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An Interdisciplinary Approach to Inflight Aircraft Icing Safety

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Abstract

Aircraft accidents in icing conditions are primarily the results of the degradation in performance and control due to the aerodynamic effects of the ice. However, despite recent advances in the ability to identify these changes, the icing sensors currently in use sense only ice thickness or accretion rate at the sensor location. No aircraft performance degradation information is available to the pilot. In this paper, a smart icing system is proposed based on the ability to sense the effect of ice on the aircraft performance, stability and control. This concept is proposed through the addition of an Ice Management System to the aircraft. This system would add an additional level of safety to supplement the current avoidance and ice protection concepts currently in use. Such a system would sense ice accretion through traditional icing sensors and use modern system identification methods to estimate aircraft performance and control changes. This information would be used to automatically operate ice protection systems, provide aircraft envelope protection and, if icing was severe, adapt the flight controls. All of this must be properly communicated to and coordinated with the flight crew. The design of such a system requires a coordinated interdisciplinary approach. In addition to describing the basic concept, this paper reviews the research needed in three critical areas; aerodynamics and flight mechanics, aircraft controls, and human factors.

1.0 Introduction

The development of safe and affordable aircraft must include better solutions for flight in icing and severe weather conditions. Between 1975 and 1988 there were 803 icing-related aviation accidents with about one-half of these resulting in fatalities.[1] Recent icing accidents, such as the American Eagle crash that killed 68 people near Roselawn, Indiana in October 1994, clearly show that icing continues to be a serious safety hazard. The FAA forecasts that if the current accident rate holds constant, and the growth in air transportation continues at the current rate, there will be more than 4,500 air travel fatalities per year worldwide by 2025. Even the current rate, about 800 fatalities per year, is unacceptable and must be improved. In response, former Secretary of Transportation Pena stressed that the only acceptable safety goal is "zero accidents".[2] To achieve this goal, proactive steps must be taken to improve safety – merely correcting the problems that led to the last accident will never achieve "zero accidents". Recently NASA has responded to the challenge from the President's Commission on Aviation Safety and Security to develop a national aviation safety research plan (ASIST). Aircraft icing was determined to be a high national priority during this process.[3]

Recent commercial aircraft icing accidents have been due to three primary causes. For large-jet transports, accidents such as the Air Florida Boeing 737 at Washington National Airport in 1982, and several more recent accidents, were the result of improper ground de-icing. In the particular instance of the Air Florida accident, reduced thrust due to an iced engine sensor and reduced aerodynamic performance due to the accumulation of ice and snow on the aircraft prior to takeoff led to the accident. Turbo-prop aircraft have suffered ice-related takeoff accidents as well as accidents due to two additional causes; tailplane stall and roll upset.

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In both of these cases the accumulation of ice on the aircraft led to loss of control. This loss of control may be the result of reduced control effectiveness or changes in control forces on aircraft with unpowered controls.

Consider the ATR 72 aircraft which had experienced several roll anomalies prior to the roll upset accident in 1994.[4] The cause of this accident was determined to be ice accretion on the wings and the resulting loss in aileron control.[4,5] The ice accreted aft of the operating wing de-icing system due to exposure to supercooled large droplets, SLD, which accreted aft of the wing boots. The overall ice protection system on this aircraft had evolved into a fairly sophisticated system. Inflight information on the icing encounter was provided to the pilots through an ice evidence probe, IEP, and through the anti-icing advisory system, AAS. This system alerts the flight crew to the presence of ice as sensed with an electronic ice detector which activates a flashing amber light on the flight deck and a single aural chime. If the ice protection system is activated in Level II, which includes propeller and engine protection as well as control surface horn anti-ice, the stall protection system is modified to an iced aircraft mode.[4]

The ATR stall protection system, SPS, controls the envelope protection features of the aircraft. The multi-function computer receives various aircraft information including whether the IPS is in Level II, in which case it sets the angle of attack, AOA, at which the aural warning, stick shaker and stick pusher occur. When Level II or higher is activated, the AOA at which envelope protection occurs is reduced. For the baseline case, IPS activation decreases the AOA from 18.1° to 11.2° for the start of the aural warning and stick shaker. This margin is a design feature set by the manufacturer and is not modified based on any inflight icing information. For the ATR accident, the roll anomaly occurred at about 5° AOA when flow separation from the iced wing caused a reversal in aileron control force.[5] Therefore, the SPS failed to protect the aircraft against the roll upset which occurred since it was set at too high an AOA. The system was designed to protect for the worst case set by the designer and could not adapt to the actual conditions experienced by the aircraft.

