AERODYNAMICS OF SUPERCOOLED-LARGE-DROPLET ICE ACCRETIONS AND THE EFFECT ON AIRCRAFT CONTROL

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ABSTRACT

The effect of large-droplet ice accretion on aircraft control is examined. Supercooled-large-droplet icing conditions can result in the formation of a ridge of ice aft of the upper surface boot. By comparing this ice shape to data acquired with a spanwise protuberance on an airfoil, it is clear that a ridge of ice aft of the boot can lead to large losses in lift, increases in drag and changes in the pitching moment. This effect is most likely due to the formation of a large separation bubble aft of the ice accretion which grows with angle of attack and eventually fails to reattach, leading to premature airfoil stall. The bubble alters the pressure distribution about the airfoil resulting in a more trailing edge up (negative) hinge moment on the aileron and the resulting change in aileron stick force. This can lead to aileron hinge moment reversal and aileron snatch. The fundamental aerodynamic cause of this lateral control problem is the same as that experienced when elevator control is lost due to horizontal tail stall.

INTRODUCTION

It is well known that ice formation on aircraft surfaces can lead to deterioration of performance and handling characteristics. Loss of aircraft control, where structural ice accretion has been identified as a probable cause, has in some cases been attributed to the presence of supercooled large droplets (SLD) in the atmosphere.

Supercooled large drops (SLD) can form in several ways[1]. One way for the SLD to form is through the melting of snow as it falls through a warm layer of air. This can happen when a warm frontal layer penetrates through a cold layer of air, causing a temperature inversion with increasing altitude. Clouds above the warm layer produce snow which melts while falling through the warm layer and forms drizzle or rain drops. As the drops continue to fall, they enter the colder air layer again and are not likely to freeze again until they impact an object. If the lower cold air layer is at a sufficiently low temperature, the drops may freeze in the air to form ice pellets.

SLD may also form from smaller cloud drops. Droplets falling at different speeds can collide with one another and coalesce to form larger drops. The presence of wind shear and a stable thermodynamic profile near stratiform cloud tops has been attributed to enhanced mixing and increased drop size[1].

On October 31 1994, an ATR-72 commuter aircraft crashed near Roselawn Indiana after loss of control in icing conditions. The meteorological conditions in the region of aircraft's holding pattern just prior to the accident suggested the possibility of the development of supercooled drizzle[1]. Supercooled large droplets, in the range of 30-400 mm, have been encountered by research aircraft while collecting data on effects of ice accretion on aircraft performance[2-5]. The reduction in the aircraft performance was reported to be unusually large during this encounter. Measured drag increased by as much as a factor of two, while the lift decreased more than 60%[5]. In another flight test in icing conditions, the worst icing encounter was identified as freezing rain[6]. The formation of ice during that encounter was described as ridges downstream of the leading edge on the wing and tails. Other accidents have also occurred due to the loss of aircraft control in conditions where SLD may have been present[7].

Recent flight tests behind a tanker at Edwards Air Force Base to reproduce large droplet icing conditions caused the formation of ice ridges downstream of the de-icing boots which might have led to an uncommanded roll[8]. Uncommanded roll was identified as the probable cause of three separate An-12 aircraft accidents[9]. The formation of ice upstream of the ailerons was cited as the cause of flow separation on the wing which led to the reversal of aileron hinge moment.

Aircraft designed many years ago experienced aileron control problems with ice, Fig.1. The measurements by Johnson[10] showed lack of aileron control power with leading-edge ice. Brumby[11] reports that a relatively small amount of ice on the wing of a commercial transport caused an accident on takeoff due to the loss of roll control. Several other loss of lateral control due to ice anecdotes have appeared in the literature as well.

The phenomenon of ice accretion leading to reduced aircraft control has been observed and documented for over 50 years. This has primarily been for Appendix C type icing clouds, but there is also evidence of large droplet icing also causing control problems. It is the intent of this paper, and its predecessor[12], to identify the underlying aerodynamic causes of reduced aircraft control due to large droplet ice accretions. A recent paper by Ashenden et al.[13] presents lift and drag data on an airfoil with computer generated large-droplet ice accretion but does not address

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the control problem. The focus of this paper is aircraft control with large droplet-ice accretion and particularly focusing on aileron control.

DISCUSSION

Ice Accretion

It is well known that as the droplet size increases, the droplet inertia increases, and droplet impingement moves further back on the airfoil surface. The combination of this, with temperatures near freezing, leads to ice accretion shapes which are only now beginning to be studied. As part of the ATR 72 accident investigation, the Air Force icing tanker was modified to produce large droplets in the 100-200 micron range. A typical ice accretion obtained on the ATR-72 test aircraft[14] is shown in Fig. 2. This ice accretion was formed at 180 KIAS, T = -2 C, MVD = 140 microns, LWC = 0.3 g/m^3 for 17.5 minutes. Fig. 4a is with the flaps at 0 degrees and Fig. 4b at 15 degrees.

With no flap deflection, the ridge of ice is seen to form aft of the de-icer boot, ahead of the 9 percent chord location on the upper surface with a small ridge also formed on the lower surface. The ridge was found to be jagged in most cases and discontinuous in the spanwise direction. When ice was accreted with the flaps at 15 degrees, the ice accretion moved back on the airfoil upper surface with a ridge at 9% and accretion to 16%. This occurred due to the reduction in angle of attack required with flaps to maintain the same lift coefficient. Therefore, the result was more exposure of the upper surface to the icing cloud and impingement further back on the upper surface. The maximum ridge height on the upper surface for the conditions tested was 0.75 inches and 0.5 inches on the lower surface. Similar results have been obtained in the Icing Research Tunnel at NASA Lewis[15].

