Vortex development analysis effects of the use of winglets on Airfoil E562 in unmanned aerial vehicles

Setyo Hariyadi S.P., Sutardi, and Wawan Aries Widodo

1 Aircraft Engineering, Politeknik Penerbangan Surabaya
Jemur Andayani I/73 Wonocolo, Surabaya 60236, Indonesia
Email: hudzaifahsetyo@gmail.com

2 Fluid Mechanic Laboratory, Mechanical Engineering Department, Institut Teknologi Sepuluh Nopember
Keputih, Sukolilo, Surabaya 60111 Indonesia

Abstract. The development of aerospace technology is always interesting to follow because designers and manufacturers of flying objects compete to produce the best performance. This invites various forms of objects and geometries to be studied and researched. The use of winglets is commonly used in flying objects in the world today. This study further explores the effects of using winglets on vortex formation in areas near the wing’s body and behind it. This research uses computational fluid dynamics using Ansys 19.1. The turbulent model used is k-ω SST with a Reynolds number of 2.34 x 10^4. The observed angle of attacks are 15° and 17° on Eppler 562 wing airfoil. This research found that each winglet configuration has different velocity path lines and vorticity magnitude characteristics different. In the areas where fluid flow jumps occur it is shown that there is an increase in fluid flow velocity. The forward wingtip fence can withstand the fluid flow jump better than other winglet configurations. The use of winglets results in a greater area of vorticity magnitude behind the wing than the plain wing even though the forward and rearward wingtip fence produces smaller values, especially behind the wing.

Keywords: plain wing, blended winglet, simple winglet, wingtip fence, Eppler 562

1. Introduction
The development of aircraft technology or other moving air objects is very much influenced by the design of the wings. Lift, drag, thrust, and weight are also affected by the design of the wings although the body of the aircraft will also be influential. This caused the designers of the aircraft rollicking to provide variations on the wings. With an optimal thrust, the lift formed on the wing will provide adequate cruising range and altitude from the aircraft.

Several lifting devices have been used on the wings that aim to increase the lift and reduce drag, including vortex generators, fences, winglets, slat slots, flaps, and the others. These components have a slightly different role from the primary and secondary control surfaces because they tend to control aircraft movements. The role of this lifting device becomes common for use on planes and other moving air objects.
Unmanned aerial vehicles (UAV) are one of the moving aerial objects that are currently widely used in the aviation world. Various kinds of things can be facilitated by the use of UAVs, causing the need for optimization in terms of UAV aerodynamics. One thing that is needed in the use of UAVs is the tendency for limited fuel or power sources from UAVs. This causes the aerodynamic aspects of the aircraft to be needed to support the cruising capabilities of the UAV.

Winglets are one of the most common lifting devices used on aircraft. With the use of winglets, the jump in airflow from the lower surface to the upper surface can be reduced. The purpose of being reduced here does not mean that the fluid flow jump can be completely lost. The geometry factor of the winglet greatly influences how much the fluid flow jump can be reduced.

Xu et al. [1] placed a small plate as a flow control on the side of the UAV wing that functions like a winglet. This study uses the unsteady computational fluid dynamics with turbulent shear stress transport (SST) models. The validation of this research uses the Hump Model [2-4] and the experimental research of the Seifert TAU0015 airfoil [5,6]. The purpose of using synthetic jet control actuators is to see how much influence the synthetic jet control is arranged asymmetrically on vortex formation in UAVs. Synthetic jet control has a large influence on aerodynamic performance and has a significant influence on the formation of a vortex in the lateral axis.

Lyu et al. [7] investigated the use of winglets in underwater gliders. This study aims to measure the hydrodynamic performance of winglet in water. The study was conducted by a computational fluid dynamics method with turbulent k-ω shear stress transport (SST) model. Blended-wing-body underwater glider (BWBUG) and winglets used in this study are based on previous research. From the results of this study, it was found that the lift and lift to drag ratio can be increased while drag remains at the same level. From the visualization, it was found that vorticity magnitude decreased in strength compared to without winglets despite the wider area.

