Landing Performance Prediction of Commuter Aircraft Due to Wings Ice Accretion on High Terrain Operation

D I Pratama¹, W Nirbito¹² and M Adhitya¹

¹ Department of Mechanical Engineering, Universitas Indonesia, Depok, West Java 16424, Indonesia
² Corresponding author: wahyu.nirbito@ui.ac.id

Abstract. Ice accretion on a wing is one of the aviation accident factors because it will interrupt the flow over an airfoil that will reduce its performance. The effect of wings leading edge ice accretion on the landing distance of commuter class aircraft in remote high terrain operation was obtained with the help of LEWICE code for ice shape predictions and XFLR5 for airfoil polar data prediction. The ice accretion process occurred within various icing atmospheric conditions based on Icing Design Envelopes 14 CFR part 25.1419, Appendix C. Two category of ice accretion, horn ice and streamwise ice, were obtained on the leading edge of the wing. The performance degradation caused by the ice accretion will increase aircraft landing speed that it will affect the landing distance.

1. Introduction
The development of commuter aircraft is important to fulfill the transportation needs for an archipelago country like Indonesia that have many semi-prepared airstrips and short runway. The problem that will be encountered by the pilot on high terrain remote areas like Papua region in Indonesia is ice accretion. Ice accretion tends to occur at high altitude that has the air temperature below freezing point.

Ice accretion on a wing is one of the factors of aviation accident because it will interrupt the flow over the wing. Ice accretion on an aircraft airfoil is a condition when supercooled liquid water on atmosphere collided with the body of the aircraft and suddenly freeze on the impact. The Ice that accreted on the airfoil will affect the plane flight characteristic because it will increase drag and reduce lift. Longitudinal stability of the aircraft will be affected too because the lift from horizontal stabilizer will be reduced. Bragg, Broeren, and Blumenthal have categorized the ice accretion based on aerodynamic behavior into four categories. There are roughness, streamwise ice, horn ice, and spanwise-ridge ice[1].

The shape of ice accretion can be investigated through flight test, wind tunnel experiment, and numerical simulation. Flight test and wind tunnel experiment will determine the shape of ice accurately but usually too expensive and not practical. Therefore, numerical simulation is used to predict the shape of ice accretion because it is economical and can simulate the icing process and provide a relatively accurate evaluation of ice accretion[2]. The purpose of this research is to predict the landing distance changes that caused by the ice accretion on the wing.
2. Methodology

Ice accretion simulation and iced airfoil wind tunnel simulation are required to obtain the performance characteristics on the iced airfoil. The performance characteristics of iced airfoil then can be calculated to predict the aircraft landing distance affected by the ice accretion. LEWICE code is used to predict the geometry of ice accretion. XFLR5 is used to predict the airfoil performance characteristics. The following methods are used to predict the landing distance.

2.1. Icing Atmospheric Condition and Flight Configuration Parameters Determination

For running an icing simulation with LEWICE code, atmosphere condition and flight configuration parameters are required. These parameters can be seen in Table 1 and Table 2. There are liquid water content (LWC), median volume diameter (MVD), static temperature, altitude, aircraft speed, and aircraft weight. Besides all of the parameters, the geometry of the airfoil is the main parameters. Icing Design Envelopes 14 CFR part 25.1419, Appendix C[3] was used to determine the atmospheric icing condition.

| Temperature (°C) | MVD (µm) | LWC (g/m³) |
|------------------|----------|------------|
| -20              | 25       | 0.15       |
| -10              | 25       | 0.31       |
| -3               | 25       | 0.44       |
| 15               | 0.74     |            |
| 25               | 0.14     |            |
| 40               | 0.6      |            |

| Altitude (ft) | Weight (kg) | Airspeed (knots) | α (°) |
|---------------|-------------|------------------|------|
| 8000          | 7031        | 153              | 3.04 |
| 10000         | 7031        | 157              | 2.32 |

2.2. Simulation Running

After all icing parameters and flight configuration obtained, the ice geometry coordinates can be obtained by LEWICE code[4]. The output iced airfoil geometry then become an input on XFLR5 for predicting the polar data of the iced airfoil with the same test condition with the previous wind tunnel test experiment that has 0.2 Mach Number and 2.9x10⁶ of Reynolds Number condition. For the XFLR5 simulation, the airfoil should be on 30° flap for the landing configuration.