Aerodynamics of Large Droplet Accretions

In 1932 Jacobs[16] conducted wind tunnel tests on an NACA 0012 airfoil to determine the effect of spanwise protuberances on the aerodynamic characteristics. The experiments were conducted at Re = 3.1×10^6 with the purpose of documenting the effects of "small projecting objects such as fittings, tubes, wires, rivet heads, lap joints, butt straps, filler caps, inspection plates and many other projections" on the performance of the airfoil. The airfoil with the locations of the spanwise protuberances are shown in Fig. 3. The protuberances were duralumin sheets placed in slots in the wing, one at a time, which acted as forward and aft facing steps. The chordwise width of the protuberance was not reported, but heights of k/c = 0.0004, 0.001, 0.002, 0.005 and 0.0125 were tested. For the large droplet case, the ice accretion shown in Fig. 2 occurs between the x/c=0.05 and 0.15 protuberances tested by Jacobs. The maximum height of 3/4 inch seen in the large-droplet tanker test ice accretions has a k/c = 0.0106 based on an airfoil chord at the aileron midspan location of 5.9 ft. At the conditions of the tanker test, this section would have been operating at a chord Reynolds number of 8.95×10^6. The NACA test was conducted at sufficiently high Reynolds number that with these roughness heights, which are very large compared to the local boundary-layer thickness, the simulation should be representative of the behavior of airfoils with large-droplet ice accretions at full-scale commuter aircraft Reynolds numbers.

In Fig. 4 section lift, drag and pitching moment results are shown for the NACA 0012 airfoil with 4 different roughness height protuberances all at x/c=0.05 on the airfoil upper surface. For protuberances of k/c=0.001 and 0.002 the effect on lift is a slight reduction in lift curve slope and a sizable reduction in maximum lift. For k/c=0.005 the lift curve is further reduced, but here only a local maximum in lift is seen with the lift continuing to increase as angle of attack is increased. This trend is continued for k/c=0.0125 with no maximum or local maximum seen in lift. The lift breaks sharply around α = 6°, becomes almost constant until α = 12°, where it increases again at a reduced, but linear, lift curve slope. The drag polar in Fig. 6 b) shows that this loss in lift is accompanied by a large increase in drag, especially for the 2 largest protuberance sizes. The pitching moment data in Fig. 6 c) shows a much more negative, nose down, pitching moment for the k/c=0.0125 case starting at α = 6° where the lift curve breaks. The effect on pitching moment is much less for the smaller roughness cases where the primary effect is a reduced maximum lift at almost the same stall angle. For the large roughness, this change in moment is indicative of a large change in pressure distribution on the airfoil which accompanies the loss in lift. A NACA 0012 airfoil has much of its lift on the forward part of the airfoil. A loss in lift on the forward part of the airfoil along with an increase in lift on the aft part of the airfoil due to the separation would account for the large increase in nose-down moment.

The data of Jacobs[16] can also be used to determine the effect of protuberance location on lift loss. Figure 5 shows the measured lift on the airfoil with the k/c=0.0125 protuberance at 5 different surface locations. For angles of attack in the 8 to 16 degree range the largest lift loss is due to the protuberance at the x/c=0.05 location on the upper surface. The lift with the protuberance at x/c= 0. and 0.15 is higher at all angles in this range. With the protuberance at the leading edge, a very gentle stall is seen at a reduced angle from the clean case with a large reduction in maximum lift. The x/c=0.15 case behaves much like the x/c=0.05 case described earlier where around α = 6° a large reduction in lift curve slope is observed. A protuberance on the lower surface had almost no effect on the airfoil lift. Wenzinger and Bowen[17] tested round and flat spoilers on the upper surface of a 3-D wing in the Langley 19-foot wind tunnel. The effect on lift and drag was very similar to that seen by Jacobs. Wenzinger and Bowen concluded that the largest lift loss came from the spoiler placed on the upper surface between 5 and 20% chord. Therefore, for the large droplet ice accretion case, the observed upper surface ice accretion locations of between 7 and 9% chord are in the most sensitive region on the airfoil for loss in lift due to a protuberance.

Figure 6 provides some information as to the effect of the shape of the cross-section of the protuberance on the lift loss[16]. Jacobs faired some of the protuberances using plaster-of-Paris to make them approximately 1/2 airfoil shape. The effect on the lift for the k/c=0.005 protuberance at x/c=0.05 on the upper surface is quite dramatic. Here the maximum lift is increased from 0.82 to 1.27 by fairing the protuberance as compared to the clean airfoil maximum lift of 1.52. The reduction in the drag coefficient is also dramatic. These data demonstrate that the shape of the protuberance has a significant effect on the resulting aerodynamic penalty. Again, similar results were reported by Wenzinger and Bowen[17] showing flat spoilers more effective than round spoilers. Jacobs does not report the exact shape of the faired or original protuberance, but the large-droplet ice accretion will most likely fall some place between these two shapes. No data on the effect of a spanwise variation in the protuberance as might be expected on an ice accretion could be found in the literature.

The lift performance of the airfoil with the large protuberance at x/c=0.05 and 0.15 as seen in Fig. 6 is very similar to that seen on an airfoil which experiences thin airfoil stall[18,19]. In thin airfoil stall, a separation bubble forms from the airfoil leading edge and grows in chordwise extent as the angle of attack is increased. When the bubble fails to reattach, or reaches the trailing edge, the airfoil stalls. In most sections a discontinuity can be seen in the lift versus angle of attack curve at the angle of attack where the bubble forms and begins to grow, Fig. 7. In some sections, the discontinuity can be so large due to the sudden and rapid growth of the bubble as to actually cause a local maximum in lift, followed by increased lift as α is increased further. This type of behavior is seen in Fig. 6 in the unfaired protuberance data. The k/c=0.0125 protuberance caused a discontinuity in the lift at $\alpha = 6°$ when placed at x/c=0.05 or 0.15, Fig. 7. This is probably due to the thin airfoil-like behavior of the separation due to the protuberance. As the angle of attack reaches 6°, the separation bubble caused by the protuberance grows rapidly, causing the abrupt change in lift performance at this angle. Above this angle of attack, the bubble grows more slowly with angle of attack. This slow growth effectively decambers the airfoil reducing the lift curve slope. The bubble reduces the suction peak pressure and in creases the load on the aft airfoil resulting in the more negative, nose down, pitching moment which was measured, Fig. 4.

