Wind Tunnel Testing Study of Segmented Slat with Simulated Icing for Civil Aircraft

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Abstract. Icing accretion on civil aircraft have a severe impact on safety and performance, and the leading edge icing of wing resulting in maximum lift coefficient reduction, drag increasing, stalling incidence forward, control and stability worsening and even stalling. This article is to explore aerodynamic characteristics variation of civil aircraft with simulated icing accretion on different segmented slats through the means of wind tunnel testing, and the typical aerodynamic characteristic parameters involve maximum lift coefficient, stalling incidence and lift-to-drag ratio. Forces and moments measurement for configurations of the cruising, take-off and landing had been carried out, the results and analysis of testing data could be used for anti-icing design and operation strategy making.

1. Introduction
Icing accretion on the surface of civil aircraft would bring severe impact on safety. 645 flight accidents caused by icing were recorded by NTSB database from 1978 to 2002[1]. Icing will change the aerodynamic shape and destroy the airflow field, and the icing accretion on the leading edge of wing result in maximum lift coefficient reduction, drag increasing, stalling incidence forward, control and stability worse and even stalling [2]. The countries and districts, such as The united states, Europe, China and Russia, have made airworthiness regulation on icing, and the applicant should prove that the transport aircraft could operate safely in the condition of icing according to the definition of appendix C in FAR25 and CS25[3][4], prediction of aerodynamics characteristics after icing is important for applicant to evaluate the performance and stability and assess the compliance with airworthiness.

Wind tunnel testing with simulated icing is an important means for prediction of aerodynamics characteristics after icing, which is clearly emphasized in airworthiness regulations [3]. Meanwhile the wind tunnel testing and analysis is also stated in Advisory Circular [5], the icing shape is realized by manufacture of simulated ice model, the ice model was installed on the aircraft model to be measured in the wind tunnel based on the flight conditions. Wind tunnel testing has a wider testing range, more accurate aerodynamics characteristics capturing ability after separation and lower risk compared to the CFD and flight test. Leading edge of transport aircraft is normally equipped anti-icing system, and study on icing accretion for different combination of slat segments is helpful for anti-icing design and de-icing. This article is to explore aerodynamic characteristics variation of civil aircraft with simulated icing accretion on different segmented slats through the mean of wind tunnel testing, the typical aerodynamic characteristic parameters involve maximum lift coefficient, stalling incidence and lift-to-drag ratio, and so on. Forces and moments measurement for configurations of the cruising, take-off and landing had been carried out, the results and analysis of testing data could be used for anti-icing design and operation strategy making.
2. Wing Tunnel Equipment and Models
The wind tunnel is FL-12 of China Aerodynamics Research and Development Center, which is a single-return low speed wind tunnel with a closed test section. The test section is 8m in length, 4m in width, and 3m in height, the cross section is rectangular with cut corners and the effective area is 10.72m². The maximum stable wind speed of the empty wind tunnel is 100m/s, the minimum stable wind speed is 10m/s, and the wind tunnel turbulence It is 0.12%, and the average airflow deflection angle is less than 0.1°. Full metal model of a certain passenger aircraft was used in this test, and scale is 1:13. The model includes wings, fuselage, flaps, nacelles, landing gear, etc. The abdominal support was adopted.

![Figure 1. Model installed in the wind tunnel.](image)

The corresponding flight altitude of this icing type is 5000m, liquid water content (LWC) is 0.451g/m³, Mean Volume Diameter (MVD) is 20μm, and the wing slats are the protection zone. 22.5 minutes of icing simulation, 45 minutes of icing in the winglet non-protected area. The slat simulated ice model fabricated in this test are divided into three segments: inner, middle and outer. The slat segment combinations used in the test are three types, namely S1 (inner slat with ice alone), S2+S3 (The inner section and the middle section slats with icing together), S1+S2+S3 (the inner, middle and outer slat sections with ice together, that is, the front edge of the wing is full of ice).

3. Testing conditions
The icing model of the slats simulate the protected area for 22.5 minutes’ icing after the failure of the anti-icing system. The winglets are in the non-protected area, and the icing in the simulated non-protected area is 45 minutes. Different slat icing instructions are indicated in Table 1. The testing wind speed is 70m/s, the angle of attack ranges from -6° to 24°, and the Reynolds number is 1.26×10⁶. The test configurations include icing and non-icing configurations for cruise, take-off, and landing.

| Area | Instruction                          |
|------|-------------------------------------|
| S1I  | Inner slat with 22.5minutes’ icing  |
| S2I  | Middle slat with 22.5minutes’ icing |
| S3I  | Outer slat with 22.5minutes’ icing  |
| WLI  | Winglet with 45 minutes’ icing      |

4. Testing Results and Analysis
As to the cruise configuration, it can be seen from Table 2 and Figures 2-5 that the combination of three different slats has a small effect on the slope of the lift line, the stalling angle of attack and the
longitudinal static stability, the influence is less than 3%. The inner slat reduces the maximum lift coefficient by 5.7% and the maximum lift-to-drag ratio by 14.2%; the inner and middle slat with ice combination reduces the maximum lift coefficient by 14.6% and the maximum lift-drag ratio by 20%; the full slat icing make maximum lift coefficient drop by 18.8%, and the maximum lift-to-drag ratio was reduced by 25%.