Buzica et al. [8] conducted a study on the vortex structure of a diamond wing. The Reynolds number used is $Re_\mu = 2.7 \times 10^6$ and $Ma = 0.15$ at the angle of attack $\alpha = 12^\circ$. Experiments were carried out on the geometry of the AVT-183 diamond wing with a NACA64A006 airfoil. Measurement in the wind tunnel using stereoscopic particle-image-velocimetry (PIV) and Hot-wire anemometry which is supported by visualization of oil flow visualization. The experimental results were compared with the results of numerical simulations using turbulent SST k-ω models. Another thing that was investigated was the natural flow and forced transition. The results of this study indicate that there is a significant separation of laminar, transition, and turbulent boundary layer. With the forced transition, it can be seen that the role of turbulent kinetic energy is very important in the dynamics of the flow. With this flow transition, it will cause delays in the backside of the wing.

Bravo-Mosquera et al. [9] used winglets with modified wing grid on AG-Nel 25 aircraft. The development of this UAV aircraft was based on the classical method of making aircraft for agriculture based on Raymer [10], J. Roskam [11], Nikolai [12], and Sadraey [13]. To improve the reliability of the aircraft, it was developed based on research by Goraj [14] and Panagiotu [15]. For aircraft design and analysis, Computer Aided Design (CAD) tools and CFD numerical simulations were used. CFD numerical simulations were performed at $Re = 6.9 \times 10^5$ using the Ansys CFX 14.5 application. Wing grid was arranged using 5 configurations compared to tip tanks. In aerodynamic performance, it is shown that the entire wing grid configuration produces higher lifts and lower drag compared to tip tanks. This supports better-induced drag factor, aerodynamic efficiency, range factor, and pitching moment coefficient.

From some of the researches above, there is a need for further analysis of the deeper aspects of UAV design. This research seeks to further explore the use of winglets that have been carried out by Hariyadi [16–18] and Turanoguz [19] in the analysis of velocity and vorticity magnitude. The use of several types of winglets that have been widely used in the aviation community is used in
the use of UAVs. This will further demonstrate the effect of using winglets on several geometrical dimensions for the design of UAV utilization.

2. Methodology
This study uses numerical simulations to see the extent of the development of vortex in plain wing and the effect of winglet addition to the value and area of vorticity produced. The role of the Computational Fluid Dynamic methodology and approach plays an important role in the pre and post-processing of research results. This numerical simulation model and methodology are expected to produce good visualization so that it can help analyze the effects of winglet addition.

2.1 Computational fluid dynamic (CFD)
This study uses Ansys Fluent 19.1 with the turbulent model k-ω SST. Reynolds number used is $Re = 2.34 \times 10^4$ which is calculated based on the chord line (Table 1). The angle of attack (α) used is 15° and 17°. Comparisons made on the plain wing, blended, simple winglet, and wingtip fence. Reynolds number is determined based on the chord where the length of the chord used is 20 cm (Figure 1). is the geometry of set up and boundary condition while Figure 2 is the simulation domain and the boundary conditions used in the simulation.

| Table 1. Description of the research model condition |
|------------------------------------------------|
| **Model** | 3D, Unsteady/Transient |
| | Plain wing |
| | Plain wing with simple winglet |
| | Plain wing with blended |
| | Plain wing with forward wingtip fence |
| | Plain wing with rearward wingtip fence |
| **Airfoil** | Eppler 562 |
| **Fluid** | Air |
| **Fluids Properties** | Density 1.225 kg m$^{-3}$ |
| | Viscosity 0.000017894 kg m$^{-1}$s$^{-1}$ |
| **Boundary condition** | Wing |
| | Wall |
| | Outlet |
| | Outflow |
| | Inlet |
| | Velocity inlet |
| | Wall |
| | Wall |
| **Reynolds Number** | $Re = 2.34 \times 10^4$ |

Figure 1. Geometry set up and boundary conditions
2.2 Grid independence
The accuracy of the research is desirable with the independence Grid. This is necessary especially for visualization and calculation using numerical applications. The type of meshing and grid independence used in this study refers to Hariyadi’s research [16–18] where the type of meshing used is unstructured mesh. In table 2, it can be seen the independence grids sorted by the number of cells of each meshing. Based on Anderson [21], the most optimal results are obtained when the difference between the drag coefficient and previous meshing is less than 2%. Likewise in the other criteria, the $y^+$ used is less than 1 as was done in the Kontogiannis research [22]. Based on table 1, $C_D$ values that tend to be smaller occur in Meshing B.