Thin airfoil stall behavior has been observed before on an airfoil with a simulated leading-edge ice accretion. Bragg et. al.[20,21,22] tested simulated gaze ice accretions on a NACA 0012 airfoil. The airfoil experienced a large separation bubble aft of the upper surface horn which grew in chordwise extent as the angle of attack was increased, Fig. 8. At 6 degrees and above the flow was very unsteady and the bubble failed to reattach in a time averaged sense. This corresponds to the measured lift coefficient for the clean and iced airfoil shown in Fig. 9. The iced airfoil has a slightly reduced lift curve slope at low angles, but the most dramatic effect is the large break in the lift above 5 degrees. This is where the bubble grows rapidly and eventually failed to reattach to the surface. No measurements were taken above $\alpha = 9°$ due to the large unsteady loads on the model. It is possible that the lift would have increased as α was further increased. This leading-edge ice accretion, simulating a conventional Appendix C cloud encounter, is indeed behaving much like the cases with a large protuberance near the leading edge measured by Jacobs[16]. It also has all the characteristics of a very severe thin airfoil stall. The pressure distribution confirms that this is a thin airfoil stall. In Fig. 10 the pressure distribution[20] for the clean airfoil is compared to the simulated ice case at three angles of attack. At $\alpha = 4°$ the spike in Cp seen on the leading edge of the clean airfoil is replace by a region of constant pressure. This constant pressure region is due to the separation bubble aft of the ice horn. As the angle of attack increases, the constant pressure region grows as the bubble grows in length. At $\alpha = 8°$ the separation bubble fails to reattach and the character of the pressure distribution changes. Note the almost constant pressure region extends to x/c = 0.40 with only a small amount of pressure recovery occurring from this location to the trailing edge (i.e. the Cp at the trailing edge is much more negative indicating a lower pressure). The effect of this large change in trailing-edge pressure on an aileron will be discussed later. These pressure distributions are very similar to those on an airfoil with thin airfoil stall, such as in Fig. 9.

In this section the aerodynamics of an airfoil with a large-droplet ice accretion have been examined using prior studies on airfoils with protuberances, thin airfoil stall and a large leading-edge ice accretion. Based on this analysis it is very likely that an airfoil with a large-droplet ice accretion behaves as shown in Fig. 11. The ice accretion causes a separation bubble to form aft of the ice accretion. At low angles of attack the effect is a reduction in lift curve slope and a small change in zero lift angle of attack. In some angle of attack range depending on the size and location of the ice accretion, the separation grows rapidly causing a large change in lift curve slope and maybe a local maximum in lift coefficient. Further increase in α sees the lift increase again, but at a much reduced lift curve slope. Similar aerodynamic effects were seen on an airfoil with a leading-edge ice accretion. There are not enough data at this time to compare the aerodynamic effects of leading-edge and large-droplet ice accretions. In fact, it maybe that for smaller ice accretion and ice roughness the stall mechanism may be enhanced trailing-edge stall and not the thin airfoil or leading-edge stall discussed above. However, based on Jacobs' work, it may be that ice accretions on the upper surface, back slightly from the leading edge produce larger aerodynamic penalties for the same ice accretion height.

Aerodynamic Hinge Moments

Perhaps the most dangerous effect of ice accretion on aircraft is the change in the pilot's ability to control the aircraft. Not only are the effectiveness of the controls crucial, but also the feedback the pilot receives through the hinge moments and ultimately the stick forces. In this section, the basics of control surface hinge moments will be reviewed, followed by a discussion of how ice accretion on the wing can affect the aileron control.

Background

Elevators, ailerons and the rudder are used to provide the pilot with a means to control of the aircraft in pitch, roll and yaw, respectively. These control surfaces are typically plain flaps mounted on the trailing-edge sections of the respective airfoils. A plain flap is simply some portion of the airfoil trailing-edge (typically .15c to .20c) that is hinged about a point within the contour. If no gap is present as a result of the hinge, deflecting the flap essentially changes the camber of the airfoil. For a given section angle of attack, a plain flap of 0.20c is capable of producing increments in sectional lift ranging up to about 1.0.[23] Deflection of the flap also increases the $C_{\ell\,max}$ of the section. When used as ailerons, the plain flaps on each side of the wing are deflected asymmetrically.

The pressure distribution over a control surface creates a moment about the control surface hinge referred to as a hinge moment. If the control surface is free to float, or move without restriction, it will rotate up or down depending upon the pressure distribution over the surface. For most cases, the low pressure created over the upper surface (suction side) of the wing will cause the control surface to want to rotate trailing edge up (toward the suction side).

For a given airfoil, there are two major variables which control the pressure distribution over the control surface. These are the angle of attack of the section and the deflection angle of the flap or control surface. Changes in both the angle of attack of the section and deflection angle of the control surface affect the pressure distribution over the entire airfoil and as a result change the magnitude of the hinge moment. The magnitude of the hinge moment for any combination of sectional angle of attack and control surface deflection angle can be developed from a linear summation of the effects of each. Typical pressure distributions for a section at zero degrees angle of attack, but with varying control surface deflection angles, along with pressure distributions resulting simply from changes in angle of attack are shown in Fig. 12. The suction created over the upper surface of the flap as the flap is deflected downward can be represented as the reaction R acting through the centroid of the pressure area and thereby creating the hinge moment about the hinge line. Stick force is usually considered positive when, in an unpowered system, it opposes an aerodynamically generated positive hinge moment. Stick forces and hinge moment are in reality much more complicated than presented here. Stick force trim, nonlinear effects, dynamic effects, etc. have been ignored here, but are covered in some detail in many books[24]. In addition, aileron stick force results from the combination of the hinge moment produced by the right and left ailerons which are deflected in opposite directions to produce the desired rolling moment.

