International Journal of Engineering & Technology, 7 (4.5) (2018) 450-454

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Numerical Investigation on Effect of Multiple Winglets for Wind Turbine Applications

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Abstract

The present article is an effort to examine the potential of multiple winglets to reduce the induced drag of the aerodynamic surface. The advantages of using multiple winglets include reduction of induced drag, increased L/D and improved performance of the Wind turbine. Computational Fluid Dynamics is utilized as to approach the effects of multiple winglets with NACA 24012 airfoil section for untwisted, rectangular wing. The testing of configurations is done at Reynolds number 290,000. FLUENT solver incorporated in ANSYS used for the numerical investigation of the steady flow over the wing. A substantial improvement in lift curve slope occurs with dihedral spread of the winglets. The dihedral spread also distributes the tip vortices.

Keywords: *Wind Turbine, Winglets, Induced Drag, Computational Fluid Dynamics*.

1. Introduction

Clean Energy has a significant role in renewable energy sources, determining the quality of the output produced. Many private sectors and public entities like government agencies and educational institutions are nowadays looking for clean, renewable energy sources to meet their clean and sustainable energy solution needs. The motivation can be financial needs, driven by regulatory mandates and desire to be more socially responsible. Sustainable energy solutions are literally found in the air, deep underground and in our oceans. Each of the following can be tapped directly or indirectly by organizations striving for "Go Green" concepts. Harnessing wind to create power is one of the elements of clean energy and the fastest growing technology throughout the world. Wind flow can be captured by turbines and converted into electricity as clean energy. The flow over a finite wing is different from that of flow over a wind turbine blade. This is because flow over an airfoil is two-dimensional. In contrast, finite wing is a three-dimensional body; that is, there is a component of flow in the span-wise direction. The physical mechanism for generating lift on the wing is the existence of a high pressure on the bottom surface and a low pressure on the top surface. The net imbalance creates the lift on the wing. The method of reducing the drag [1] [2] and the experimental procedure are proposed [3].

2. Induced Drag

The wing-tip vortices downstream of the wing induce a small downward component of air velocity in the neighbourhood of the wing itself. These two vortices tend to drag that causes flow separation the surrounding air around with them, and this secondary movement induces a small velocity component in the downward direction of the wing. This downward component is called downwash. In turn, the downwash combines with the free stream velocity V_∞.

Table 1:.Aerodynamic impacts on effect due to winglets

Aerodynamic Impact	***Effect due to winglets***
Fuel	L/D improvement by 15-20 %
Range, high/low speed	Improved range by 20-25%
Speed flexibility	Possible higher cruising speeds, Steeper landings due to grid aerodynamics
Smoother ride	Smoother ride due to higher wing loading
Installed thrust, Smaller wake energy	Less thrust needed due to higher L/D, Less vortex induced impacts near airports
Fuel	Emission reduction due to less thrust

The presence of downwash and its effect on local relative wind in the downward direction has two important effects are the angle of attack actually seen by the local airfoil section is the angle between the chord line and the local relative wind and the local lift vector is aligned perpendicular to the local relative wind, and hence is inclined behind the vertical by the angle.
Wright biplane concepts are especially attractive. However, Gall and Smith [5] demonstrated that the addition of single winglets onto the biplanes added a 13% improvement in endurance, as well as increasing the lift-curve slope and the maximum lift coefficient of the vehicle.

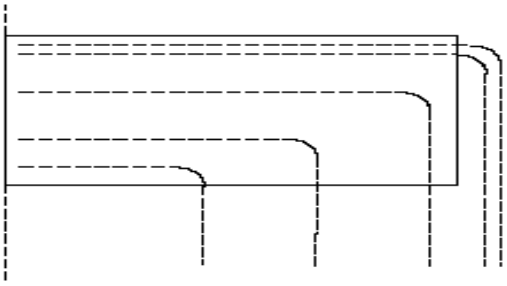


Fig.1: Planar rectangular wing without wingtip-device

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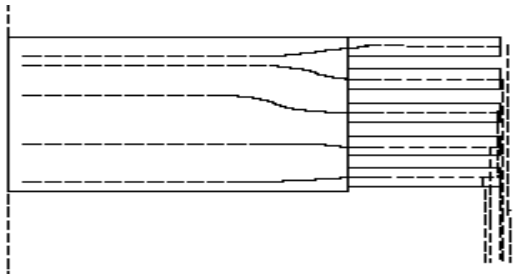


Fig.2: Planar rectangular wing with wingtip-device

Ruhlin, Bhatia, and Nagaraja [7] investigated that the addition of a winglet substantially reduced the flutter speed of the wing. In addition, the effect of sideslip[8] on winglets is to produce increased loads analogous to wing loads caused by angle of attack. Satran [9] investigated the static and dynamic stability and control and free-flight behavior.

