The Effects of Tailplane Ice Accretion on Flight Stability of Commuter Category Aircraft for High Terrain Remote Areas Flight Operation

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Abstract. The effect of ice accretion on the surface of the horizontal tail on aerodynamic characteristics and stability of commuter category aircraft is reviewed using predicted ice shapes and polar predictions using CFD software. Ice accretion prediction is carried out in various atmospheric conditions already listed in Appendix C FAR25 within remote high terrain flight operation condition. The predicted results of ice shapes are categorized according to the main shapes which will then be simulated using XFOIL. The resulting polar data then combined with data obtained from wind tunnel test to give lift coefficient predictions and the overall moment of the aircraft at zero flap condition. The most severe impact of ice accretion on the surface of the horizontal tail is found in the decreasing values of stalling angle of attack and maximum lift coefficient due to flow separation, with stalling angle of attack and maximum lift coefficient as low as 9.54 degrees and 0.765. The most visible decrease in static longitudinal stability and the static margin point are 6.88% and 6.34% from the normal condition.

1. Introduction
Commuter category aircraft development is important for short distance flight. While using commuter category aircraft can maintain the operational cost, it is also important to use commuter category aircraft that capable of taking off and landing on the short runway operating in remote and mountainous areas, especially on islands or Papua Region. The problem in high terrain remote areas flight operation is the likelihood of ice accretion because of certain weather [1]. To ensure the safety of an aircraft during flight, certification for flight in icing condition is required. Before undergoing the certification process, it is better to make predictions in advance to save the cost of developing the aircraft, such as the wind tunnel test. Prediction must be in accordance with applicable regulations with results as accurate as possible from the actual conditions. The purpose of this study was to obtain the degradation value of aerodynamic characteristics of horizontal tail commuter category aircraft and the aircraft flight stability parameters that experienced ice accretion, that can be used as a reference before undergoing the certification process.

2. Methodology
To obtain stability and static point margin of an aircraft, certain procedures have to be done starting from data retrieval of an aircraft. The flowchart shown in Figure 1 represents an overview of those procedures starting from data collection to analysis and discussion.
2.1. Determining Atmospheric and Flight Configuration

Ice accretion simulation using LEWICE requires atmospheric and flight configuration [2]. Atmospheric configuration parameters required are Liquid Water Content (LWC), Median Volume Diameter (MVD) of water droplet, and static ambient temperature. The flight configuration of a commuter category aircraft displayed in the following Table 1.

| Altitude (ft) | Weight (kg) | Airspeed (knot) | $\rho$ (kg/m$^3$) | $\alpha$ (deg.) |
|--------------|-------------|-----------------|------------------|----------------|
| 10000        | 7031        | 153.04          | 0.86             | 3.04           |
| 8000         | 7031        | 157.09          | 0.91             | 2.32           |

In addition to these geometry variables, the coordinates of the airfoil to be simulated must also be prepared first. In this study, the airfoil that is used is symmetrically modified trailing edge of NASA/LANGLEY MS (1) -0313 airfoil as shown in Figure 2.

![Figure 2. NASA / LANGLEY MS (1) -0313 airfoil](image)

After obtaining the input parameters, the simulation of ice accretion is done by using LEWICE code. The result of ice accretion simulation then simulated using XFOIL [3] with the same test conditions with the actual wind tunnel test, with the Reynolds number around $2.9 \times 10^6$ and Mach number of 0.2.

2.2. $C_L$ and $C_M$ Prediction

XFOIL simulation result is in the form of infinite wing lift polar, therefore, it is necessary to correct the lift polar into 3-dimensional or finite wing lift polar so that the simulation results of XFOIL can be used to predict the overall lift polar of the aircraft. The first thing to do is to get the lift slope of infinite wing lift polar, then the finite wing lift coefficient correction can be done using Prandtl’s Lifting Line theory [4].

Prediction is done by calculating the degradation of lift and moment coefficient on the horizontal stabilizer and substitute the degradation value into the wind tunnel results. To find the degradation of lift coefficient, the following equation is used [5]
After obtaining the degradation value of lift coefficient on the horizontal stabilizer, the next thing to do is predict the lift coefficient of the aircraft by using the following equation

\[ \Delta C_{L_h} = C_{L_{h, \text{clean}}} \eta_h \frac{s_h}{S} - C_{L_{h, \text{ice}}} \eta_h \frac{s_h}{S} \]  

(1)

The moment experienced by the aircraft is influenced by wing moment \( C_{M_{AC_w}} \) and the horizontal tail \( C_{M_{AC_h}} \) and the moment generated by the lift from the wing and horizontal tail with c.g. as the reference point, however, \( C_{M_{AC_h}} \) does not have such a large influence that it can be ignored.