Effect of Ice on Hinge Moments

The effect of ice accretion on control effectiveness and control feel can be quite pronounced. These serious effects are the result of flow separation due to the presence of the ice accretion. When the amount of flow separation is small, usually at low angle of attack or small ice accretions, the effect on aircraft control is also small. However, tests (see Figs. 4, 5, 6 and 9) show that the break in the lift curve, and therefore the onset of large regions of separated flow, begins at lower angles of attack with simulated ice on the airfoil. This early separation leads to a larger suction force on the top of the control surface and therefore a more negative hinge moment than would exist on the uniced airfoil. Compare the pressure distributions shown in Fig. 10 with and without simulated ice. The lift just ahead of the trailing edge is much larger on the iced airfoil due to the separation induced by the ice shape. As a result, there is a large increase in trailing-edge up (negative) hinge moment.

The effect of ice accretion and early flow separation on the horizontal tail was addressed by Ingelman-Sundberg and Trunov[25] and later by Trunov and Ingelman-Sunberg[26]. Figure 13 shows lift and elevator hinge moment for a 3-D horizontal tail tested on a force balance in a wind tunnel. The tail was tested with a hinge moment balance on the elevator. Several different ice accretion simulations were tested as shown. Note that the airfoil leading edge tested was modified from its original shape to increase the leading-edge radius to simulate the NACA 0012 airfoil. The tail was tested at negative angles of attack simulating the download needed at low speed during landing. All the ice simulations tested, even the leading-edge roughness (S5) reduced the maximum lift coefficient significantly. The hinge moment becomes more positive as the iced tail plane stalls. Therefore, at an angle of attack after the iced tail stalls, but before the clean tail stall, the hinge moment is approximately twice as large. This corresponds to a trailing-edge down moment since the tail is at a negative angle of attack. Although the ice simulations are of conventional leading-edge ice, and not large-droplet ice accretions, this effect is similar to what would be expected for large-droplet ice as well.

Trunov and Ingelman-Sundberg[26] show the same relationship between the airfoil pressure distribution and control surface hinge moment as discussed earlier. In Fig.14, taken from their report, the pressure distribution shows the results of an ice induced separation which is apparently of a thin airfoil or leading edge stall type. This can be determined noting the almost constant pressure on the forward lower surface of the airfoil. In this case the suction side is the airfoil lower surface due to the negative angles of attack.

In Fig. 15 pressure distributions from three airfoils[18] have been integrated to yield the aileron hinge moment for a 20% chord plain flap at zero degrees flap deflection. The NACA 63-018 airfoil has a gradual trailing-edge stall, while the NACA 64A006 and the double diamond airfoil (see also Fig. 7) both have thin airfoil stalls which are thought to be similar to that occurring on iced airfoils. Note that when the leading-edge separation bubble grows rapidly on the diamond airfoil at 6 degrees angle of attack, a large trailing-edge up hinge moment is generated. The trailing-edge stall airfoil which can be thought of as the uniced airfoil, has a much more gentle break in its C_h curve and at much higher angle of attack.

It should be clear now that when the flow about an airfoil begins to separate, the pressure distribution changes, which produces a large change in control surface hinge moment. This occurs whether an ice accretion is present on the airfoil or not. However, with the ice accretion present it will typically occur at lower angle of attack and at lower lift coefficient. The control surface may still be effective at this point, but the maximum lift of the surface is reduced and therefore the maximum force that can be generated by the entire surface is reduced. The change in hinge moment, and therefore control force in an unpowered control system is a even larger potential hazard for the safety of the flight.

Trunov and Ingelman-Sundberg[26] cover the effect of ice on the horizontal tail and its effect on elevator effectiveness and hinge moments. Therefore, here a brief analysis of the effect on the aileron will be presented in the context of a recent aircraft accident.

Iced wing roll upset

The digital flight data recorder trace[27] of the recent ATR accident which occurred near Roselawn Indiana provides a good example of the effect of ice on aileron control. Ten seconds prior to disengaging the autopilot the aircraft was flying with 15° flaps down, slightly nose down and in a 15° bank to the right. In the 7 seconds before autopilot disconnect, the flaps were retracted from 15° to 0° and as a result the aircraft angle of attack increased from around zero to over 5°. When the autopilot was disengaged, the aircraft ailerons deflected rapidly to over 10 degrees right aileron up, left down and the aircraft rolled to approximately 70° right wing down. During the roll the aircraft pitched nose down and the angle of attack was reduced. The bank angle reduced momentarily, but as the angle of attack increased again the aircraft rolled further to the right and pitched down drastically. Control was lost and an accident occurred.

Based on the tanker flight tests[14] it is likely that a spanwise ridge of ice existed on the aircraft wing at the 9% wing chord station ahead of the ailerons. At the warm temperatures thought to be present, it is very plausible that the ice accretion was asymmetric due to self shedding. Assume that the ice accretion was more severe on the right wing ahead of the ailerons. At low angle of attack before massive separation occurred on this wing, little change in aileron hinge moment or control effectiveness would result, Fig. 13. However, as the flaps were retracted and the angle of attack was increased, the flow began to separate on the iced right wing and the hinge moment became more trailing edge up on this wing. This resulted in a change in stick force required, and a force to the left being required to maintain the desired roll angle. However, this force was unknown to the pilot since the autopilot was on and supplied this control force.

The autopilot disconnected shortly after the wing flaps reached 0° and slightly before the wing angle of attack reached its maximum value of over 5°. The aileron deflected rapidly to the right (right aileron up and left down) at this time. If the pilot, for what ever reason, does not oppose the separation induced hinge moment with sufficient control force, the ailerons will deflect as described. This self induced roll is referred to as aileron snatch. The reduction in angle of attack which occurred shortly after the initial roll reduced the ice induced separation, reducing the right aileron up hinge moment, and allowing the roll to be temporarily reduced. However, when the angle of attack increased for the second time, the roll increased again due to the same affect on the aileron hinge moment.