The blended winglet [10] reduces drag by eliminating the discontinuity between the wing tip and the winglet. The first industry application of the winglet concept was in sailplanes. Colling [12] gives an excellent review of winglets for sailplanes. Marchman, Manor, and Faery[13] noticed that symmetric winglets are suitable for general aviation aircraft, but were less effective on tapered wings. Robert Jones[14] described the advantages of single winglets for small transports, on which they can provide 10% reduction in induced drag compared with elliptical wings. Winglets are being incorporated into most new transports[15], the Boeing and McDonnell Douglas airliners, and the McDonnell Douglas military transport.[16] The induced drag of a non-planar system can be lower than that of a planar system of the same lift and span. Imamura [17] analyzed the application of winglets to conventional wind turbines. They found that a small winglet installation angle causes a large increase in the power coefficient but a small increase in the flatwise bending moment compared with the blades with radially extended winglets. Rechenberg [18] describes a concentrator principle for wind turbines, which is used by birds with split wing ends.

The split-tip design (19) by Heinz Klug for aerospace can be considered a primitive multiple winglet. It was created to exploit the non-planar wake geometry by reducing induced drag and wing stress. Vance Tucker, a biologist with an aerodynamics background, demonstrated that the tip slots of soaring birds reduce induced drag and increase the span factor of the wings [20]. The evolutionary theory has been emulated in an aircraft optimization algorithm developed by Kroo and Takai [21], which has "discovered" a C-wing configuration with a winglet and a horizontal extension that shows reduced drag for fixed lift, span, and height. Jonathan Santos anticipated the innovation in the current proposal in his patent on wing-tip airfoils [22].

At the Cranfield Institute of Technology in England, J. J. Spillman [23] carried out a series of programs to investigate devices akin to the wing tip airfoils, which he called "wing tip sails". This effort examined the basic principles of multi-winglets. The multi-winglet design was evaluated to demonstrate its advanced performance potential over the baseline wing and an equivalent single winglet.

In the present work, first of all we have analyzed the effect of number of winglets required to reduce the induced drag. We computed flow over the wing with different configurations of winglet angles. We took a benchmark test velocity as 25 m/s. The two configurations of models are wing with winglets with 5° decrement in dihedral angle (10º,5º,0º,-5º) and wing with winglets with 10° decrement in dihedral angle; that is, (20°, 10°, 0°, -10°). Flow parameters like lift and drag have been calculated for all angle of attack of the test cases. Numerical results have been compared to the experimentally reported results from the literatures.

2.1. Computational Modeling of Fluid Flow

Computational Fluid Dynamics is a computer-based mathematical modeling tool that incorporates the solution of the fundamental equations of fluid flow, the Euler equations, and other allied equations. CFD incorporates empirical models for modeling turbulence based on experimentation, as well as the solution of heat, mass and other transport and field equations. This technique is very powerful and spans a wide range of industrial and non industrial applications. FLUENT is the CFD solver of choice for complex flows providing optimum convergence and accuracy for a wide range of fluid regimes. Either structured or solution-adaptive unstructured mesh can be used. Boundary conditions are specified. CFD is now a widely accepted and validated engineering tool for industrial applications.

The equation for mass conservation or continuity equation for viscous flow is given by

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho V) = 0 \tag{1}$$

∇ operator is given by

$$\nabla = \frac{\partial}{\partial x} i + \frac{\partial}{\partial y} j + \frac{\partial}{\partial z} k \tag{2}$$

The equation for the Newton's second law or momentum equations for viscous flow are given by

$$\begin{aligned}
\frac{\partial(\rho u)}{\partial t} + \nabla.(\rho u V) &= -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \\
\frac{\partial(\rho v)}{\partial t} + \nabla.(\rho v V) &= -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho f_y \\
\frac{\partial(\rho w)}{\partial t} + \nabla.(\rho w V) &= -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z
\end{aligned} \tag{3}$$

3. Numerical Results

In order to ensure that the numerical stimulation of steady flow over a wing and wing with multiple winglets at different orientations using FLUENT are properly carried out, a few benchmark test cases for validation were simulated first.