Modification of the flight envelope to protect aircraft can occur in various forms in different classes of aircraft. The simplest scheme is for the pilot to increase takeoff and landing speeds to avoid high angle of attack where stall and loss of performance and control may occur. Certain configurations may also be restricted in icing conditions. From the simple pilot-based approach, to the more sophisticated ATR stall protection system, current envelope protection schemes can not adapt to the actual icing conditions.

Another cause of aircraft icing incidents and accidents has been the failure of the flight crew to activate the ice protection system in a timely fashion, or IPS failure, when icing conditions are encountered in flight. Included in this category of accidents are failure to properly ground de-ice prior to takeoff. Many of these accidents and incidents involve flame out of the engine due to improper or no operation of the engine ice protection. For example a Boeing 757 incident occurred in 1992 in Miami when both engines flamed out on approach when engine anti-ice had not been activated by the pilots. Numerous accidents/incidents can be found in the NTSB statistics when aircraft have lost control on landing due to failure to properly de-ice the aircraft.

Aircraft icing accidents are caused by the effect of ice accretion on the performance, stability and control of the aircraft. Accidents occur when aircraft are not properly protected against ice accretion either on the ground or inflight. Little if any information about the state of the aircraft in terms of performance, stability and control in icing conditions is available to the pilot. The ATR 72 digital flight data recorder, DFDR, recorded 96 distinct parameters including aileron position, roll attitude, and many other parameters relevant to the accident. While a careful analysis of these data during the post-crash investigation was critical in determining the cause of the accident, none of this information was available to help the flight crew prevent the accident. A reasonable person might ask, whether it would not be possible to use these data during a flight to prevent aircraft accidents.

If we are serious about an order of magnitude reduction in aircraft accidents, including icing accidents, we must learn how to use all the information available during a flight. The research to accomplish this goal must be multi-disciplinary and include experts in human factors, aircraft controls, aerodynamics, propulsion, flight mechanics, and aircraft icing. This paper describes the concept and the research necessary to develop a new and innovative human-centered automated system, a smart icing system, which has the potential to improve aviation safety in icing conditions.

2.0 Approach

The new approach to aircraft icing safety, that will be presented and discussed in this paper, is principally a better way to manage the ice protection system and the operation of an aircraft in icing conditions where some degradation in performance and control can be anticipated. However, this safety system or concept is not intended to operate in a vacuum from other, well established icing safety procedures.

2.1 Current Systems

The safest way to operate when icing conditions exist in the atmosphere is, of course, to avoid these conditions. Whether through the use of strategic weather information in the preflight planning process or the use of new systems which will be developed to provide tactical weather information, ice avoidance is a viable safety strategy in many situations. Ice avoidance is certainly the safest icing strategy for small aircraft and other unprotected aircraft. It may also be the best strategy for larger aircraft when severe icing conditions, such as freezing rain and drizzle, are present.

Another well developed safety strategy is ice protection. The ideal system would anti-ice the entire aircraft such that no ice would accrete anywhere on the airframe or propulsion system. This, of course, is not practical. However, many aircraft have excellent ice protection systems, IPS, which combine de-ice and anti-ice systems to provide overall aircraft protection. The concept proposed in this paper is intended to work in unison with the IPS to provide an additional level of safety beyond that provided by a simple IPS system. Since for a variety of reasons aircraft can not always avoid ice, and since during encounters situations arise which jeopardize safety, additional safety measures are required for a meaningful reduction in icing accidents beyond current levels.

The current model of an aircraft encountering icing conditions is depicted in Fig. 1. As ice accretes on the aircraft the ice accretion sensors relay this information to the pilot. This could include a variety of means, from simple visual detection by the flight crew to sophisticated electronic sensors. In most cases, this then leads to the appropriate pilot response which is to activate the ice protection system, IPS. If the pilot activates the IPS, this is referred to as an advisory system. Less common is a primary system where the ice protection system is automatically activated. At any point in time, with or without the IPS on, the ice accretion on the aircraft affects the aircraft dynamics (performance, stability and control) through its impact on the propulsion system and aircraft aerodynamics. This may be relatively small for a well anti-iced aircraft, or quite large for an aircraft with no IPS operating. The pilot or the automation system (auto-pilot system) interacts through the usual flight control inputs to control the flight path of the aircraft. This is done without any situation-specific knowledge of the change in aircraft dynamics caused by the ice, except what is fed back through the pilot/automation's perception of the input/output response of the system. Simple envelope protection functions may be included, such as a change in stick shaker angle of attack.