So the likely aerodynamic explanation was a significant large-droplet ice accretion on the right wing which caused early flow separation as the angle of attack was increased. This resulted in a trailing-edge up hinge moment on the right wing and an aileron snatch when not accounted for when the autopilot disconnect occurred. The result was a rapid roll to the right and loss of control of the aircraft.

SUMMARY

Large droplet icing conditions can result in the formation of a ridge of ice aft of the upper surface boot. By comparing this ice shape to data acquired with a spanwise protuberance on a different airfoil it is clear that this can lead to large losses in lift, increases in drag and changes in the pitching moment. This effect is most likely due to the formation of a large separation bubble aft of the ice accretion which grows with angle of attack and eventually fails to reattach leading to premature airfoil stall. This is very similar to the flowfield observed on airfoils with thin airfoil stall and leading-edge ice accretions which have similar lift performance.

The upper surface bubble alters the entire pressure distribution about the airfoil. In particular, it greatly reduces the surface pressure on the upper surface of any trailing edge flap (aileron or elevator). For an airfoil at positive angle of attack this results in a more trailing edge up (negative) hinge moment and a change in stick force. In a severe case on a wing, this could lead to aileron hinge moment reversal and aileron snatch. In aileron snatch the hinge moments are altered to the extent that the aileron is pulled up by the low pressure on the top with sufficient force to induce a rapid roll if a large stick force is not immediately exerted to oppose it. It is possible that this could have occurred in the recent ATR accident.

It has been speculated that this problem may be peculiar to aircraft with “modern” airfoils and only occur with large-droplet ice accretions. However, there is evidence in the literature, some of it reviewed here, which shows that similar lateral control problems are possible with other types of ice accretions and on older designed airfoils. Also, horizontal tail stall control problems due to essentially the same aerodynamic phenomena are not limited to “modern airfoils”.

There simply is not enough research to know if some airfoils behave in a significantly different way with ice than other airfoils. Most research on the aerodynamic effect of ice on airfoils has been on older sections. This problem is now being addressed by NASA and more information should be available in the future. What is clear is that all airfoils are in some degree susceptible to a loss in performance due to the accretion of ice and a change in control surface hinge moments and that this should be considered in the design and operation of the aircraft.

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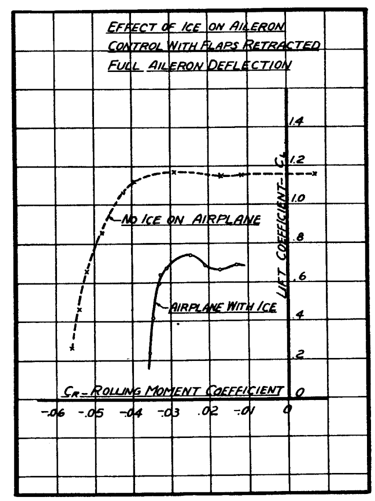
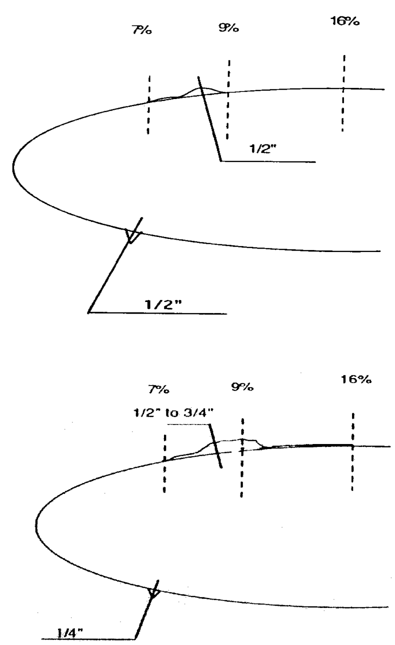


Figure 1. Effect of ice on aileron control[10].



a)

b)

Figure 2. Icing tanker large droplet ice accretion[14]. (180 KIAS, T = -2 C, MVD = 140 microns, LWC = 0.3 g/m^3, 17.5 minutes, with a) δ_f = 0 deg and b) δ_f = 15 deg.)

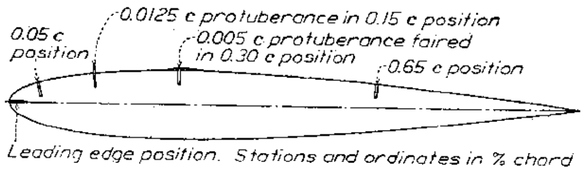


Figure 3. Airfoil and protuberance geometry[16].