3.1 Test Cases

- Inviscid flow over a wing with multiple winglets (10º,5º,0º,-5ºDihedral) Re = 290,000
- Inviscid flow over a wing with multiple winglets (20º, 10º, 0º,-10ºDihedral) Re = 290,000
- For the numerical stimulation of flow over wing at velocity (V=25m/s), a commercial package FLUENT incorporated in ANSYS 13.0 has been used to solve the basic governing equations for velocities and other quantities. The equations were discretized using the finite volume method on a collocated grid in fully implicit form. Second order upwind scheme is used for solving convective terms and central differencing scheme is adopted for solving diffusion terms. The second order implicit scheme was used for time integration of each equation. Semi-Implicit Method for Pressure-Linked (SIMPLE)algorithm was used for coupling the pressure and velocity terms
- The schematic representation of the computational domain is shown in Fig 4 and Fig 8. Structured grid in Cartesian coordinates is chosen, where x-axis is along the

free stream direction, y-axis is in the vertical direction, z-axis is in the span wise direction. Two grid arrangements of size 45,220 and 65,997 cells were tested for grid independency. Results are presented for the 45,220 grid size. The solution is started and allowed to converging and attains periodic nature. The flow over a wing for Reynolds number 290,000 is computed and incorporated in ANSYS 13.0 produced wing tip vortices.

3.2 Inviscid Flow over A Wing with Multiple Winglets (10º, 5º, 0º,-5º Dihedral)

For the numerical stimulation of inviscid flow over a wing with multiple winglets (10º, 5º, 0º, -5º dihedral) at Reynolds number (Re=290,000), the same schemes taken for the flow over a wing are given. The schematic representation of the computational domain is shown in Fig 3 Structured grid in Cartesian coordinates is chosen, where x-axis is along the free stream direction, y-axis is in the vertical direction, z-axis is in the span-wise direction. A grid arrangement of size 46,604 and 68,250 was tested. Results obtained using this grid matched excellently with the existing numerical results computed by various researchers. The solution is started and allowed to converging and attains periodic nature.

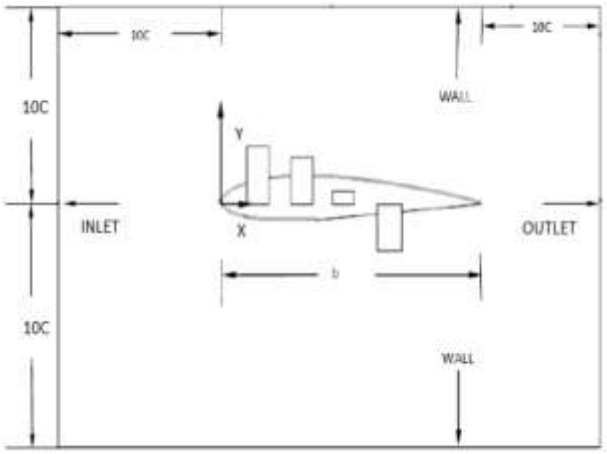


Fig. 3:: Computational Domain For Flow Over A Wing With Winglets

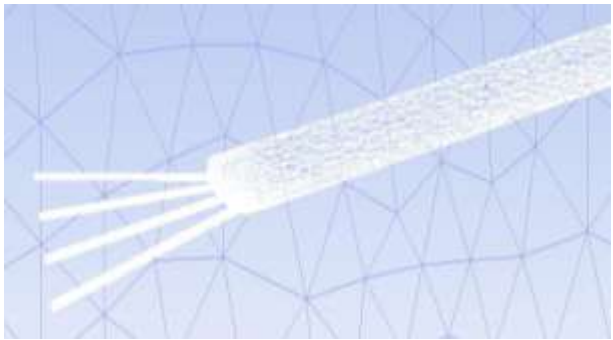


Fig. 4: Computational mesh for flow over a wing with 4 winglets (0º, 0º, 0º, 0º, 0º Dihedral)

The steady flow over a wing with multiple winglets at (10º, 5º, 0º, -5ºdihedral) computed using FLUENT 6.0 produced wing tip vortices. The winglets distribute the wing tip vortices which in turn reduce the induced drag of the wing. The variation of lift as a function of angle of attack, the multiple winglets value compared with the wing is shown in Fig 5. Static pressure versus position of the wing with winglets shown in the Figure-6 . The values of the coefficient of lift and coefficient of drag obtained by the present computation are presented in the Table 2.

