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Engineering Notes

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Aircraft Characterization in Icing Using Flight-Test Data

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Introduction

THE effect of ice accretion on aircraft has been observed and systematically investigated since the 1940s. Aircraft icing degrades both the performance and control of aircraft by disrupting the flow of air over the aircraft. Excessive accretion can lead to flow separation, loss of control effectiveness, and stall of both the main wing and tail. Incidents such as the American Eagle roll upset near Roselawn, Indiana, in October 1994 and the Com Air accident in January 1997, are just two examples of the dangers of aircraft icing. Quantifying the amount of ice accretion, its effect on the aircraft and when the aircraft has reached the edge of its effective flight envelope is challenging. Different icing conditions lead to different types, sizes, and locations of ice accretion, which might or might not lead to significant loss of control and performance. The most straightforward way to monitor the effect of any type of icing is to measure, in flight, the stability and control derivatives and the trim state of the aircraft. Any change in these values, outside of those changes expected for a clean aircraft, would indicate that something, in this case icing, is affecting the control and performance of the aircraft.

Research into the effects of icing on aircraft has been ongoing since the 1940s when investigations into the effect of icing on propellers became a concern.[1] More recently, an investigation by Ranaudo et al.[2] found that glaze icing led to a decrease in lift of up to 10% and increased drag up to 55%. Estimates of stability and control derivatives for the Twin Otter were calculated from flight data, using a maximum likelihood method by Ranaudo et al. in 1986.[3] Reductions of 10 to 15% in horizontal tail pitching moment, elevator power, and elevator effectiveness were documented. Ratvasky and Ranaudo[4] observed similar results in 1993 using a modified stepwise regression analysis. They also recorded reductions in static stability of up to 10% and reductions in directional stability of up to 20% for the zero-thrust case. A recent NASA tailplane icing study[5] revealed significant reductions, over 30%, in elevator effectiveness with 40-deg flap deflection, as well as strong static instability at high angles of attack with 20 and 30 deg of flap deflection. These results were indicative of the problems leading to icing incidents during approach to landing.

In the winter of 2001 and 2002, a flight-test program was conducted, with the support of the NASA Glenn Research Center, to aid in the development of the Smart Icing System.[6] The primary goal was to identify the parameters that best indicated the onset of icing and the effects of various levels of icing on the performance and control of the aircraft. Additionally, it was important to identify the activation of the deicing system of the aircraft. To accomplish this, stability and control derivatives were extracted from the flight data using System Identification Programs for Aircraft (SIDPAC) in addition to trim and atmospheric data.

This research has shown that stability and control derivative estimation along with trim state estimation is an effective method to characterize an iced airplane in real time.

Results and Discussion

Flight data were analyzed using a set of programs called System Identification Programs for AirCraft[7] (SIDPAC); stability and control derivatives were extracted from the dynamic response of the aircraft to input control doublets. SIDPAC provided linear, quasi-steady-state identification from flight data. Results from this analysis are presented in this technical Note, including icing effects, detection of IPS activation, and correlations with icing severity.

Detailed results from the two flight tests were published by Whalen et al. in 2002 (Ref. 8) and 2004 (Ref. 9). A typical selective de-icing sequence is depicted in Figs. 1 and 2. Figure 1 presents the value of $C_{L\alpha}$ during the de-icing process. A set of doublets were carried out before entering the icing cloud and then after each component was de-iced. The aircraft was in icing conditions for approximately 20 min prior to the selective deicing. Figure 1 shows that, as expected, the only surface that substantially affected the value of $C_{L\alpha}$ was the wing. The flight log reported "lots of residuals" on the wing following the deicing, which led to a value of $C_{L\alpha}$ 7% below the clean value. Figure 2 reveals the effect on C_{D0} of de-icing the other components of the aircraft. De-icing the wing at 13:55 and the vertical stabilizer, wing struts and landing gear at 14:02 had the largest impact on the drag coefficient. De-icing of the horizontal stabilizer had little affect on the drag.

An investigation of the trim state of the airplane further reinforced the utility of parasite drag estimation in the identification of aircraft icing. Figure 3 is a plot of δe vs C_D, and Fig. 4 is a plot of δe vs α for

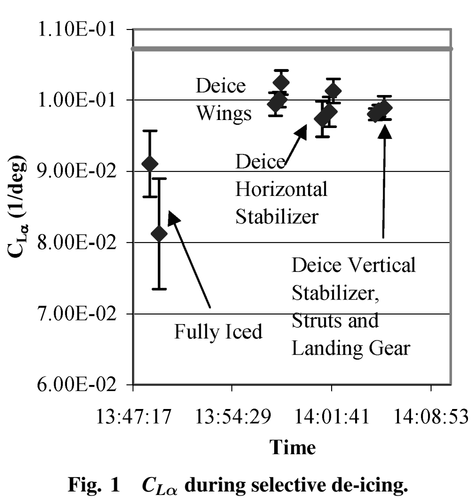

Fig. 1 $C_{L\alpha}$ **during selective de-icing.**

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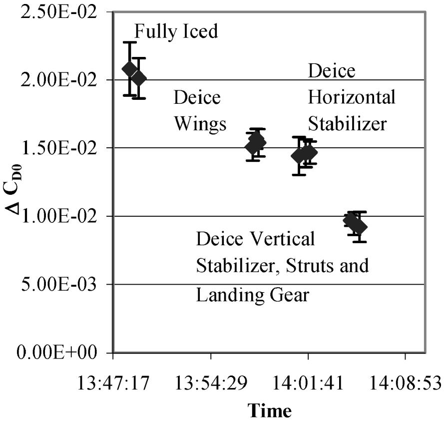

Fig. 2 ΔC_{D0} during selective de-icing.