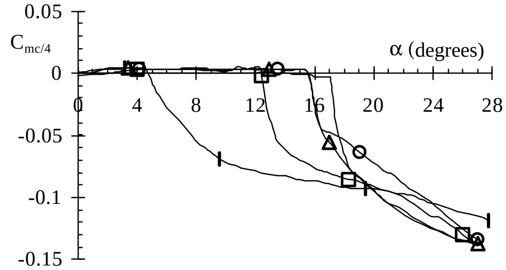
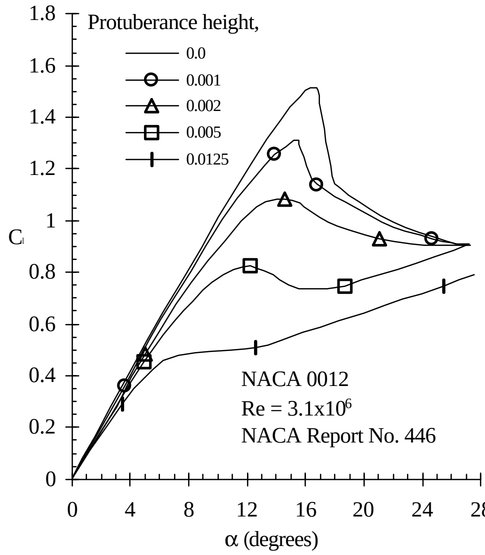
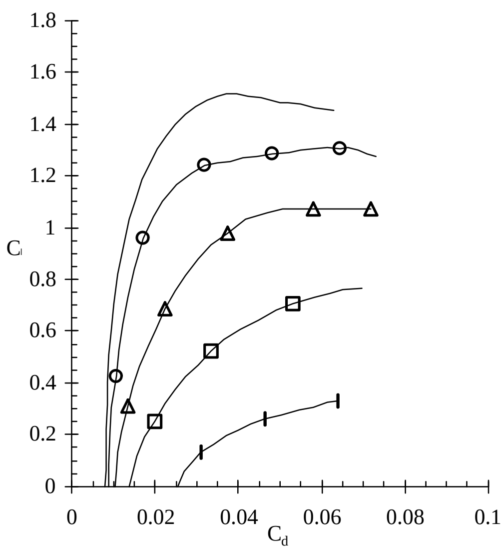
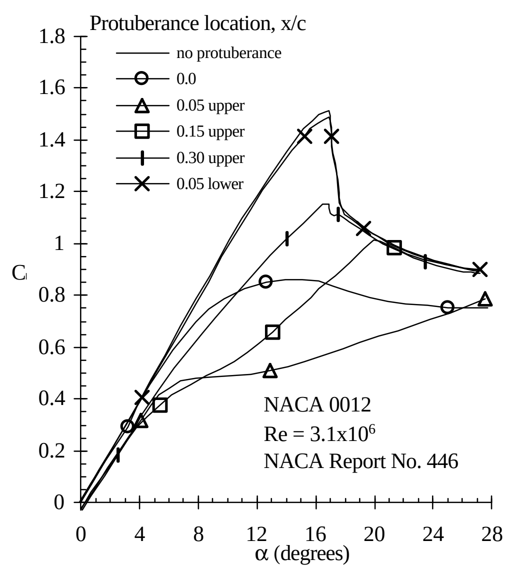


Figure 4. Airfoil performance with protuberance at x/c=0.05 on the upper surface[16].



a)





b)

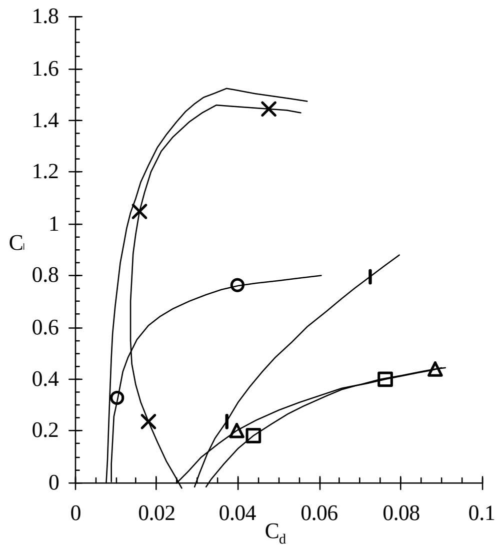


Figure 5. Airfoil performance with 0.0125c protuberance at 5 locations[16].

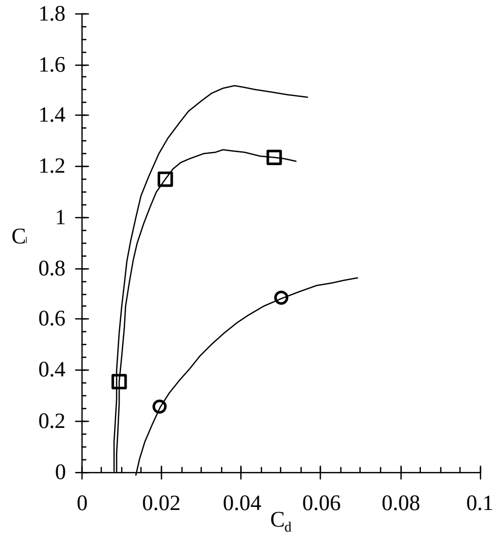
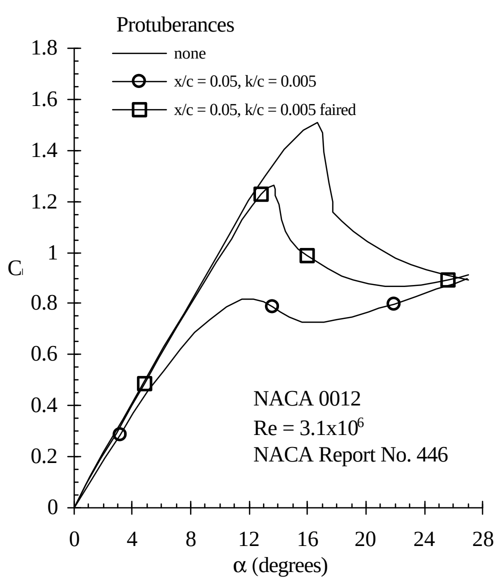


Figure 6. Effect of fairing the 0.005c protuberance at x/c=0.05[16].

a)



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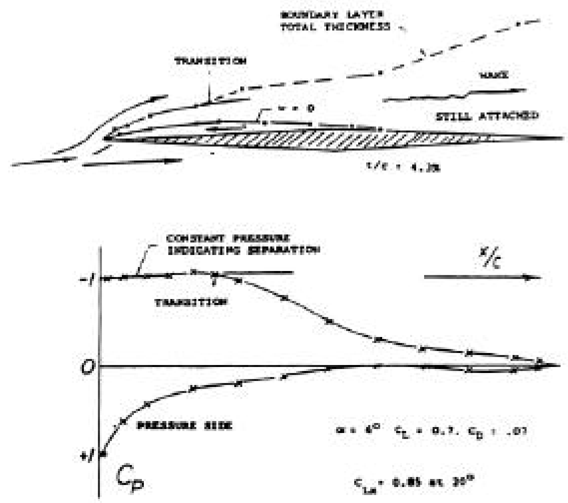

