Numerical Study of Secondary Flow Characteristics on the Use of the Winglets

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Abstract. The upper surface of the wing is constantly observed by experts on the wing. In this area, a variety of phenomena cause how much aerodynamic performance is demonstrated. Changing or adding geometry to the wing changes the flow characteristics of the upper surface. The use of winglets will certainly change the flow characteristics around the wingtip which will have a large effect on the area behind and next to the winglet itself. This research was carried out using Ansys 19.1 and the turbulent k-\omega SST model. The airfoil used is Eppler 562 which is commonly used in unmanned aerial vehicles. Freestream flow velocity that will be used is 10 m/s (Re = 2.34 x 10\textsuperscript{4}) with an angle of attack (\(\alpha\)) = 12\textdegree{} and 15\textdegree{}.

1. Introduction

To improve the cruising range of aircraft or unmanned aerial vehicles, researchers and tool makers have done a variety of things. Some parties have tried to increase the elevator as high as possible and some are trying to reduce drag as low as possible. From both of these efforts will produce the most optimal aerodynamic performance. This is not only done on airplanes that have a high Reynolds number, but also on unmanned aerial vehicles that on average have a low Renolds number.

The researchers tried to combine several primary control surfaces and secondary control surfaces as done by Dam [1]. Some researchers also provide additional variations on existing control surfaces as performed by Kauertz [2] and Brüderlin [3]. However, many researchers are still focusing their research on variations in the geometry of the control surface. One of the targets of geometry variation is the winglet. Several types of winglets are used on aircraft both commercially and struggling only in the laboratory, including simple winglets, blended winglets, wingtip fences, spiroids, elliptical winglets, semicircular winglets, raked wingtips, scimitar winglets, maxi winglets, and the others.

Azlin et al [4] investigated geometrical variations in elliptical winglets and semicircular winglets. The type of airfoil used is NACA 653218 at an \(\alpha\) = 0\textdegree{}, 4\textdegree{}, 8\textdegree{}, and 12\textdegree{}. The speed used is 40 m/s, 45 m/s and 50 m/s. By giving cant angle to each winglet it is found that elliptical winglet with cant angle 45 degree
has the highest lift coefficient, elliptical winglet with cant angle 45 degree produces the lowest drag coefficient, and elliptical winglet with cant angle 45 degree produces the highest lift-to-drag ratio. Turanoguz [5] examined the use of winglets in medium-range tactical UAVs. Winglet types used are hoerner winglets, shifted downstream wingtip type devices, and blended winglets. His research uses experimental methods and numerical simulations using Ansys and CATIA. The velocity used is 45 m/s on the wing with Eppler 562 airfoil. From these studies, it was found that the blended winglet produces aerodynamic efficiency and better performance than other winglet types. Panagiotou et al [6] examined wake and wingtip vortices on unmanned aerial vehicles using experimental visualization and 3D Laser Doppler Anemometry (LDA). The study was conducted on a closed-circuit subsonic wind tunnel using a smoke wire and smoke probe system. With these two experimental methods, the results in velocity, vorticity, and wake circulation are compared with each other. Using a winglet greatly influences the structure of the wake and wing vortex significantly. Maximum vorticity strength can be reduced by using winglets. This study will further discuss the effects of using winglets on a relatively low Reynolds number. The Reynolds number is chosen based on the minimum speed used by an average unmanned aerial vehicle. Winglet types used are simple, blended winglet, forward, and rearward wingtip fence. Observation is focused on the pressure contour on the upper surface of the wing. By comparing the four types of winglets most commonly used it is expected to show the form of secondary flow and upper surface flow characteristics.

2. Methodology

2.1. Domain Simulation

This research was conducted with a numerical simulation using Ansys 19.1 with the turbulent model k-ω SST. Freestream flow velocity that will be used is 10 m/s (Re = 2.34 x 10^4) with an angle of attack (α) = 12°, and 15° [7]. The specimen model is the E562 airfoil with and without a winglet. Winglets that will be used are simple, blended winglets, and wingtip fence with forward and rearward variations. Figure 1 is the simulation domain and the boundary conditions used in the simulation. Figure 2 is the shape and geometry of the winglet used in this study.

![Figure 1. Domain simulation and boundary conditions](image)

The test specimen is in the form of an Eppler 562 type airfoil with and without a winglet attached to the tip of the tip in the form of a wingtip fence as shown in figure 2 and the dimensions of the modeling dimensions in figure 3 [8]. In numerical simulation research, geometry, meshing, and boundary types are made for the test objects. After making the geometry, the next step is to do the meshing process and determine the boundary type. The type and properties of the material are entered according to the conditions of the environment, at a temperature of 30°C and a pressure of 1 atm. This model uses air as a working fluid with (ρ) = 1.17 kg / m³, viscosity (μ) = 1.86 x 10⁻⁵ N.s / m². The intensity of turbulence in this numerical modeling is 0.8% and the length scale on the inlet side is 0.024 m. The turbulence modeling used is viscous turbulent k-ω SST. The solution uses a second order for pressure, turbulent
kinetic energy-momentum, and turbulent dissipation rate. Convergence criteria are set at $10^{-5}$, meaning that the iteration process is declared to have converged after the residual reaches a price less than $10^{-5}$.