Table 2:. Cland Cd values at different angle of attack in wing with 4 winglets (10º, 5º, 0º,-5º dihedral)

Different Angle Of Attacks	Coefficient of lift(C_l)	Coefficient of drag(C_d)
0	0.031	0.0002
2	0.05	0.0005
4	0.069	0.0009
6	0.088	0.0014
8	0.098	0.002
10	0.1	0.0024

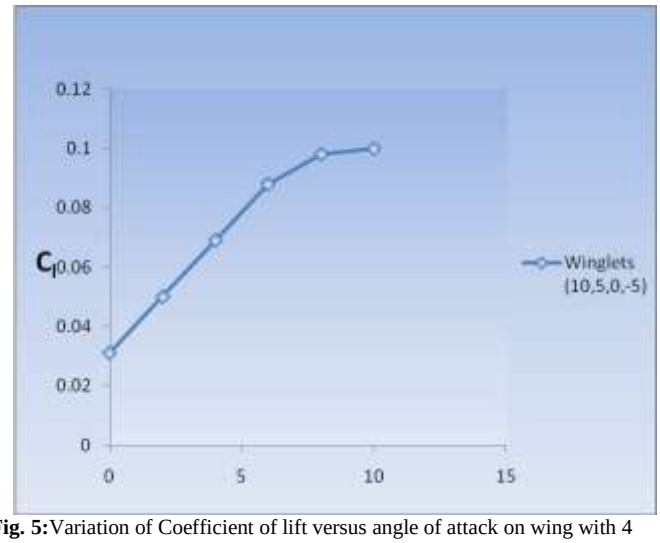


Fig. 5: Variation of Coefficient of lift versus angle of attack on wing with 4 winglets(10º,5º,0º,-5º dihedral)

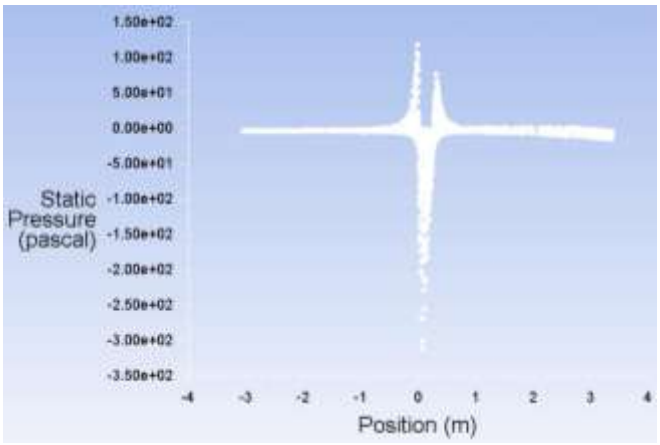


Fig. 6: Static pressure versus position of the wing with multiple winglets (10º, 5º, 0º, -5º dihedral)

3.3 Inviscid Flow Over A Wing With Multiple Winglets (20º, 10º,0º,-10º,-20º Dihedral)

For the numerical stimulation of flow over a wing with multiple winglets (20º, 10º, 0º, -10ºDihedral) at Reynolds number (Re=290,000), the same schemes taken for the flow over a wing and wing with multiple winglets(20º, 10º, 0º, -10ºdihedral) are given.

The schematic representation of the computational domain is shown in Fig 7 Structured grid in Cartesian coordinates is chosen, where x-axis is along the free stream direction, y-axis is in the vertical direction, z-axis is in the spanwise direction illustrated in Fig 8. A grid arrangement of size 45,763 and 67,970 was tested. Results obtained using this grid matched excellently with the existing numerical results computed by various researchers. The solution is started and allowed to converging and attains periodic nature.

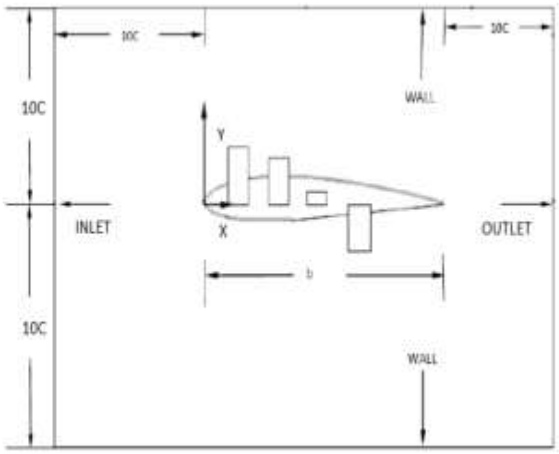


Fig. 7: Computational Domain For Flow Over A Wing With Winglets



Fig. 8: Computational mesh for flow over a wing with 4 winglets (20º, 10º, 0º, -10ºDihedral)

The flow over a wing for Reynolds number 290,000 is computed using FLUENT solver incorporated in ANSYS 13 produced distributed wing tip vortices because of dihedral spread of winglets. Static pressures versus position on wing with multiple winglets (dihedral spread) were shown in the Fig 10. The values of the coefficient of lift, coefficient of drag and Coefficient of Pressure obtained by the present computation are 0.0581, 0.002, and 0.5 respectively.