| Meshing Type | Number of Cells | $C_D$ | $y^+$ | Skewness Average |
|--------------|-----------------|-------|-------|------------------|
| Meshing A    | 768,081         | 0.883 | 1.4   | 0.347            |
| Meshing B    | 569,313         | 0.902 | 0.8   | 0.343            |
| Meshing C    | 469,682         | 0.858 | 2.1   | 0.346            |
| Meshing D    | 353,120         | 0.921 | 2.1   | 0.334            |
| Meshing E    | 335,582         | 0.933 | 2.8   | 0.351            |

3. Result and discussion
In order to show the flow phenomenon to show the role of winglet on the plain wing, velocity pathline, and vorticity magnitude are displayed. Velocity magnitude uses z-axis slices while vorticity magnitude uses x-axis slices.

3.1 Velocity pathline
The picture shows the visualization of velocity magnitude contours in the form of a pathline on the model. The cut on the z-axis is taken at $z = s$ at the angle of attack $\alpha = 17^\circ$. The figure is equipped with an isometric view to show the extent of fluid flow jumps and changes in the flow trajectory. The color of the pathline shows the value of the flow velocity magnitude.

In Figure 3 a, the velocity magnitude contour visualization is shown in the form of a pathline on the plain wing at $z = s$ at the angle of attack $\alpha = 17^\circ$. In Figure 3a, it is shown that there is a significant increase in the flow of fluid flow. When a jump occurs, it appears that an increase in the speed value of the pathline. The effect of the jump in the form of pathline twisting looks up to about 2 lengths when calculated from the leading edge.
Figure 3. Visualization of velocity magnitude contours in the form of a pathline on the plain wing and plain wing with winglet at $z = s$ at the angle of attack $\alpha = 17^\circ$.

In Figure 3b, the velocity magnitude contour visualization is shown in the form of a pathline on a plain wing equipped with a blended winglet at $z = s$ at the angle of attack $\alpha = 17^\circ$. In Figure 3b, it is shown that there is still a fluid flow leap to the inside of the fence. This shows that the blended winglet cannot perfectly resist the leap of fluid water from the lower surface to the upper surface.
The increase in velocity magnitude is also seen from the color of the pathline when there is a flow jump.

In Figure 3c, the velocity magnitude contour visualization is shown in the form of a pathline on a simple winglet with a simple winglet at \( z = s \) at the angle of attack \( \alpha = 17^\circ \). Fluid flow leaps that occur have densities and effects that are wider than blended winglets. Besides being unable to withstand fluid flow jumps, the effect of twisting from the pathline behind the wing is also wider than the blended winglet.

In Figure 3d, the velocity magnitude contour visualization is shown in the form of a pathline on the rearward wingtip fence at \( z = s \) at the angle of attack \( \alpha = 17^\circ \). At the edge of the leading edge, there is a fluid jump that has a higher velocity magnitude value. But on the opposite side of the fence, there is a real process and a low-velocity magnitude value. At the intersection, at the meeting area the flow between inside and outside the fence there is a process that looks real and has a blend of high and low velocity pathlines. This processed form does not exist in the addition of other winglets or the plain wing. Fluid flow leaps from the lower surface to the upper surface at the end of the rearward wingtip fence show a significant processing effect and an effect up to the back of the trailing edge.

In Figure 3e, the velocity magnitude contour visualization is shown in the form of a pathline on the forward wingtip fence at \( z = s \) at the angle of attack \( \alpha = 17^\circ \). With the addition of the forward wingtip fence, it is shown that the flow is relatively more stable compared to plain wing and other winglet configurations. This shows that the forward wingtip fence can withstand fluid flow leaps from the lower side to the upper side. In the addition of rearward wingtip fence and forward wingtip fence, there are some interesting areas for further study and will be discussed in the next article.