2.3. Data Correction

The polar data that were obtained by XFLR5 is still in the form of 2-dimensional airfoil polar. The 3-dimensional aircraft polar is required to achieve the landing distance. Therefore an approach is applied by assuming the degradation of airfoil performance on simulation will be the same as the degradation that will happen in the wind tunnel experiment. The following data in Table 3 is the previous aircraft wind tunnel experiment polar data on 30° flap configuration.

| Flap | (C_l)ₐ | (C_l)ₐₐ | (C_l)ₘₐₓ | (C_l)ₘᵢₙ | (C_D)ₘᵢₙ | k     |
|------|--------|--------|--------|--------|--------|-------|
| 30°  | 1.0839 | 0.0945 | 2.6379 | 0.3394 | 0.0763 | 0.0532 |
The following formula can be used to obtain the maximum aircraft coefficient of lift

\[(C_L)_{\text{max~iced}} = (C_L)_{\text{max~clean}} - (C_L)_{\text{max~clean}} - (C_L)_{\text{max~iced}}\]  

(1)

To obtain the aircraft ground coefficient of lift and drag, the airfoil polar data at 2° is used because of the angle of incidence. Aircraft ground coefficient of lift and drag value is assumed the same for each of ice category. Therefore these 4 following equation can be used to obtain the aircraft ground coefficient of lift and drag.

\[
\Delta(C_L)_0 = (C_L)_2 \text{clean} - (C_L)_2 \text{ice} \\
(C_L)_0 \text{ iced} = (C_L)_0 \text{clean} - \frac{1}{n} \sum_{i=1}^{n} \Delta(C_L)_0 \\
\Delta(C_D)_0 = (C_D)_2 \text{clean} - (C_D)_2 \text{iced} \\
(C_D)_0 \text{iced} = (C_D)_0 \text{clean} - \frac{1}{n} \sum_{i=1}^{n} \Delta(C_D)_0 
\]

(2)至(5)

When the aircraft is in a ground roll phase and the wing is near enough to the ground, there will be a ground effect that will change slightly the coefficient of lift and drag. An approach is applied by assuming these coefficient change at the previous wind tunnel experiment will be the same for the case in this study. The coefficient change due to ground effect from the previous wind tunnel experiment is +/-0.02696 for lift coefficient and -0.00466 for drag coefficient. Therefore these two following formula can be used

\[(C_L)_2 \text{iced GE} = (C_L)_2 \text{iced} + \Delta(C_L)_{\text{wind~tunnel~ground~effect}} \]

(6)

\[(C_D)_2 \text{iced GE} = (C_D)_2 \text{iced} + \Delta(C_D)_{\text{wind~tunnel~ground~effect}} \]

(7)

2.4. Landing Distance Calculation

After all iced aircraft polar data is obtained, landing distance can be calculated in ILAGA airstrips in Papua that located at 7,500ft and only have 600m runway available. The total landing distance is the sum of the approach distance \(s_a\), flare distance \(s_f\) and ground roll distance \(s_g\). To obtain all of the distance required the following formula can be used

\[s_a = \frac{50 - h_f}{\tan \theta_a} \]

(8)

For the approach distance, the flare height \(h_f\) is constant at 10ft height and the approach angle is about \((3.9° - 4.4°)\) depends on the aircraft \(V_{\text{stall}}\).

\[s_f = R \sin \theta_a \]

(9)

For the flare distance, the radius of flare \(R\) can be obtained by the following formula while assuming the value of load factor is 0.2

\[R = \frac{V_f}{0.2g} \]

(10)

For the ground roll distance, this formula was used and assuming the time of touchdown transition \(N = 2\), \(V_{TD} = 1.15 V_{\text{stall}}, \) maximum landing weight \((6,940 \text{ kg})\), \(\mu_r = 0.025 \) (asphalt) and there is no braking force or reversed thrust[5].

\[s_g = N V_{TD} + \frac{W V_{TD}^2}{2g} \left[\frac{1}{\sqrt{V_{\text{req}} + D + \mu_r(W - L)}}\right]_{0.7} V_{TD} \]

(11)

3. Results and Discussion

3.1. Ice Geometry

The prediction of ice geometry case (-10121) and (-20123) that simulated using LEWICE code with atmospheric parameters from Icing Design Envelope 14 CFR Part 25. Appendix C can be seen in Figure 1. On this prediction, the shape of horn ice and streamwise ice were obtained and can be seen in Table 4.
### Table 4. Ice Shape

| Ice Case Code | MVD (μm) | LWC (g/m³) | T (°C) | Altitude (ft) | Ice Shape |
|---------------|----------|------------|--------|---------------|-----------|
| -3111         | 15       | 0.74       | -3     | 10000         | Horn      |
| -3112         | 25       | 0.44       | -3     | 1000          | Horn      |
| -3113         | 40       | 0.14       | -3     | 1000          | Horn      |
| -3121         | 15       | 0.74       | -3     | 8000          | Horn      |
| -3122         | 25       | 0.44       | -3     | 8000          | Horn      |
| -3123         | 40       | 0.14       | -3     | 8000          | Horn      |
| -10111        | 15       | 0.6        | -10    | 10000         | Horn      |
| -10112        | 25       | 0.31       | -10    | 1000          | Horn      |
| -10113        | 40       | 0.1        | -10    | 1000          | Steamwise |
| -10121        | 15       | 0.6        | -10    | 8000          | Horn      |
| -10122        | 25       | 0.31       | -10    | 8000          | Horn      |
| -10123        | 40       | 0.1        | -10    | 8000          | Steamwise |
| -20111        | 15       | 0.3        | -20    | 10000         | Steamwise |
| -20112        | 25       | 0.15       | -20    | 1000          | Steamwise |
| -20113        | 40       | 0.06       | -20    | 1000          | Steamwise |
| -20121        | 15       | 0.3        | -20    | 8000          | Steamwise |
| -20122        | 25       | 0.15       | -20    | 8000          | Steamwise |
| -20123        | 40       | 0.06       | -20    | 8000          | Steamwise |

