Characteristics of Separation and Induced Drag in the Use of Swept-back Wing Unmanned Aerial Vehicle

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Abstract. The swept-back wing has been used in almost all aircraft wings. This is necessary to reduce the pressure drag from the wings so that there is an increase in aerodynamic performance. The aerodynamic performance is the ratio between the total drag coefficient and the lift coefficient. This research attempts to explain the swept-back wing phenomenon in unmanned aerial vehicles (UAV) on Eppler 562 airfoil. The numerical simulation uses the k-ε turbulent model at Reynolds number (Re) = 2.34 x 10⁴. Variation of backward swept angle Λ = 0°, 15°, and 30°. The separation growth Λ = 0° occurred more on the wing root, while Λ = 15° and Λ = 30° occurred more on the wingtip. At Λ = 15°, as the angle of attack increases, the area of the separation increases, and the area of the transition towards the separation decreases. The re-attach area also has an increase in the area of the trailing edge. At Λ = 30°, with an increase in the angle of attack, there is a shift from the wingtip area to the mid-span. The area of separation and transition to separation has increased significantly. The re-attach area at α = 8° has not been seen, so at α = 12° it has been seen significantly. The vorticity on the x-axis shows Λ = 15°, and Λ = 30° has a wider area while on the z-axis, Λ = 15°, and Λ = 30° have stronger vortex strength. However, in the mid-span, Λ = 0° has a stronger result.

Keywords: airfoil, Eppler 562, swept-back wing, UAV

1. Introduction

Airfoil is an aerodynamic structure that is widely used in human life. Airfoil can be used for external flow or internal flow. The Airfoil on UAVs and aircraft are used to lift the body from the aircraft. The difference in pressure from the upper and lower surface produces lift which is then driven by the force from the aircraft engine. Researchers have developed various types of airfoils for use on various objects. It must be admitted that airfoils are the most widely used in the world of aviation, especially the configuration of the wings. The use of the airfoil greatly determines the shape of the airfoil itself. In addition, the airfoil can be increased in three dimensions, namely the wing. The wing's performance can be improved by changing its shape characteristics. One of the methods used is by providing a tilt angle or swept angle. Wings with backward swept angles are commonly used on commercial aircraft such as Boeing, Airbus, Bombardier, and others. Meanwhile, wings with forward-swept angles are used on military combat aircraft. However, in other flying objects such as the unmanned aerial vehicle (UAV), there is no specific use of the swept angle. This is interesting to observe because the type of flow used
has a different speed range. In addition, at present, the use of unmanned aerial vehicles (UAVs) has penetrated various lines of life and human needs.

The use of rectangular wings on airplanes and unmanned aerial vehicles is the most basic shape of the wing. Lots of research has been done to further explore the influence of these geometric shapes. There are many variations of geometric shapes that are used, including swept-back, swept front, elliptical, tapered, and others. For airplanes, the swept-back wing is mostly used on commercial aircraft, both with a large number of passengers and a small number of passengers.

The rectangular wing or often called the unswept wing is more often used in Reynold numbers below 0.3 (Incompressible flow). The construction is also quite simple because it has the same ribs on almost the entire wing. This causes the manufacturing cost to be cheaper. This type of planform has little efficiency in load distribution so that it is more widely used in private or small aircraft. Only a few uses for large aircraft have been made, including the SD360 series and the Britten-Norman (BN) Islander [1].

The use of the rectangular wing results in a higher $C_l$ but there is often a sudden change in value. This is because the rectangular wing is more sensitive to changes in the angle of attack [2]. In addition, the lift distribution on each wing planform has an important role in its selection. The rectangular wing will have a strong lift distribution on the wing root side but tends to decrease at the wingtip. The elliptical wing has a strong lift distribution on the wing root side and increasingly on the wingtip side [3]. Therefore, it cannot be denied that the choice of the wing planform will greatly determine the lift and aerodynamic performance of the wing.