### 3.2 Vorticity contour

The picture shows the development of vortex formation on the model. Slices on the x-axis are taken at \( x = 0.3c, x = c, x = 2c, \) and \( x = 3c \). This is needed to show the development of the formation of the vortex on the plain wing and plain wing equipped with winglets. Generally in several articles, the results of vorticity magnitude are revealed in the area behind the wing but this study will show the development of the vortex ranging from around the winglet to the area behind the wing.

In Figure 4a, the vortex development on the plain wing is shown at \( x = 0.3c, x = c, x = 2c, \) and \( x = 3c \) at the angle of attack \( \alpha = 15^\circ \). At \( x = c \) shows that vortex has a large enough value. In this case, the vorticity magnitude value is greater than the legend in the numerical simulation application so it cannot be caught with a certain color. The picture shows that the development of vortex has appeared when it starts \( x = 0.3c \).

Figure 4b shows the development of vortex on a plain wing with a blended winglet at \( x = 0.3c, x = c, x = 2c, \) and \( x = 3c \) at the angle of attack \( \alpha = 15^\circ \). At \( x = 0.3c \) shows that the vorticity magnitude has experienced a large enough value but has decreased at \( x = c \). However, the area and value of vorticity magnitude plain wing equipped with a blended winglet are greater when compared to the plain wing. Larger values are concentrated behind the edge of the fence of the winglet. The same thing is seen in Figure 4c where vortex development is shown there is a plain wing equipped with simple winglet at \( x = 0.3c, x = c, x = 2c, \) and \( x = 3c \) at the angle of attack \( \alpha = 15^\circ \). The magnitude and vorticity magnitude formed by the simple winglet shows a greater area and value when compared to the blended winglet. In Figure 4c it is also shown that the area near the fence has a greater vorticity magnitude value than the area farther from the fence.

In Figure 4d, the vortex development on the plain wing which is equipped with rearward wingtip fence at \( x = 0.3c, x = c, x = 2c, \) and \( x = 3c \) at the angle of attack \( \alpha = 15^\circ \). The area near the fence has a smaller value of vorticity magnitude compared to the blended and simple winglet. Although the area of vorticity magnitude at \( x = 3c \) and \( x = 3c \) is wider, the wing with a rearward wingtip winglet has a smaller value than the blended and simple winglet.
In Figure 4e, the vortex development on the plain wing is shown with a forward wingtip fence at $x = 0.3c$, $x = c$, $x = 2c$, and $x = 3c$ at the angle of attack $\alpha = 15^\circ$. The area near the fence has a slightly larger vorticity magnitude compared to the rearward wingtip winglet. However, in the vorticity area, the magnitude of the forward wingtip winglet at $x = 2c$ and $x = 3c$ has a smaller value than the wing which is equipped with a rearward wingtip fence, blended and simple winglet.

Figure 4. Vortex development on plain wing and plain wing with winglet at $x = 0.3c$, $x = c$, $x = 2c$, and $x = 3c$ with the angle of attack $\alpha = 15^\circ$. 
4. Conclusion
Numerical simulation research has been carried out on Eppler 562 wing airfoil. The effect of the use of winglets on the plain wing can be seen in the visualization of velocity pathline and vorticity magnitude. In the fluid flow jump at the edge of the leading edge at both the plain wing, blended, simple, and rearward wingtip fence, there is a slight increase in speed marked by a red pathline. The flow velocity is increasingly decreasing so that it reaches behind the wing. However, the meeting in front of and behind the fence at the rearward wingtip fence showed a relatively large velocity decline. This also brings up the velocity pathline process in that area.

Vortex development shown through contour vorticity magnitude shows the influence of dominant geometry. As the size of the winglet geometry increases, the area of vorticity behind the wing is also greater. Vortex formation starts from the front side of the winglet so that it grows backward with a large value that is getting smaller and smaller. Despite having a relatively large geometry, the forward wingtip fence can produce a smaller vorticity magnitude than other winglet configurations. This is closely related to the ability of the forward wingtip fence to resist fluid flow leaps on the leading edge.