\[ \Delta C_{M_h} = -\left( C_{L_{h, \text{clean}}} \eta_h \frac{s_h}{S} \frac{(x_{AC_h} - x_{c.g})}{c} - C_{L_{h, \text{ice}}} \eta_h \frac{s_h}{S} \frac{(x_{AC_h} - x_{c.g})}{c} \right) \]  

(3)

After obtaining the coefficient of moment degradation on the horizontal stabilizer, the next step is to predict the overall moment coefficient of the aircraft by using the following equation

\[ C_{M_{\text{ice}}} = C_{M} - \Delta C_{M_h} \]  

(4)

2.3. Stability and Static Margin Calculation

The stability characteristic can be examined taking into consideration the increased pitching moments by changing the angle of attack in trim conditions and calculated using the following formula

\[ C_{M_{\alpha}} = \frac{dC_{M}}{d\alpha} \]  

(5)

The slope of the moment coefficient \( C_{M_{\alpha}} \) is used to assess how stable a plane is. The calculation of the static position of the plane margin is done by using equation as follows

\[ S_{M} = -\frac{C_{M_{\alpha}}}{C_{L_{\alpha}}} \]  

(6)

3. Results and Discussion

Accreted ice from simulation results can be categorized into 2 types based on the aerodynamic effect [6], namely double horn and streamwise. At a temperature of about -5 °C, the ice accreted is double horn while the ice at -10 °C may change depending on the atmospheric configuration.

Table 2. Simulation results at -5 °C

| Name      | T (°C) | MVD (mic.) | LWC (g/m²) | Ice Shape      |
|-----------|-------|------------|-------------|----------------|
| 10kHW-5111 | -5    | 15         | 0.7         | Double Horn    |
| 10kHW-5112 | -5    | 25         | 0.4         | Double Horn    |
| 10kHW-5113 | -5    | 40         | 0.13        | Double Horn    |
| 8kHW-5111  | -5    | 15         | 0.7         | Double Horn    |
| 8kHW-5112  | -5    | 25         | 0.4         | Double Horn    |
| 8kHW-5113  | -5    | 40         | 0.13        | Double Horn    |

At a temperature of -5 °C, the resulting ices shown in Table 2 are always in the form of a double horn. The temperature conditions allow the droplets to hit the surface of the airfoil to flow aft stagnation point before freezing. Under the -5 °C temperature conditions, atmospheric configuration variations may affect ice thickness. Atmospheric configuration’s effect on ice thickness is due to the amount of air content in the air affecting the mass of water that can be frozen on the surface of the airfoil. The resulting ice shapes at -5 °C are shown in Figure 3.
Figure 3. Ice shapes at -5 °C

At -5 °C temperature conditions, there is a significant difference. The resulting ice simulation 8kHW-5113 and 10kHW-5113 has a smaller thickness than other simulation results and still follow the leading edge contours, although there is still an ice horn around the stagnation point.

Table 3. Simulation results at -10 °C

| Name          | T (°C) | MVD (mic.) | LWC (g/m³) | Ice Shape          |
|---------------|--------|------------|------------|--------------------|
| 10kHW-10111   | -10    | 15         | 0.6        | Double Horn        |
| 10kHW-10112   | -10    | 25         | 0.3        | Double Horn        |
| 10kHW-10113   | -10    | 40         | 0.1        | Streamwise         |
| 8kHW-10111    | -10    | 15         | 0.6        | Double Horn        |
| 8kHW-10112    | -10    | 25         | 0.3        | Double Horn        |
| 8kHW-10113    | -10    | 40         | 0.1        | Streamwise         |

In the streamwise case at -10 °C shown in Table 3, ice formation is affected by variations of LWC and MVD. This is evidenced by simulation 10kHW-10113 and 8kHW-5113, the resulting ice is precisely streamwise, unlike the others that produce double horn shapes as shown in Figure 4.

Figure 4. Ice shapes at -10 °C

Of the 12 ice shapes produced, only 5 ice shapes alone can be simulated using XFOIL software. The method used XFOIL has limitations in doing airfoil simulations are covered with ice, especially ice in the form of double horn. The simulation results are shown in Figure 5.
The graph above shows that the ice shape on the leading edge affects $\alpha_{\text{stall}}$ and $C_{\text{max}}$ of the airfoil. According to research conducted by Lee and Bragg [7], the decreasing value of $\alpha_{\text{stall}}$ and $C_{\text{max}}$ on ice-covered airfoils can be caused by separation bubble aft of the horn, one example is a double horn ice shape. The greatest effect is produced by ice in the form of double horn, however, the formation of ice does not exert too much influence on the slope lift of the airfoil. This means the effect of ice accretion on stability will not be dominant.