Likewise, the selection of a planform wing with a swept-back wing has been done by many experts. The swept-back wing causes quite a large difference in the characteristics of the fluid flow that passes through the upper surface, as was done by Yen's research [4][5]. Flow characteristics are not only in the mid-span area but also in the vortex structure in the tip vortex area [6]. This will affect the wake that is formed on the back of the wing [7].

Experts have further investigated the use of swept-back on commercial aircraft which generally have a high Reynolds numbers and are controlled by pilots. In the use of unmanned aerial vehicles, it is more likely to use a low Reynolds number and be controlled remotely. This shows the different conditions in the use of unmanned aerial vehicles that require further exploration. The purpose of this research, of course, is not only to see the phenomenon of the use of these geometric variations but to see the most appropriate geometric variations for the use of unmanned aerial vehicles. This article will discuss more the use of the swept-back wing as opposed to the rectangular wing for the use of unmanned aerial vehicles.

2. Methods
The research method used in this research is the three-dimensional numerical simulation method. The software used is Ansys Fluent 19.1. The turbulent model used is the k-ω SST. In general, there are three stages in numerical simulation, namely: Pre-processing, processing, and post-processing. The test object used is an Eppler 562 airfoil which is simulated as if the test object is in a wind tunnel that is flowed by air. The geometry of airfoils and wind tunnels is based on Hariyadi's research [8] and Turanoguz [9], [10] so that the results obtained can be validated. Aspect ratio (AR) on wings are 5. The angle of attack is determined, namely $(\alpha) = 0^\circ, 2^\circ, 4^\circ, 6^\circ, 8^\circ, 10^\circ, 12^\circ, 15^\circ, 16^\circ, 17^\circ, 19^\circ,$ and $20^\circ$. The selection of the use of swept-wing geometry is based on the geometry of Sandra's research [11].

2.1. Simulation Domain and Boundary Conditions
A model that represents a test object is called a domain. Determination of the domain must be adjusted to the ideal conditions to have the appropriate results. In this numerical simulation, the domain is an airfoil inside the test section in the form of a wind tunnel. All of the boundary conditions can be seen in Figure 1 The boundary condition at the inlet uses an inlet velocity of 10 m/s or $Re = 2.54 \times 10^4$ and a pressure of 1 atm. At the outlet, the boundary condition used is the pressure outlet which is set at 0 atm.
Simulation domain refers to Mulvany [12] which is modified with Hariyadi's research [13], [14] where the distance between the object and the outlet is extended to 10 times the cord-line so that it can show the effect of the wing on the flow behind the trailing edge can be seen clearly.

![Figure 1. Simulation Domain dan Boundary Condition](image)

2.2. Meshing
Meshing is the division of the test specimen model area into smaller elements. The element is formed from nodes made on the specimen model which serves as a structural boundary. The meshing process will be carried out for the first time with line meshing. Furthermore, the face and volume will have meshed. The amount of meshing is too much because it will take a longer time, but the results obtained are more convergent. Whereas in the more tenuous meshing, it will be difficult to achieve a convergent condition. The selected mesh shape is unstructured mesh with the mesh distribution made tighter in the airfoil wall area. The independent grid used in the mesh uses Anderson and Kontogiannis criteria [15][16], which uses a maximum $C_D$ difference of 2% and $y+$ below 1. By using this criterion, meshing B is used in Table 1.

| 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. Numerical Simulation Results
The appearance of induced drag in the numerical simulation is more related to the skin friction coefficient on the upper surface and the vorticity magnitude behind the wing. The skin friction will show where the points begin the separation. Meanwhile, the vorticity magnitude will show the form of vorticity and how much strength the vorticity is. The visualization in this study focuses on the angle of attack $\alpha = 12^\circ$ because based on Hariyadi's research [8] the critical angle of attack for a stall occurs at $\alpha = 12^\circ$. At $\alpha = 8^\circ$ and $\alpha = 12^\circ$, it is intended to see the transition, separation, and change towards stall. This phenomenon is interesting to see, especially on the wing planforms $\Lambda = 0^\circ$, $\Lambda = 15^\circ$, and $\Lambda = 30^\circ$.