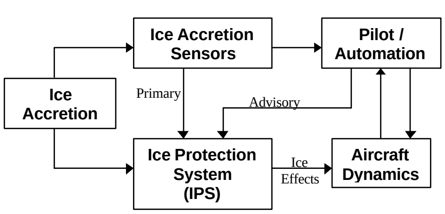

Fig. 1. Current aircraft icing encounter model

2.2 New Approach

The new approach described below adds another level of safety. Assume that for whatever reason the icing conditions are not avoided and that flight through icing conditions is required. The aircraft is equipped with a state-of-the-art IPS, but now an additional level of safety is available through the Ice Management System, IMS, depicted in Fig. 2.

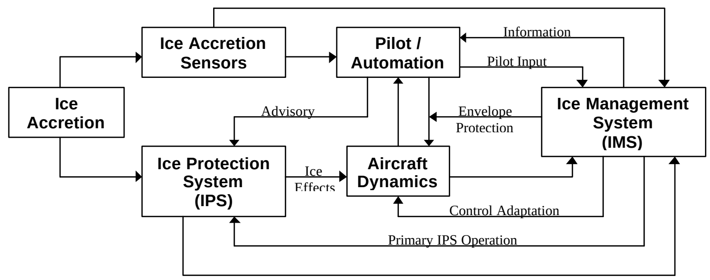

Fig. 2. New aircraft icing encounter model

The new model shown in Fig. 2 is similar to the current model with the addition of the Ice Management System, IMS, box on the right-hand side. The purpose of the IMS is to monitor the ice accretion and its effect, and assist the pilot/automation in the safe operation of the aircraft in the iced aircraft state. The operation of the IMS can be summarized by the three functions below:

1. Sense the presence of ice accretion including its effect on measured aircraft performance, stability and control. Sense ice accretion and ice protection system performance.
2. Automatically activate and manage the ice protection systems, and provide the pilot with feedback on the system status and behavior of both the aircraft and the ice protection system.
3. If the performance degradation becomes significant, modify the aircraft flight envelope by use of the flight control system to avoid conditions where flight could potentially be uncontrollable. Notify the pilot of this action and its implications for the flight envelope.

The fundamental principle behind the IMS is that the important effect of ice on an aircraft is its influence on the performance, stability and control of the aircraft system. Safety will be achieved in an ice tolerant aircraft if the pilot/aircraft system can continue to maintain the desired flight path with an acceptable safety margin, regardless of atmospheric icing conditions.

To accomplish these objectives the IMS would receive inputs from the traditional ice sensors, the IPS system, flight crew, the aircraft flight dynamics and other aircraft state information. The IMS would control the IPS much as a primary ice protection system does now; however, it would have several other functions. The IMS would analyze the available information to determine the effect of the ice accretion on the aircraft performance, stability and control. All of this information would then be used to provide flight envelope protection based on the actual, real-time ice accretion experienced by the aircraft. This could include angle of attack protection through the stick shaker as is commonly done today; however, the angle of attack for stick shaker would be a variable determined by the IMS. Other envelope protection features could also be supplied through a digital flight control system. These might include maximum g loads, bank angles, control deflections, flap deflections, pitch and roll rates, etc.

As an additional level of safety control adaptation could be added. Control adaptation, or reconfigurable controls, would modify the control laws to maintain acceptable flying qualities in the presence of the effects of the ice accretion. This would be most useful in emergency situations where, for some reason, the aircraft was allowed to accrete significant ice. Reconfiguring the control laws would allow the pilot/automation to maintain control of the aircraft within some limited flight envelope until the icing conditions could be exited safely.

Figure 3 illustrates the concept underlying the proposed new icing safety system. We can think of this overall system as a series of defenses-in-depth[6] where multiple layers of protective mechanisms are introduced to reduce the likelihood of mishaps. Each layer has gaps that may be penetrated as a result of failures, errors, or violations. However, a complete accident trajectory becomes possible only if all gaps are lined up precisely - a very unlikely event. The first layer of protection in the current approach to icing safety is avoidance of icing conditions. If this step fails or is not feasible, the ice protection system (IPS) is engaged to prevent ice accretion. In the current model, the IPS is the last defense mechanism which, if unsuccessful, requires the pilot to take over in a potentially uncontrollable situation. In contrast, the proposed new system introduces yet another layer between the IPS and the pilot - the ice management system (IMS) - whose function is to compensate for the effects of icing on performance, stability, and control. These effects, if uncorrected, can lead, and actually have led, to aircraft accidents. Our goal is to develop techniques that will allow the IMS to assess these effects in flight, to counteract them in appropriate ways, and to keep the pilot informed about the icing situation and the intentions, actions, and limitations of the system.