![Image of winglets](image)

**Figure 2.** The shape of the winglet in research

**Figure 3.** Simulation domain and research boundary conditions [8]

### 2.2. Grid Independence

The use of simulation software requires the accuracy of data both in the post-processing and preprocessing steps. The grid independence step is needed to determine the level and structure of the best and most efficient grids so that the modeling results are close to true. This independence grid is done to get the amount of meshing that tends to be constant so that it is obtained in this independence grid, the number of meshing is divided into 4 types. From this type of meshing we will look for the smallest value difference of each meshing by comparing the numerical $C_D$ graph. The $C_D$ value of the independent grid is shown in table 1. Table 1 shows the variation of the meshing of the independence grid of the three-dimensional test model at the Reynolds number $2.34 \times 10^4$.

Grid Independence is a method for determining the optimum point of experimental value. It must be understood that the use of the number of elements in numerical modeling influences the results. The more elements the more accurate the results but the running time becomes longer. The optimum point is the point at which the results show the minimum possible number of elements. Besides, other considerations are based on the most optimal results obtained if the difference in the drag coefficient with the previous meshing is approximately $2\%$ [9].
The use of CFD software requires accuracy of data both in the post processing and preprocessing steps. The grid independence step is needed to determine the level and structure of the best and most efficient grids so that the modeling results are close to true. To get more complete information on the area around the wall, it requires the calculation of $y^+$ on each meshing. The calculation of $y^+$ is based on the flat-plate boundary layer theory calculations. In addition to the calculation of $y^+$, the inflation layer is needed so that the area around the wall uses a type of quadrilateral meshing so that information around the wall is more accurate. To calculate the smaller number of nodes, the area far from the wall will use meshing type tetrahedrons.

| Meshing Type | Number of Cells | Inflation Layer | $C_D$ | $y^+$ |
|--------------|-----------------|-----------------|-------|-------|
| Meshing A    | 768.081         | 40              | 0.8833| 1.4   |
| Meshing B    | 569.313         | 40              | 0.90198| 0.8  |
| Meshing C    | 469.682         | 40              | 0.8588| 2.1   |
| Meshing D    | 353.120         | 40              | 0.9207| 2.1   |

In this study, to get the best results, the $y^+$ used is less than 1, as was done in the Kontogiannis study [10]. Based on table 1. $C_D$ values that tend to be smaller occur in Meshing B. One of the considerations in conducting numerical simulations is the time and memory used, then the meshing used for subsequent simulations is Meshing B.

In this step modeling the flow characteristics, including the selection of the solver model and determining the turbulence model used. The solver used is unsteady. The turbulence model used for this airfoil is the k-ω SST model. The k-ω SST model was developed by Menter to combine the stable and accurate k-ε standard model formulation in the area near the wall with the k-ω model which has advantages in freestream flow. To achieve this, k-ω SST model was made. [11].

3. Result and Discussion
3.1. Visualization of The Pressure Contour Y-Z Plane
Figure 4 shows the comparison of pressure contours in a position directly behind the wing at an angle of attack $\alpha = 12^\circ$. The low-pressure contour in the y-z plane indicates the low pressure behind the wing due to the separation caused by the interaction of fluid flow with the wing surface. Besides, there is also the influence of fluid flow jumps from the lower surface to the upper surface as a result of the pressure difference between the two [12].

Figure 4 (a) shows the plain wing pressure contour at $x = c$ behind the wing when measured from the leading edge. Low-pressure contours are visible at the end of the trailing edge. This is a result of a jump in fluid flow from the lower surface to the upper surface. This round shape contour is an accumulation of fluid flow jump from the leading edge to the trailing edge. On the side behind the midspan, the pressure with a minimum value has not yet been seen even though negative areas have begun to form. This shows that separation has begun and that backflow is possible in the area around the trailing edge. Figure 4 (b) shows the plain wing pressure contour which is equipped with a simple winglet at $x = c$. The area with a negative value has formed behind the winglet, although it is smaller than in the plain wing. However, the area behind the midspan has formed a negative area with an area wider than the plain wing and has a smaller pressure value than the plain wing. In these circumstances, it is possible to have severe separation in the area around the trailing edge.

A plain wing equipped with a blended winglet (figure 4 (c)) shows a pattern that is almost the same as a simple winglet but with the less negative area. The circle shape behind the winglet has the same shape but with a smaller area. Similarly, the area behind midspan shows the same thing. The pattern formed by the area behind the midspan begins to show a reduction in the amount of separation in the midspan area. The patterns formed show the concentration of the strong separation area in the area in front of the trailing edge.
The area behind the midspan on the plain wing which is equipped with a forward wingtip fence (figure 4 (d)) shows a reduction in separation compared to the plain wing which is equipped with a blended winglet. The negative area pattern is still patterned with the concentration of the area but with a smaller area. In the area behind the winglet, it shows a smaller area than the blended winglet and shows imperfect circular patterns as occurs in simple winglets and blended winglets.

