | 13.1434 | 15              |
| 0.3       | 3      | 1.1736 | 15.6146 | 0.1086 | 1.4452 | 13.3049 | 10              |
| 0.5       | 3      | 1.2051 | 16.296 | 0.1115 | 1.5083 | 13.5224 | 6               |
| 0.6       | 3      | 1.2118 | 16.4905 | 0.1122 | 1.5263 | 13.6086 | 5               |
| 0.7       | 3      | 1.2259 | 16.7652 | 0.1135 | 1.5517 | 13.6754 | 4.2857          |
| 0.8       | 3      | 1.2308 | 17.0418 | 0.1139 | 1.5773 | 13.8458 | 3.75            |
| 0.9       | 3      | 1.2573 | 17.3737 | 0.1164 | 1.608 | 13.8179 | 3.3333          |
| 1         | 3      | 1.2617 | 17.54 | 0.1168 | 1.6234 | 13.0155 | 3               |
| 1.3       | 3      | 1.2895 | 18.2557 | 0.1194 | 1.6896 | 12.1569 | 2.3076          |
| 1.4       | 3      | 1.2936 | 18.27 | 0.1197 | 1.691 | 12.1232 | 2.1428          |
| 1.5       | 3      | 1.3234 | 18.7724 | 0.1225 | 1.7375 | 12.1854 | 2               |
**Table 3. Winglet span for 5m Wing**

| Winglet m | Wing m | Drag N | Lift N | C_D  | C_L   | C_L/C_D | Winglet |
|-----------|--------|--------|--------|------|-------|---------|---------|
| 0.1       | 5      | 1.76388| 27.7114| 0.1633 | 2.5648 | 15.7105 | 50      |
| 0.2       | 5      | 1.76839| 28.0927| 0.1637 | 2.6001 | 15.886 | 25      |
| 0.3       | 5      | 1.79589| 28.567 | 0.1662 | 2.644  | 15.9069 | 16.6667 |
| 0.4       | 5      | 1.80649| 28.8543| 0.1672 | 2.6706 | 15.9726 | 12.5    |
| 0.5       | 5      | 1.82335| 29.0991| 0.1688 | 2.6932 | 15.9591 | 10      |
| 0.6       | 5      | 1.83033| 29.4781| 0.1694 | 2.7283 | 16.1053 | 8.3333  |
| 0.7       | 5      | 1.83281| 29.6297| 0.1696 | 2.7424 | 16.1663 | 7.1429  |
| 0.8       | 5      | 1.84582| 29.7305| 0.1708 | 2.7517 | 16.1069 | 6.25    |
| 0.9       | 5      | 1.86174| 30.2191| 0.1723 | 2.7969 | 16.2316 | 5.5556  |
| 1         | 5      | 1.86239| 30.0863| 0.1724 | 2.7846 | 16.1547 | 5       |
| 1.1       | 5      | 1.88246| 30.6131| 0.1742 | 2.8334 | 16.2623 | 4.5455  |
| 1.2       | 5      | 1.88595| 30.9004| 0.1746 | 2.86   | 16.8453 | 4.1667  |
| 1.3       | 5      | 1.89138| 31.1033| 0.1751 | 2.8787 | 16.9445 | 3.8462  |
| 1.4       | 5      | 1.90066| 31.2786| 0.1759 | 2.895  | 16.4567 | 3.5714  |
| 1.5       | 5      | 1.91199| 31.3854| 0.177  | 2.9048 | 16.415  | 3.3333  |
| 1.6       | 5      | 1.94068| 32.0228| 0.1796 | 2.9638 | 16.5008 | 2.9412  |
| 1.8       | 5      | 1.95718| 32.3455| 0.1811 | 2.9937 | 16.5266 | 2.7778  |
| 1.9       | 5      | 1.97631| 32.3041| 0.1829 | 2.9899 | 16.3457 | 2.6316  |
| 2         | 5      | 1.98906| 32.697 | 0.1841 | 3.0262 | 16.4384 | 2.5     |
| 2.1       | 5      | 1.99926| 32.9368| 0.185  | 3.0484 | 16.4745 | 2.381   |
| 2.2       | 5      | 2.02553| 33.2582| 0.1875 | 3.0782 | 16.4195 | 2.2727  |
| 2.3       | 5      | 2.02598| 33.3429| 0.1875 | 3.086  | 16.4577 | 2.1739  |

*Figure 10. Graph between winglet span and L/D*
Similarly for the wing with span of 5m and 7m also the aerodynamic efficiency changes after the installation of winglet and the highest value of aerodynamic efficiency is noted at 1.3m of winglet for a 5m wing and 1.8m for a 7m wing.