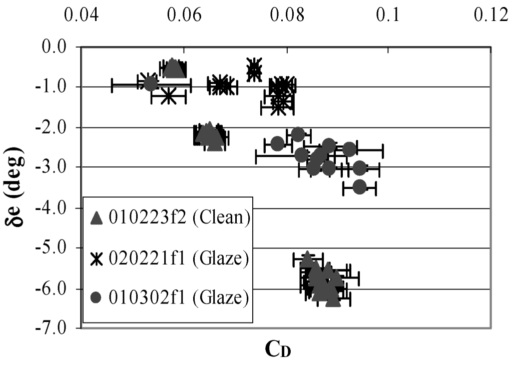

Fig. 3 Elevator deflection vs drag coefficient.

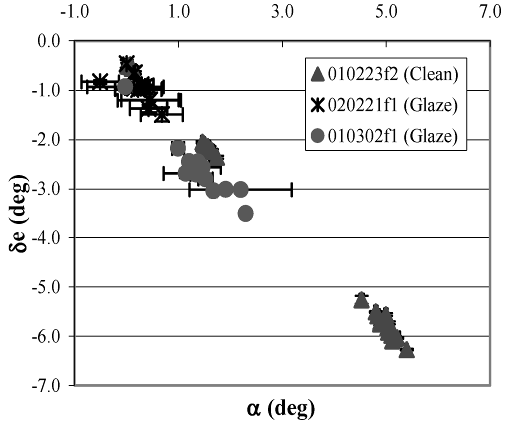

Fig. 4 Elevator deflection vs angle of attack.

two icing encounters. In each figure, data from the clean airplane were presented to establish a baseline trim state. Two icing flights are considered here and are compared to a baseline clean flight. The scatter in the icing data is caused by changes in the state of the airplane as a result of icing and de-icing.

Flight 010302f1 was conducted at a nominal trim speed of 110 kn. The clean trim point near -2.0-deg elevator deflection was obtained at 110 kn as well. Selective de-icing was used during this flight, as discussed earlier in this Note, and the stability and control derivatives varied throughout the flight. Figure 3 showed that the drag coefficient of the aircraft increased from 0.06 in the clean case to greater than 0.09 in the iced case. Figure 3 also showed that the elevator deflection to trim at 110 kn ($\delta e \approx -2$ deg) increased by over 0.5 deg in some cases. Thrust coefficient was higher for flight 010302f1, $C_T \sim 0.08$, vs the baseline, $C_T \sim 0.06$. However, Ratvasky and Ranaudo showed that elevator effectiveness increased with thrust coefficient, which is the opposite of the trend observed. This indicated that the elevator had lost some effectiveness as a result of the ice accretion. Also, the high drag coefficient indicated that, in addition to the wing, the airplane was most likely contaminated with a significant amount of ice on the unprotected areas of the airplane.

Flight 020221f1 was another glaze ice encounter with selective de-icing, this time at 130 kn. This flight was conducted at a nominal trim airspeed of 130 kn. For reference, the clean trim point near -0.5-deg elevator deflection (Fig. 3) was also obtained at 130 kn. During that flight, the airplane was de-iced component by component once and completely de-iced for the final doublet maneuvers. The airplane maintained steady level flight over an angle-of-attack range of approximately 1 deg, with a significant increase in drag of up to 50% over the baseline value. However, the increase in elevator deflection to trim, when compared to the clean curve, was small compared to flight 010302f1. The angle of attack to trim did vary by approximately 1 deg during the flight (Fig. 4), most likely because of variations in airspeed, but the elevator required to trim that angle of attack followed the clean trim curve. This indicated that the elevator effectiveness was not significantly degraded. Again, a significant increase in drag was observed as a result of ice buildup on unprotected areas of the airplane.

Using trim variables to identify and characterize the effects of icing on airplanes has shown to be a useful tool especially when used to supplement traditional parameter identification methods. Changes in drag coefficient, trim lift coefficient, and trim elevator deflection can easily be detected from trim data and are not significantly affected by atmospheric turbulence. These changes indicate specific effects of icing on the stability and control and performance of the airplane.

Atmospheric turbulence substantially degraded the accuracy of the stability and control estimates calculated by SIDPAC. SIDPAC identification incorporates an instrument calibration step that uses a data compatibility analysis based on the kinematic relations of the flight dynamics to provide maximum likelihood estimates of instrument biases and scale factors. Ideally, the scale factor would be zero if the flight data were consistent with the kinematic relations. However, because the kinematic relations used in the data compatibility analysis do not include turbulence effects, the turbulence can result in biased estimates of the instrument scale factors and biases. These biased estimates, in turn, can introduce biases into the spacecraft derivative estimates. However, C_{D0} estimates, as well as other trim variables estimates, were not significantly affected by the turbulence and are capable of indicating icing onset as well as overall icing severity.

Combining both stability and control derivative estimates with trim state estimates resulted in a robust method for identifying the effects of icing on airplane performance and control. The synthesis of these two techniques is critical to overcoming the effects of turbulence on stability and control estimates.

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