5. Acknowledgement
This research was funded using the Politeknik Penerbangan Surabaya research fund.

6. References
[1] Xu X and Zhou Z 2016 Analytical study on the synthetic jet control of asymmetric flow field of flying wing unmanned aerial vehicle Aerospace Science and Technology 56 90–9
[2] Cui J and Agarwal R K 2005 CFD validation of turbulent separation control on a 2D hump (NASA Langley Workshop Validation: Case 3) 35th AIAA Fluid Dynamics Conference and Exhibit 1–7
[3] Rumsey C L 2009 Successes and challenges for flow control simulations International Journal of Flow Control 1 1–27
[4] Rumsey C L 2007 Reynolds-averaged Navier-Stokes analysis of zero efflux flow control over a hump model Journal of Aircraft 44 444–52
[5] Seifert A, Darabi A and Wygnanski I 1996 Delay of airfoil stall by periodic excitation Journal of Aircraft 33 691–8
[6] Yazzie R, Truman C R and Salari K 2004 Prediction of Oscillatory Flow Excitation 5–8
[7] Lyu D, Song B, Pan G, Yuan Z and Li J 2019 Winglet effect on hydrodynamic performance and trajectory of a blended-wing-body underwater glider Ocean Engineering 188 106303
[8] Buzica A and Breitsamter C 2019 Turbulent and transitional flow around the AVT-183 diamond wing Aerospace Science and Technology 92 520–35
[9] Bravo-Mosquera P D, Cerón-Muñoz H D, Díaz-Vázquez G and Martini Catalano F 2018 Conceptual design and CFD analysis of a new prototype of agricultural aircraft Aerospace Science and Technology 80 156–76
[10] Raymer D 2019 Aircraft Design: A Conceptual Approach, Sixth Edition and RDSwin Student SET
[11] Anon 14 AIRPLANE DESIGN PART V ( PDFDrive.com ).pdf
[12] Nicolai L M and Carichner G E 2010 Fundamentals of Aircraft and Airship Design vol I
[13] Sadraey M H 2013 AIRCRAFT DESIGN Aerospace Series List Design and Analysis of Composite Structures: With applications to aerospace Structures
[14] Goraj Z, Frydrychewicz A, Świtkiewicz R, Hernik B, Gadomski J, Goetzendorf-Grabowski T, Figat M, Suchodolski S and Chajec W 2004 High altitude long endurance unmanned aerial vehicle of a new generation - A design challenge for a low cost, reliable and high performance aircraft Bulletin of the Polish Academy of Sciences: Technical Sciences 52 173–94
[15] Panagiotou P, Kaparas P and Yakinthos K 2014 Winglet design and optimization for a MALE UAV using CFD Aerospace Science and Technology 39 190–205
[16] Setyo Hariyadi S P, Sutardi, Widodo W A and Mustaghfirin M A 2018 Aerodynamics analisys of the wingtip fence effect on UAV wing International Review of Mechanical Engineering 12 837–46

[17] Setyo Hariyadi S P, Sutardi and Widodo W A 2018 Numerical study of flow characteristics around wing airfoil Eppler 562 with variations of rearward wingtip fence AIP Conference Proceedings 1983

[18] Hariyadi S S P, Sutardi and Widodo W A 2018 Drag reduction analysis of wing airfoil E562 with forward wingtip fence at cant angle variations of 75°and 90° AIP Conference Proceedings 2001

[19] Turanoguz E and Alemdaroglu N 2015 Design of a medium range tactical UAV and improvement of its performance by using winglets 2015 International Conference on Unmanned Aircraft Systems, ICUAS 2015 1074–83

[20] Mulvany N, Chen L, Tu J and Anderson B 2004 Steady-State Evaluation of Two-Equation RANS (Reynolds-Averaged Navier-Stokes) Turbulence Models for High-Reynolds Number Hydrodynamic Flow Simulations Department of Defence, Australian Government 1–54

[21] Anon [John_David_Anderson]_Computational_fluid_dynamics(BookFi.org).pdf

[22] Kontogiannis S G, Mazarakos D E and Kostopoulos V 2016 ATLAS IV wing aerodynamic design: From conceptual approach to detailed optimization Aerospace Science and Technology 56 135–47