![Graph between winglet span and L/D of 5m wing](image1)

Figure 11. Graph between winglet span and L/D of 5m wing

| Winglet Wing | Drag | Lift | C_D | C_L | C_L/C_D | Wing : Winglet |
|--------------|------|------|-----|-----|---------|----------------|
| m            | N    | N    |     |     |         | Winglet        |
| 0.1          | 7    | 2.34103 | 41.0248 | 0.2167 | 3.797 | 17.5243 | 70 |
| 0.2          | 7    | 2.33699 | 41.3498 | 0.2163 | 3.8271 | 17.6936 | 35 |
| 0.3          | 7    | 2.35336 | 41.3982 | 0.2178 | 3.8316 | 17.5911 | 23.333 |
| 0.4          | 7    | 2.36989 | 41.7802 | 0.2193 | 3.8669 | 17.6296 | 17.5 |
| 0.5          | 7    | 2.40373 | 42.4291 | 0.2225 | 3.927 | 17.6514 | 14 |
| 0.6          | 7    | 2.4069 | 42.639 | 0.2228 | 3.9464 | 17.7153 | 11.6667 |
| 0.7          | 7    | 2.43256 | 42.9805 | 0.2251 | 3.978 | 17.6688 | 10 |
| 0.8          | 7    | 2.43682 | 43.1864 | 0.2255 | 3.9971 | 17.7224 | 8.75 |
| 0.9          | 7    | 2.40836 | 43.0688 | 0.2229 | 3.9862 | 17.883 | 7.7778 |
| 1            | 7    | 2.44344 | 43.6132 | 0.2262 | 4.0366 | 17.8491 | 7 |
| 1.1          | 7    | 2.45226 | 43.5393 | 0.227 | 4.0297 | 17.7548 | 6.3636 |
| 1.2          | 7    | 2.47625 | 44.1185 | 0.2292 | 4.0833 | 17.8167 | 5.8333 |
| 1.3          | 7    | 2.46519 | 44.2576 | 0.2282 | 4.0962 | 17.953 | 5.3846 |
| 1.4          | 7    | 2.4915 | 44.4474 | 0.2306 | 4.1138 | 17.6396 | 5 |
| 1.5          | 7    | 2.49163 | 44.695 | 0.2306 | 4.1367 | 17.7381 | 4.6667 |
| 1.6          | 7    | 2.53768 | 45.0907 | 0.2349 | 4.1733 | 17.7685 | 4.1176 |
| 1.8          | 7    | 2.51926 | 45.3621 | 0.2332 | 4.1984 | 18.4061 | 3.8889 |
| 1.9          | 7    | 2.54685 | 45.6196 | 0.2357 | 4.2223 | 17.7122 | 3.6842 |
| 2            | 7    | 2.56074 | 45.8786 | 0.237 | 4.2462 | 17.6161 | 3.5 |
| 2.1          | 7    | 2.56517 | 45.8081 | 0.2374 | 4.2397 | 17.8577 | 3.3333 |
| 2.2          | 7    | 2.58521 | 46.4896 | 0.2393 | 4.3028 | 17.9829 | 3.1818 |
| 2.3          | 7    | 2.56952 | 46.3047 | 0.2378 | 4.2857 | 17.8208 | 3.0435 |
| Winglet Span (m) | L/D Value (m) | Drag Coefficient | Lift Coefficient | L/D Ratio | Span Efficiency |
|------------------|--------------|------------------|------------------|-----------|-----------------|
| 2.4              | 7            | 2.60105          | 46.7853          | 0.2407    | 4.3302          | 17.9871          | 2.9167          |
| 2.5              | 7            | 2.6473           | 47.2901          | 0.245     | 4.3769          | 17.8635          | 2.8             |
| 2.6              | 7            | 2.64149          | 47.3228          | 0.2445    | 4.3799          | 17.9152          | 2.6923          |
| 2.7              | 7            | 2.62548          | 47.1856          | 0.243     | 4.3672          | 17.9722          | 2.5926          |
| 2.8              | 7            | 2.65351          | 47.5331          | 0.2456    | 4.3994          | 17.9133          | 2.5             |
| 2.9              | 7            | 2.66322          | 47.7773          | 0.2465    | 4.422           | 17.9397          | 2.4138          |
| 3                | 7            | 2.67821          | 47.7778          | 0.2479    | 4.422           | 17.8395          | 2.3333          |
| 3.1              | 7            | 2.70386          | 48.3455          | 0.2503    | 4.4746          | 17.8802          | 2.2581          |
| 3.2              | 7            | 2.69801          | 48.3986          | 0.2497    | 4.4795          | 17.9386          | 2.1875          |
| 3.3              | 7            | 2.73436          | 48.6638          | 0.2531    | 4.504           | 17.7971          | 2.1212          |
| 3.4              | 7            | 2.73124          | 49.0739          | 0.2528    | 4.542           | 17.9676          | 2.0588          |

**Figure 12.** Graph between winglet span and L/D of 7m wing

**Figure 13.** Graph between all winglet and L/D
Figure 14 shows the graph between the wing to winglet ratio against the aerodynamic efficiency. From the graph it is clear that, around a wing to winglet ratio of 3.8 the maximum aerodynamic efficiency is obtained for different wing span and winglet dimensions studied.