3.1. Skin Friction Coefficient Contour
Figure 2 shows the visualization of the skin friction coefficient on wing planforms $\Lambda = 0^\circ$, $\Lambda = 15^\circ$, and $\Lambda = 30$. On the rectangular wing ($\Lambda = 0^\circ$) with $\alpha = 8^\circ$, it is shown that the point of separation starts to
appear in the trailing edge area in dark blue. The area in front of it began to show a transition to the occurrence of separation with a lighter color. At $\alpha = 12^\circ$ it is shown that the separation point is progressing towards the leading edge which is indicated by the wider dark blue color that has exceeded the middle of the upper surface. On the wingtip, there is an indication of a leap of fluid flow from the lower surface to the upper surface which is shown in light blue. This happened both at $\alpha = 8^\circ$ and $\alpha = 12^\circ$. At $\Lambda = 15^\circ$ with $\alpha = 8^\circ$, it is shown that the separation starts to occur in the wingtip area which is shown in dark blue. In the mid-span area, there is a transition area towards separation. The area is wider than the area that has been separated. In a small area on the trailing edge, there is a small area which is the re-attaching area of the separation. As the angle of attack increases, the re-attach area becomes wider as seen at the angle of attack $\alpha = 12^\circ$. In the area in front of it, it can be seen that the separation area is slightly wider and the transition area of the separation becomes narrower. This reduces the area that has not yet been separated in the leading edge. At $\Lambda = 30^\circ$ with $\alpha = 8^\circ$, the separation area is narrower and occurs more towards the mid-span than the wingtip area. However, the region of transition to separation and which has not yet been separated has a wider area $\Lambda = 15^\circ$ with $\alpha = 8^\circ$. At $\Lambda = 30^\circ$ with $\alpha = 12^\circ$, the area of separation has a significant increase in area compared to $\alpha = 8^\circ$. The area of transition towards separation and has not yet experienced a quite drastic decline as well. In the re-attach area which is not visible at $\alpha = 8^\circ$, $\alpha = 12^\circ$ is already there, although when compared to $\Lambda = 15^\circ$ with $\alpha = 12^\circ$ it looks a little narrower.

![Figure 2](image1.png)

**Figure 2.** Skin Friction Coefficient at $\Lambda = 0^\circ$, $\Lambda = 15^\circ$, dan $\Lambda = 30^\circ$

### 3.2. Vorticity Magnitude X and Z-Axis Contour Visualization

The vorticity magnitude x-axis in Figure 3 shows the vorticity that occurs in one cord behind the wing. At $\Lambda = 0^\circ$ with $\alpha = 8^\circ$, $10^\circ$, and $12^\circ$, there is an increase in the value of vorticity. This is indicated by an increase in the area of red which indicates the cores with higher vorticity values. At $\Lambda = 15^\circ$, it can be seen that there is an increase in the area and value of vorticity. The increase in vorticity was seen significantly with the increase in the angle of attack. The same thing happened with $\Lambda = 30^\circ$ where there was an increase in the area of vorticity and its value even though the increase in the final area of vorticity
was smaller than that of \( \Lambda = 15^\circ \). In the three types of planform wings, namely \( \Lambda = 0^\circ \), \( \Lambda = 15^\circ \), and \( \Lambda = 30^\circ \) because the wingtip shapes are the same and there is no addition of high lift devices, the shape of the vorticity is round.