The area behind the midspan on the plain wing with a rearward wingtip fence (figure 4 (e)) shows a decrease compared to the forward wingtip fence. Concentration patterns of negative values are hardly noticeable in the area behind the trailing edge. However, the imperfect circular shape behind the wingtip fence shows a slight increase in the area.
3.2. Visualization of The Pressure Contour X-Z Plane with Streamline

Figure 5 shows the velocity contour and streamline area of the upper surface airfoil x-z plane on the plain wing (a), the plain wing with simple winglet (b) the plain wing with blended winglet (c), the plain wing with forward wingtip fence (d), and the plain wing with rearward wingtip fence (e) angle of attack $\alpha = 15^\circ$. Pressure contour analysis and streamline area of the upper surface airfoil of the x-z plane are useful for displaying the shape of the x-z vector fluid flow movement on the upper surface of the airfoil. The appearance of a pressure contour can provide a separation point that forms a line in the viewing area.

In figure 5 (a), a flow curve is observed on the tip of the airfoil. This indicates a secondary flow from the lower surface area towards the upper surface. This fluid flow jump results in a reduction in the effective area of the airfoil in producing lift. Also shown in the picture is a fluid flow leap whose movements have reached the leading edge. This fluid flow jump will start from the trailing edge at a low flood angle and will increase towards the leading edge as the angle of attack increases. [13–15]. The value of pressure on the upper surface still has a higher value on the trailing edge. This shows that there are still areas that have not been straddled on the trailing edge.

Figure 5 (b) shows the detailed shape of the pressure contour and streamline area of the upper surface airfoil of the x-z plane on the airfoil with a simple winglet at an angle of attack $\alpha = 15^\circ$. On the wingtip side, there is no visible bending of flow due to spills of flow from the lower surface airfoil that move urgently to the upper surface. Instead, in the area around the wingtip visible secondary flow in the form of a circle on the inside of the winglet. This secondary flow already has a large area towards the flow and has the potential to disrupt the flow coming from the leading edge. This can be seen by the direction of rotation of the secondary flow opposite the direction of the incoming flow.

In figure 5 (c), we can see the contour of the upper surface pressure with the blended winglet at an angle of attack $\alpha = 15^\circ$. In the visualization, it can be seen that the secondary flow that forms around the blended winglet is more directed towards the midspan than the simple winglet. In the area next to the
winglet another secondary flow is formed which is smaller. The total area of the secondary flow is relatively the same as a simple winglet.

In figure 5 (d) we can see detailed pressure and streamline contours from the forward wingtip fence at the $\alpha = 15^\circ$. The secondary flow is formed attached to the inside of the winglet and has a smaller area than the simple and blended winglet. The value of the pressure on the upper surface is still an area that has a higher value on the trailing edge. This shows that there are still areas that have not been straddled on the trailing edge.

In figure 5 (e) we can see detailed pressure and streamline contours from the rearward wingtip fence at the angle of attack $\alpha = 15^\circ$. The secondary flow formed is attached to the inside of the winglet and has a wider area than the forward wingtip fence. The value of pressure on the upper surface almost all of them has low values starting from the leading edge to the trailing edge. This shows that almost all areas are separation.
Figure 5. Visualization of pressure contours on the upper surface at $\alpha = 15^\circ$

4. Conclusion
In the visualization of pressure contours in the x-z plane as far as $x = c$ shows the formation of an area with a negative value in the area behind the winglet. Likewise, the visualization of pressure contours on the upper surface shows the widening of the area with negative values on the upper surface. From the above description, several conclusions can be drawn, including:

- The addition of winglets shows a reduction in the shape of the pressure contour from the perfect circle on the plain wing to an imperfect circle. However, the area of the circle has become wider in the use of a rearward wingtip fence.
- The use of winglets influences the area of negative value in the area behind the midspan. A simple winglet shows the broadest negative area compared to other configurations. This shows that the separation that occurs in the wings with the use of simple winglets more quickly has a higher intensity.
- In the use of forward wingtip fence, the upper surface area which shows a higher pressure value in the trailing edge area has a wider area than the other configurations. This shows the possibility of stalling that has not occurred in the forward wingtip fence compared to other configurations.
- Secondary flow occurs in all configurations in both the plain wing and winglet usage. In the plain wing, there is an area affected by fluid flow leaps due to pressure from the lower surface towards the upper surface. With the use of winglets, this can be prevented in all winglet configurations.
- The use of a rearward wingtip fence shows a secondary flow area around the winglet that is wider than the others. Whereas in the blended winglet, there is a shift in the position of the secondary flow although in addition to the winglet a new secondary flow is formed.

To support the results of this study, other research needs to be continued by taking a higher angle of attack and at a higher speed as well.
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