3. Result
The study begins with the selection of airfoil that suits the collected wind data. The selection of airfoil is done by comparing the L/D ratio of different airfoil from NACA series and NACA 4412 with L/D value of 48.3862 is found as the best airfoil. The 3D model of NACA 4412 and aerodynamic characteristics analysis with the aid of ANSYS Fluent is conducted. The 3D blade was successfully designed and its aerodynamic efficiency is found as 8.84. The variations in the aerodynamic characteristics of the blade with and without the addition of winglet to its wing tip is studied. After the successful addition of winglet, analysis was expanded with different cant angles and different winglet dimension to find the optimum cant angle. After the addition of winglet an improvement in the aerodynamic efficiency from 8.84 to 13.84 is found with an optimum cant angle of 50° and winglet span of 0.8m. Finally the experiment focus on the optimum ratio between the wing and winglet after the addition of winglet to the blade tip. It is found that for a wing span of 3m the maximum aerodynamic efficiency was found at 0.8m span of wing and at 1.3m and 1.8m winglet span for 5m and 7m wing respectively.

4. Conclusion
The problem associated with the development of wind farms was the low output and low return of investment. While considering the reason we found that the tip vortex generate induced drag which causes reduction in the aerodynamic efficiency. The addition of winglet causes a reduction in tip vortex, hence the amount of energy to overcome the tip vortex can also be converted to useful energy which influence the increase in the aerodynamic efficiency. A study is also conducted to find an optimum ratio between the wing and winglet to benefit turbine blade design with winglet. It is found that a ratio of 3.8 should be maintained so as to obtain the maximum aerodynamic efficiency.

In this project a comprehensive experimental study is done on the aerodynamic efficiency by modifying the blade by adding winglet. As part of future work experimental research can be conducted using wind tunnel to validate the above findings. Also this project dealt with the only one airfoil cross section, it can be tested by different airfoils considering its twist properties and by different winglets also a full model CFD analysis with 3 blades connected to a central hub HAWT turbine model can be conducted. Tip vortices which influence most part of noise generation from a wind turbine. An
experimental research on the noise sources and its reduction method can also be done. As the winglet shape varies, there can be changes in tip vortices and its associated noise.

References

[1] Mamadaminov U M 2013 Review of airfoil structures for wind turbine blades Oregon Institute of Technology
[2] Madhu Nair 2012 Report on Wind Energy in Kerala Akshay Urja Volume 6 Issue 2
[3] Mohammad Adom Safiullah, Muhammad Rubayat Bin Shahadat and Md. Raf E Ul Shougat 2016 Feasibility study of wind turbine for low wind condition of Bangladesh International Conference on Mechanical, Industrial and Energy Engineering
[4] Ajayi O O, Okeowo O, Aasa S A, Aboyade A and Willoughby A A 2015 Novel Airfoil Design for Small Horizontal Axis Wind Turbine: A Preliminary Result Third Southern African Solar Energy Conference181-186
[5] Manikandan N, Stalin B 2013 Design of Naca63215 Airfoil for a Wind Turbine IOSR Journal of Mechanical and Civil Engineering 10 (2) 18-26
[6] Schubel P J and Crossley R J 2012 Wind turbine blade design Energies 5(9) 3425-3449.
[7] A report of Micro, Small & Medium Enterprises- DI Baiss Goddam Industrial Estate Jaipur on the Setting up of wind power plant 2010.
[8] European Union Report on the feasibility study for offshore wind farm development in TamilNadu 2018
[9] Kurtulmus F, Vardar A and Izli N 2007 Aerodynamic analyses of different wind turbine blade profiles Journal of applied sciences 7(5) 663-670
[10] Kevadiya M and Vaidya H A 2013 2D analysis of NACA 4412 airfoil. International Journal of Innovative Research in Science Engineering and Technology 2(5) 1686-1691
[11] Mourad M G, Shahin I, Ayad S S, Abdellatif O E and Mekhail T A 2020 Effect of winglet geometry on horizontal axis wind turbine performance Engineering Reports 2(1) 1–19
[12] Ning Z and Yang Z 2013 An experimental investigation on the control of tip vortices from wind turbine blade 51st AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition 1104
[13] Prabhu Kishore N and Ravi S 2016 Performance Analysis of Winglet at Different Angle of Attack International Research Journal of Engineering and Technology 771–774