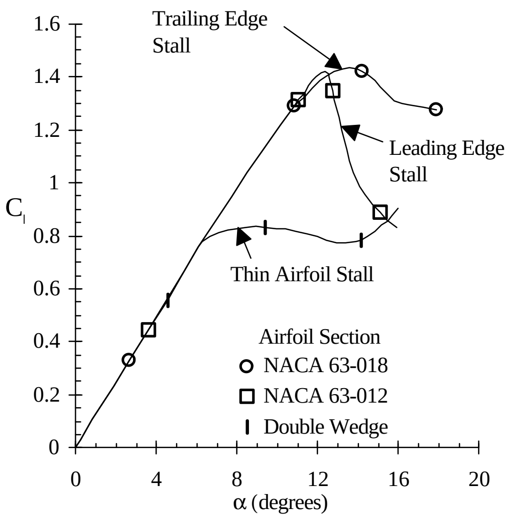

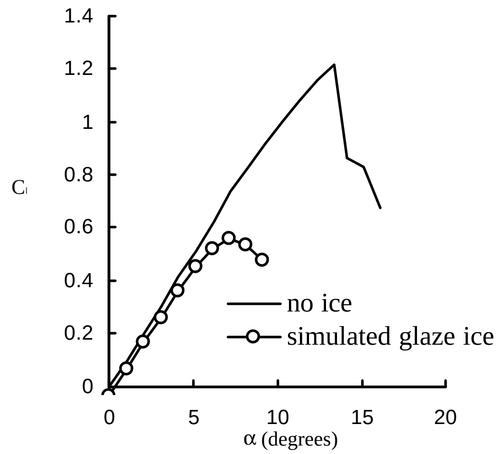

Figure 7. Thin airfoil stall[18,19]. a) diamond airfoil flowfield at stall, b) diamond airfoil Cp at stall, and c) lift of diamond airfoil and other airfoils.

Figure 9. Lift performance of an airfoil with leading-edge ice[21].

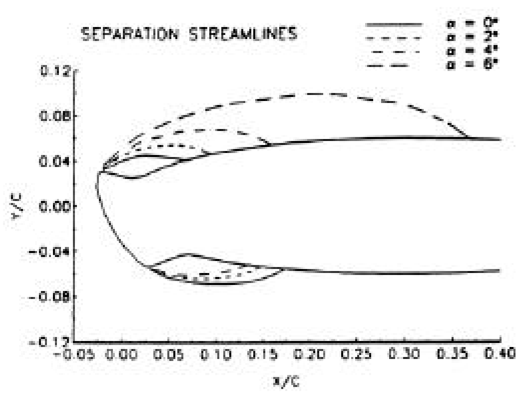

Figure 8. Separation bubble due to a leading-edge ice accretion[22].

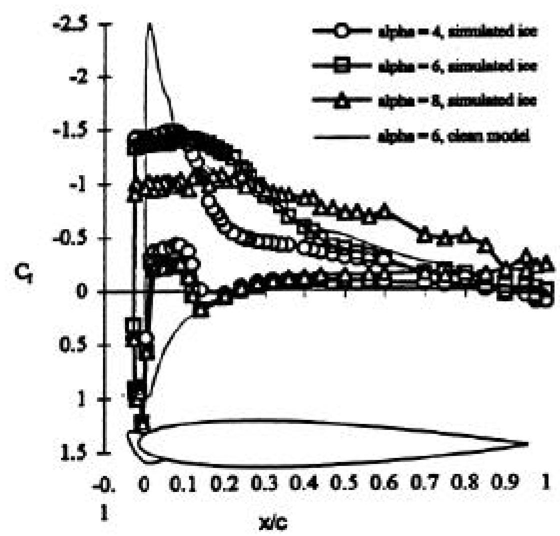

Figure 10. Pressure distribution on an airfoil with leading-edge ice[21].

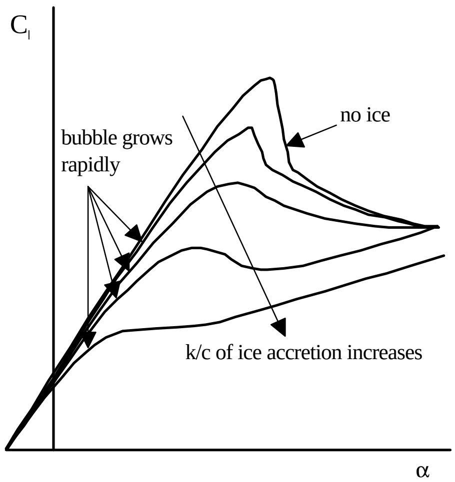

Figure 11. Possible flowfield and lift of an airfoil with a large-droplet ice accretion.