2.3 Summary

The new icing safety system proposed has been summarized in terms of the operation of a new Ice Management System, IMS. This approach assumes that

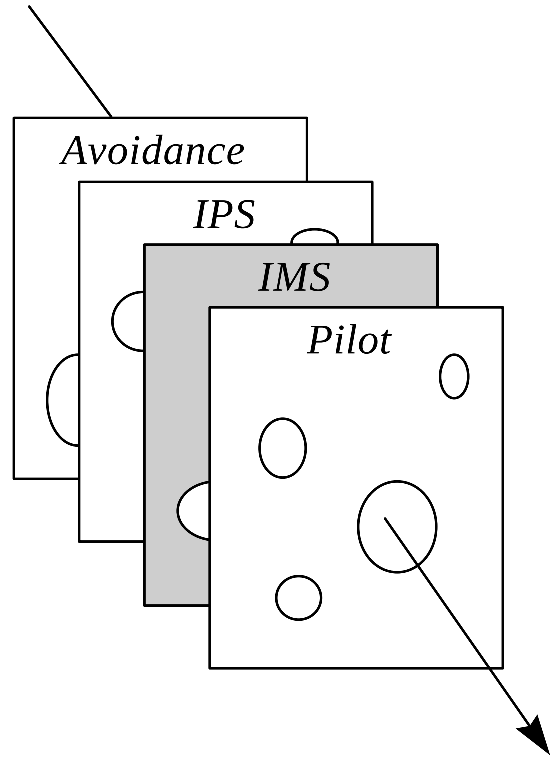

Fig. 3. “Defenses-in-depth” - An icing event penetrating the various layers of defense including the new IMS (adapted from Maurino et al.[6])

regardless of the IPS, ice accretion can and will occur in some situations. The aircraft must then be protected from the changes in performance, stability and control which, if left uncorrected, can lead to aircraft accidents. Thus the first step is to better understand the effects of ice accretion on aircraft. Then techniques to assess these effects in flight must be developed. This information must then be processed and supplied to the pilot in an appropriate way. These issues are dealt with in more detail in the aerodynamics and flight mechanics, aircraft controls, and the human factors sections to follow.

3. Aerodynamics and Flight Mechanics

In the system described in Fig. 2 the effect of ice on the aircraft is determined by the IMS. In this section the effect of ice on aircraft performance, stability and control is reviewed. Due to the inherent nonlinearity in the aerodynamics with ice accretion, challenges are anticipated and discussed.

The effect of ice accretion on the aerodynamics of an airfoil section is well known. Due to the change in airfoil geometry and added surface roughness the 2-D body suffers an increase in drag and a reduction in maximum lift, $C_{l\,max}$, at a reduced angle of attack. Reductions in lift-curve slope may also occur. Reductions in $C_{l\ max}$ of 20-30% are typical and 50% is not uncommon. Drag may rise by several hundred percent. Until recently these were the effects most often considered. However, after the recent roll upset and horizontal tail stall accidents, the effect on pitching moment and control-surface hinge moment are also recognized as critical for some aircraft.[7] These effects on the wing and tail surfaces, in addition to the effect of ice on the non-flying surfaces and propulsion system, combine to produce the overall impact of ice on the aircraft. While aerodynamic data on airfoils with real and simulated ice are widely available, little data are available which describe the effect of ice on an entire aircraft. This is due in part to the inability to obtain quality data at the low Reynolds numbers available in wind tunnels and, therefore, most available data are from flight tests in actual or simulated icing. The discussion here will be divided into a performance section, and a stability and control section. Most icing aircraft accidents can be classified as either loss of performance or loss of control events. This is based on the most critical effect of the ice which led to the accident.[8] It is thus appropriate to divide this discussion accordingly.