The horn ice is mainly formed at the higher temperature meanwhile, the streamwise ice is mainly formed at the lower temperature. On the higher temperature, droplets will freeze slower that it will have more time to spread from the stagnation point along the upper and lower surface of airfoil before it becomes frozen completely and shaped a horn geometry. On the lower temperature, droplets will freeze immediately that it will tend to follow the original shape of the airfoil. The geometry of ice may also change depends on the size of the droplets of water.

![Figure 1. Horn Ice -10121 (left) and Streamwise Ice -20123 (right)](image)

#### 3.2. Airfoil Performance (XFLR5)
Airfoil performance degradation that caused by the ice accretion is needed for calculating the landing distance. \((C_L)_{max}, (C_L)_{20}, \text{ dan } (C_D)_{20}\) is used to predicting the landing distance. Airfoil performance data were obtained by XFLR5 and combined with previous wind tunnel experiment results. These data can be seen in Table 5.
Table 5. Iced Polar Data

| Shape  | Ice Case Code | XFLR5 | Correction Calculation |
|--------|---------------|-------|------------------------|
| Horn   |               |       |                        |
| -3121  | 2.0441        | 1.7314| 0.07713  2.3698  0.97612  0.108632 |
| -3122  | 1.9915        | 1.6472| 0.08022  2.3172  0.97612  0.108632 |
| -3123  | 2.1655        | 1.7072| 0.07939  2.4912  0.97612  0.108632 |
| -10121 | 1.7565        | 1.6884| 0.07773  2.0822  0.97612  0.108632 |
| -10122 | 1.8794        | 1.7359| 0.07654  2.3172  0.97612  0.108632 |
| -3111  | 2.1259        | 1.7159| 0.078  2.4516  0.97612  0.108632 |
| -3112  | 1.8314        | 1.6326| 0.07623  2.4912  0.97612  0.108632 |
| -3113  | 2.1611        | 1.7406| 0.07642  2.4868  0.97612  0.108632 |
| -10111 | 1.9504        | 1.7   | 0.0752  2.2761  0.97612  0.108632 |
| -10112 | 1.9983        | 1.7   | 0.076  2.324  0.97612  0.108632 |
| -10123 | 2.2069        | 1.757 | 0.07558  2.5326  1.009563  0.107746 |
| -20121 | 2.17          | 1.7388| 0.07577  2.4957  1.009563  0.107746 |
| -20122 | 2.1741        | 1.7247| 0.07723  2.4998  1.009563  0.107746 |
| -20123 | 2.1607        | 1.7268| 0.07692  2.4864  1.009563  0.107746 |
| -10113 | 2.2069        | 1.7544| 0.07549  2.5326  1.009563  0.107746 |
| -20111 | 2.1838        | 1.726 | 0.07822  2.5095  1.009563  0.107746 |
| -20112 | 2.185         | 1.7022| 0.08037  2.5107  1.009563  0.107746 |
| -20113 | 2.1787        | 1.745 | 0.07577  2.5044  1.009563  0.107746 |

The graphs show that generally horn ice shape airfoil have lower coefficient of lift and higher coefficient of drag compared to the streamwise ice. It caused by the horn ice shape that have more random geometry that it will cause flow separation at lower angle of attack.

3.3. Landing Distance

Figure 2 shows that ice accretion will affect the landing distance. As the coefficient of lift decrease, aircraft have to increase the speed to maintain the lift force. The more speed increased, the landing distance needed of the aircraft to become completely stop will be longer. But if it compared to the condition where the ice accretion does not occur, some of the data shows that smaller degradation coefficient of lift has shorter landing distance.

![Figure 2](image_url)
4. Conclusion
The maximum coefficient of lift horn ice shaped airfoil decrease within a range of 6.4% - 24.12% and the maximum coefficient of lift streamwise ice shaped airfoil decrease within a range of 4.64% - 6.637%. The most severe maximum coefficient of lift degradation occurred on (-10121) horn ice case. The results of landing distance calculation showed that the landing distance will have a deviation between -2.3% – 2.5% caused by horn ice and -1.6% – -1.1% caused by streamwise ice.

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