Table 2. Aerodynamic influence of icing for cruising configuration

| Area        | CLmax | αs | Kmax | CmCL |
|-------------|-------|----|------|------|
| S1I         | -5.7% | -0.4% | -14.2% | -0.3% |
| S1I + S2I   | -14.6% | -2.4% | -20.0% | -2.2% |
| S1I + S2I + S3I | -18.8% | -2.5% | -25.0% | -3.0% |

As to the take-off configuration, it can be seen from Table 3 and Figures 6 to 9 that the inner slat with ice reduces the maximum lift coefficient by 13.1%, the stall angle of attack moved forward by 18.2%, and reduces the maximum lift coefficient by 4%. Longitudinal static stability basically almost keeps constant; the inner and middle slat ice combination reduces the maximum lift coefficient by 18.1%, the stall angle of attack is advanced by 17.5%, and the maximum lift coefficient drops by 3.8%, which basically has no effect on the static stability; The influence on the maximum lift coefficient and the stall angle of attack is slightly greater than that of the inner middle segment.
Table 3. Aerodynamic influence of icing for take-off configuration

| Area          | $C_{L_{\text{max}}}$ | $\alpha_s$ | $K_{\text{max}}$ | $C_{mCL}$ |
|---------------|-----------------------|------------|------------------|-----------|
| S1I           | -13.1%                | -18.2%     | -4.0%            | 0.2%      |
| S1I + S2I     | -18.1%                | -17.5%     | -3.8%            | -0.4%     |
| S1I + S2I + S3I | -18.9%               | -18.7%     | -5.4%            | -0.9%     |

Figure 6. Lift coefficient for taking off. Figure 7. Pitch moment coefficient for taking off.

Figure 8. Drag coefficient for taking off. Figure 9. Lift-drag ratio for taking off.

As to the landing configuration, it can be seen from Table 4 and Figures 10-13 that the inner slat icing reduced the maximum lift coefficient by 3.4%, the stall angle of attack advanced by about 1.3%, and the maximum lift coefficient decreased by 1.5%, which has basically no effect on the static stability; the inner and middle slat ice combination reduces the maximum lift coefficient by 13.7, the stall angle of attack is advanced by 20.9%, and the maximum lift coefficient is reduced by 2.8%. The full slat with ice reduces the maximum lift coefficient by 15.1%, the stall angle of attack is advanced by 25.3%, the maximum lift is reduced by 4.4%, and the longitudinal static stability is reduced by 2.5%.

Table 4. Aerodynamic influence of icing for landing configuration

| Area          | $C_{L_{\text{max}}}$ | $\alpha_s$ | $K_{\text{max}}$ | $C_{mCL}$ |
|---------------|-----------------------|------------|------------------|-----------|
| S1I           | -3.4%                 | -1.3%      | -1.5%            | 0.0%      |
| S1I + S2I     | -13.7%                | -20.9%     | -2.8%            | -0.9%     |
| S1I + S2I + S3I | -15.1%               | -25.3%     | -4.4%            | -2.5%     |
Figure 10. Lift coefficient for landing.  Figure 11. Pitch moment coefficient for landing.

Figure 12. Drag coefficient for landing.  Figure 13. Lift-drag ratio for landing

5. Conclusion
Wind tunnel testing study of wing leading edge slat segmented icing of a civil aircraft was completed, and aerodynamic impact on the maximum lift coefficient, drag, stall angle of attack, maximum lift drag, and static stability under the cruising, takeoff and landing configuration were obtained and analyzed. The icing of the inner slat has almost same reduction on the maximum lift coefficient and the stall angle of attack for the cruise and landing configurations, and greater reduction on the takeoff configuration. The icing of the inner slat has a reduction on the maximum lift coefficient for the cruise configuration by 14%, and less than 5% for take-off and landing configuration. The icing of the middle and outer slats and the full wingspan has a greater reduction on the maximum lift coefficient of the three configurations, which is up to 18.9%. The reduction of the maximum lift-to-drag ratio for take-off and landing configuration is less than the cruise configuration. The above testing results could be used for aircraft safety and performance evaluation, and wind tunnel testing means in this article could be used for aircraft anti-icing design and operational strategy making.

References
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