In Figure 4, the vorticity magnitude \( z \)-axis contour is shown at \( \Lambda = 0^\circ \), \( \Lambda = 15^\circ \), and \( \Lambda = 30^\circ \) with \( \alpha = 12^\circ \) in the mid-span area. In the mid-span \( \Lambda = 0^\circ \), it is shown that the vorticity strength has a narrow area with a length of about two chords. The length of the vorticity strength tends to be shorter but has a higher vorticity strength value than \( \Lambda = 0^\circ \). In mid-span \( \Lambda = 15^\circ \), it is shown that the resulting vorticity strength has an area that extends backward but has a lower vorticity value. Likewise, at \( \Lambda = 30^\circ \), it is shown that the resulting vorticity strength is narrower than \( \Lambda = 0^\circ \), and \( \Lambda = 15^\circ \).

In Figure 5, the \( z \)-axis magnitude contour is shown at \( \Lambda = 0^\circ \), \( \Lambda = 1^\circ \), and \( \Lambda = 30^\circ \) with \( \alpha = 12^\circ \) in the wingtip area. In the wingtip area \( \Lambda = 0^\circ \), it is shown that the vorticity strength has a wider area than the mid-span area with a length of about six chords. The length of vorticity strength tends to be longer and wider with a higher vorticity strength value than the mid-span. At wingtip \( \Lambda = 15^\circ \), it is shown that the resulting vorticity strength has an area that extends backwards and has a higher vorticity value than \( \Lambda = 0^\circ \). At \( \Lambda = 30^\circ \), it is shown that the resulting vorticity strength is narrower than \( \Lambda = 15^\circ \) but with a slightly shorter vorticity strength than \( \Lambda = 15^\circ \).

**Figure 3.** Vorticity Magnitude X-Axis one cord behind the wing
Figure 4. Vorticity Magnitude Z-Axis in the mid-span

Figure 5. Vorticity Magnitude Z-Axis in the wingtip area
4. Discussion
The pattern of separation shows a different shape at Λ = 0°, Λ = 15°, and Λ = 30°. At Λ = 0°, there is more movement on the wing root while at Λ = 15° and Λ = 30° it occurs on the wingtip side. On a wing planform with Λ = 15°, and Λ = 30°, it is possible to re-attach the flow which is possible because of the geometric shape formed. The flow re-attach occurs at the angle of attack α = 12° and does not occur at the angle of attack below it. This is following the results of Hariyadi's research [13] where the streamlined direction of the upper surface leads from the wing root to the wingtip. In the contour visualization of the vorticity magnitude, it is shown that the wingtip area has a wider area on the x-axis, especially at Λ = 15°, and Λ = 30°. This wider area is caused by the intersection of fluid flow from the leap of flow from the lower surface to the upper surface and the flow from wing root to wingtip. The vortex strength formed is more obvious on the flow visualization on the z-axis. With the planform wing Λ = 15°, and Λ = 30°, the length of viscosity is up to six times the length of the chord line. This can be reduced if the wingtip is equipped with high lift devices, such as winglets.

5. Conclusion
In this study, the induced drag characteristics are generated as shown by the flow visualization on the skin friction coefficient, flow vorticity on the x and z axes. The results obtained include:

- On a wing planform with Λ = 15°, and Λ = 30°, it results in a flow reattach in the trailing edge area while at Λ = 0°. The phenomenon of flow re-attaching occurs at the angle of attack α = 12° and is not visible at the lower angle of attack
- A contour similar to re-attaching the flow to the wingtip at Λ = 0° is due to the influence of the tip vortex. The effect of the tip vortex was not seen on the wingtip side at Λ = 15°, and Λ = 30°.
- The addition of the swept angle increases the vortex strength on the x-axis and the z-axis in the wingtip area. The x-axis is indicated by the addition of the area of vorticity magnitude. The increase in vortex strength on the z-axis is shown by the length of the vorticity so that it becomes six times the chord line
- In the z-axis mid-span area, Λ = 0° has a stronger vorticity than Λ = 15°, and Λ = 30°. This is indicated by a wider and longer vorticity core. This is due to the streamlined pattern at Λ = 0°, more towards the trailing edge than Λ = 15°, and Λ = 30° which is more towards the wingtip

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