Table 3:. $C_l$and C_d values at different angle of attack in wing with 5 winglets (20º, 10º,0º,-10º dihedral)

Different Angle Of Attacks	Coefficient of lift(C_l)	Coefficient of drag(C_d)
0	0.0581	0.002
2	0.071	0.002
4	0.08	0.002
6	0.099	0.0010
8	0.114	0.0011
10	0.128	0.002

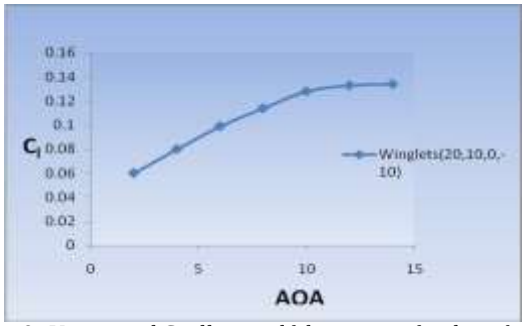


Fig. 9: Variation of Coefficient of lift versus angle of attack wing with4 winglets(20º,10º,0º,-10º,-20º dihedral)

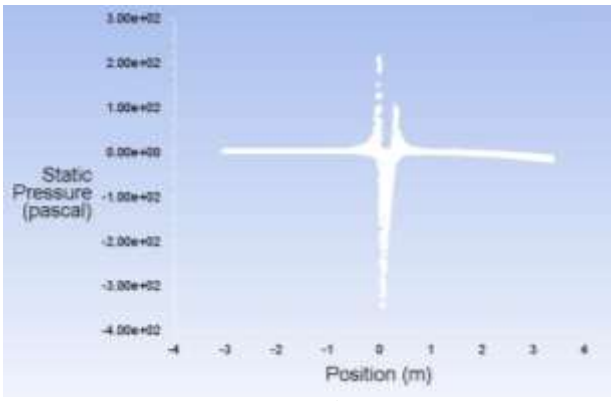


Fig. 10: Static pressure versus position of the wing with multiple winglets

Table 4. Comparison of C_l& C_d at 8 degree Angle of Attack

Configuration	Coefficient of lift(C_l)	Coefficient of drag(C_d)
Wing without winglets	0.074	0.0022
Wing with winglets(10,5,0,-5)	0.098	0.002
Wing with winglets(20,10,0,-10)	0.114	0.0011

4. Conclusion

Computational investigations have been performed to examine the effectiveness of multiple winglets mounted at varying dihedrals to improve the performance of a wing in subsonic flow. Combining the Computational analysis measurement results with the Experimental result and the previous results of Spillman[23]. Airport capacity considering transport aircraft using optimized multiple winglet systems of the type considered would get improved by specific characteristics Less vortex energy, Faster vortex disruption due to reduced vortex, Faster climb trajectory with improved L/D, Less span per weight of airplane. This benefits the wind turbine applications. Further this technique can be used in Unmanned Aerial Vehicles in future with advanced technology [24].

The following 3 mechanisms suggested for performance improvement due to multiple winglets:

1) Flat plate winglets at zero incidences improve the lift curve slope, and produce more lift than an equivalent area of the baseline wing.
2) Multiple winglets configurations reduces the wing induced drag.
3) Dihedral spread of the winglets improves lift by taking some of the winglets away from the wing plane, and redistributing the tip vortex into multiple vortices that do not merge in the near wake, thereby reducing the effective downwash at the wing plane.

Acknowledgement

Authors express sincere thanks to Bannari amman Institute of Technology, Sathyamangalam for utilizing the computing facility and resources to carry out this research work successfully. We also thank Dr. S Gollakota, Dean, Aeronautical Engineering, Bannari amman Institute of Technology, Sathyamangalam for his guidance and motivation to carry out this research work. Further we acknowledge that no funding or grant received for conducting this research work.

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