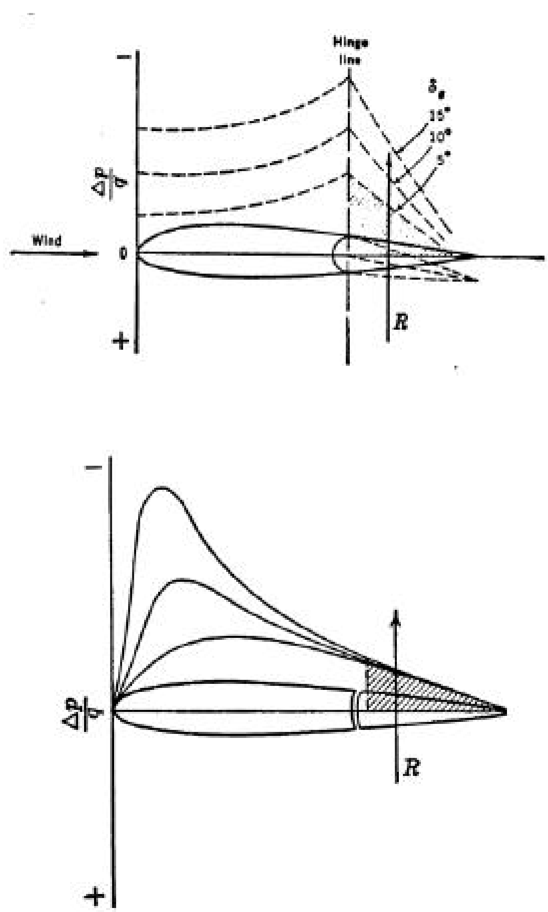

Figure 12. Pressure distribution for an airfoil with control surface deflected (above) and at three angles of attack (below).[24]

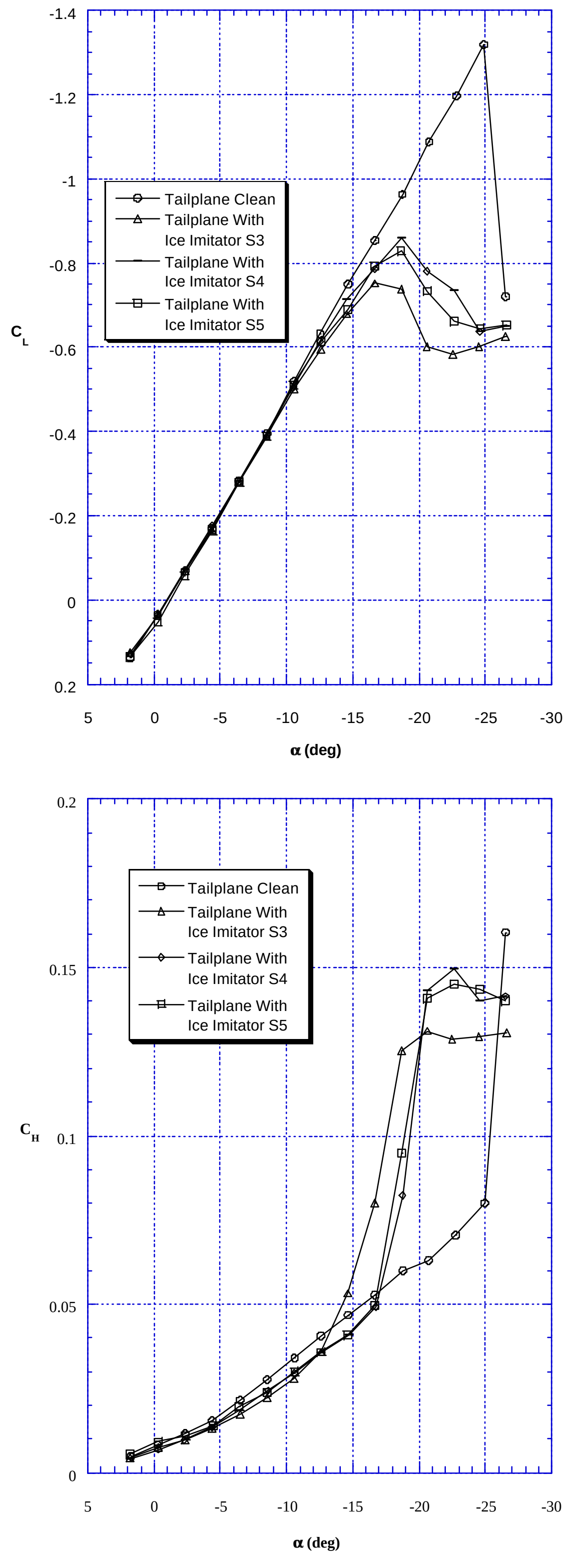

Fig 13. Effect of Icing on Horizontal Tail with Simulated Leading-Edge Thickness Addition[26].

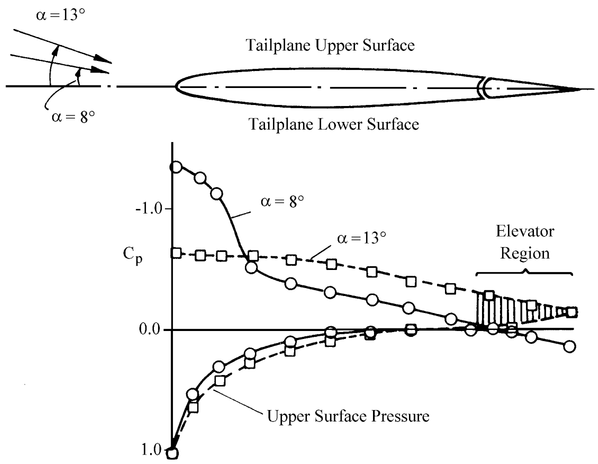

Fig. 14. Change in pressure distribution due to ice induced separation[26].

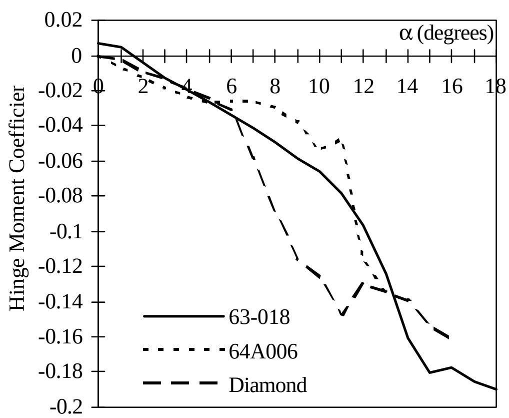

Figure 15. Hinge moments on airfoils with 20% chord plain flaps at δ_f=0. (derived from data in ref. 18)