Horn ice’s main characteristic is the presence of large separation bubbles generated around the tip of the ice. The stagnation point usually lies in the formed ice, and the boundary layer cannot overcome the large pressure gradient loss on the ice tip, thus, the location of the flow separation is usually relatively fixed at the tip of the ice over a large $\alpha$ range. A separated shear layer undergoes a transition to a turbulent stream and then usually returns to the surface of the airfoil. The existence of a separation bubble causes a considerable change in the pressure distribution causing the decrease of the pitching moment and the lift generated.

In this study, predictions were performed using polar data from XFLR5 simulation results and wind tunnel test data. From the prediction calculation of $C_L$ and $C_M$ values, the value of $C_L$ and $C_M$ of an aircraft are presented in Figure 6.

**Figure 5.** Aerodynamic performance results of various ice shapes

**Figure 6.** Stability characteristics of various ice shapes

As seen from the graph above, the $C_L$ and $C_M$ values of the aircraft from the wind tunnel test are used as comparators with the predicted $C_L$ and $C_M$ values. The biggest slope lift change occurred on ice simulation result 8kHW-5113. Stability prediction results can be viewed in Table 4.
Table 4. Stability prediction results of various ice shapes

| Name                      | V (Mach) | Re (× 10⁶) | $C_L$ | $C_M$ | SM | %$C_M$ | %SM |
|---------------------------|----------|------------|-------|-------|----|--------|-----|
| Clean                     | 0.2      | 5          | 0.0927| -0.0286| 0.3087| 0      | 0   |
| 8kHW-5113                 | 0.2      | 5          | 0.0922| -0.0266| 0.2891| -6.88  | -6.34|
| 10kHW-5113                | 0.2      | 5          | 0.0923| -0.0271| 0.2931| -5.47  | -5.03|
| 10kHW-10112               | 0.2      | 5          | 0.0923| -0.0270| 0.2927| -5.62  | -5.17|
| 8kHW-101113               | 0.2      | 5          | 0.0928| -0.0291| 0.3130| 1.55   | 1.42 |
| 10kHW-10113               | 0.2      | 5          | 0.0928| -0.0291| 0.3139| 1.86   | 1.70 |

In the streamwise case, all the simulation results show an increase in the slope lift. Increased slope lift is caused by the effect of streamwise ice that is spread evenly on the leading edge tends to improve airfoil performance by increasing the length of the cross section of the airfoil to produce lift. Although the streamwise ice shapes in this study increased the slope lift of an airfoil, the increased slope lift produced was insignificant. Since the slope lift is directly proportional to the static longitudinal stability or $C_M$, then in the streamwise case, all the simulated ice results in increased stability.

4. Conclusion
The most significant aerodynamic performance degradation shown by various ice cases lies in the decrease of $\alpha_{\text{stall}}$ and $C_{\text{max}}$, while the lift slope does not change significantly but its effect on static longitudinal stability and Static Margin is still visible, with the most significant degradation shown by simulation 8kHW-5113 with $\alpha_{\text{stall}}$ and $C_{\text{max}}$ values are 9.5 degrees and 0.76 in zero elevator deflection condition. Prediction of flight stability parameters results showed that the most significant decrease in $C_M$ was caused by simulation 8kHW-5113 around 6.88%, with the reduction of SM equal to 6.34% from normal condition.

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References
[1] K. Mortensen, “CFD Simulations of an Airfoil With Leading Edge Ice Accretion,” no. August, pp. 1–117, 2008.
[2] W. B. Wright, “User’s manual for LEWICE version 3.2,” 2008.
[3] M. Drela, “XFOIL: An analysis and design system for low Reynolds number airfoils,” in Low Reynolds number aerodynamics, Springer, 1989, pp. 1–12.
[4] J. D. Anderson, Aircraft Performance and Design. McGraw-Hill, 1999.
[5] T. R. Yechout, “Introduction to Aircraft Flight Mechanics: Performance, Static Stability, Dynamic Stability, and Classical Feedback Control,” p. 700, 2003.
[6] M. Bragg, “Aircraft aerodynamic effects due to large droplet ice accretions,” in 34th Aerospace Sciences Meeting and Exhibit, American Institute of Aeronautics and Astronautics, 1996.
[7] S. Lee and M. B. Bragg, “Experimental Investigation of Simulated Large-Droplet Ice Shapes on Airfoil Aerodynamics,” J. Aircr., vol. 36, no. 5, pp. 844–850, Sep. 1999.