3.1 Aerodynamics and Performance

Classical aircraft performance provides maximum climb rates, range, endurance and their corresponding speeds as well as takeoff, landing and maneuver performance, maximum speeds and stall speeds, etc. These performance parameters can be easily derived for an aircraft in a known atmosphere from a knowledge of the aircraft lift versus angle of attack, drag polar and engine performance. Therefore, the effect of ice on aircraft performance is usually reduced to its affect on the aerodynamic quantities, lift and drag. Aircraft aerodynamics are thus intimately connected to aircraft performance.

One of the earliest successful attempts to measure the effect of ice accretion on aircraft was that of Preston and Blackman[9] in 1948. The effect of natural ice on the drag and propeller performance of a C-46 aircraft was measured in flight. Here 87% of the icing encounters had propeller efficiency losses of less that 10%. In one flight an encounter of LWC = 0.4 g/m^3, MVD = 17 µm and 50 min duration resulted in an 81% increase in parasite drag and the “control response of the airplane approached the point of being marginal.”

The effect of ice on the performance of high performance piston-propeller general aviation aircraft has been presented by Leckman.[10] Calculated performance for a Cessna Centurion and Skymaster in continuous maximum conditions were presented along with some flight data at various icing conditions. Leckman estimated for the Centurion a drag coefficient rise of ΔC_{D0} = 0.055 with no ice protection and 0.0179 due to residual ice and increased drag of unprotected surfaces with the ice protection system operating. These correspond to a 275% increase without protection and a 90% rise with protection over the clean drag coefficient, C_{D0} = 0.020. This has a significant effect on the aircraft performance. For example the rate of climb at sea level was reduced from 940 fpm clean to 530 fpm with the ice protection operating to only 80 fpm with no ice protection. These estimates are for a severe, worst case encounter of glaze ice at LWC = 0.46 g/m^3, MVD = 20 µm for 200 miles which corresponded to about 1 inch of ice on the wings. Lift was also affected. Flight test data with ¼ inch rough glaze ice increased the stall speed from 75 mph clean to 102 mph at zero flap deflection and from 65 to 83 mph at 30 degrees flap deflection. Flight data on the Skymaster was presented for several ice thicknesses. An interesting trend was observed which was that a large maximum lift (or stall speed) penalty was measured due to a small accretion (1/8 inch) with only small additional penalties recorded as the ice grew to 1 3/8 inch. However, the drag continued to increase significantly with larger ice accretions.

Ranaudo et al.[11] have reported very carefully obtained performance flight test results for two natural icing encounters on the NASA Lewis Twin Otter aircraft. Figures 4 and 5 from ref. 11 show the measured effect of glaze ice on the lift and drag performance of the Twin Otter aircraft at a high power setting. The icing conditions were 45 minutes at 131 kts with average cloud properties of LWC = 0.20 g/m^3, temperature of -5.3° C and MVD = 15 µm. Maximum lift data were not obtained in this test; however, Fig. 4 does show a significant loss in lift curve slope (8%) for the all iced (no ice protection) case and a smaller but measurable decrease with wing, tail and struts de-iced. The drag data are shown in Fig. 5 as C_D versus C_L^2. In this form the intercept is C_{D0} and the slope is the coefficient of C_L^2 in a classical drag polar representation. Here C_{D0} increased by about 60% for the all iced case and 17% for the case where all the ice protection was used. Therefore, for this case almost 30% of the drag rise was from miscellaneous non-ice protected components. A slight increase in the slope of the curve with ice indicates that the drag due to lift increased as ice was accreted. This effect became more pronounced at the lower power setting.[11] These drag effects were not as significant as Leckman’s[10], but the actual flight conditions reflected in Ranaudo’s data were not as severe.

Ashenden and Marwitz[12] have compiled the data for over 20 years of operation of a Beech King Air in icing conditions. The aircraft was equipped for performance measurements and was fully instrumented to obtain meteorological data. Twenty five flights are summarized and some analyzed in more detail. Drag was found to increase by as much as 200% and increases of 50% were common. The most severe conditions were found to be freezing drizzle encounters. The rate of performance degradation was found to be the best indicator of the severity of the icing encounter.

The effect of surface roughness as it relates to ground icing and aircraft take-off performance was discussed by Brumby[13] for swept-wing large-jet transports. A compilation of data on the effect of surface roughness on maximum lift gives penalties as high as 50% for upper surface roughness and 40% for roughness at the leading edge. This results in significant increases in stall speed and reductions in stall angle of attack. Lift losses on aircraft with leading-edge slats were observed to be less severe.

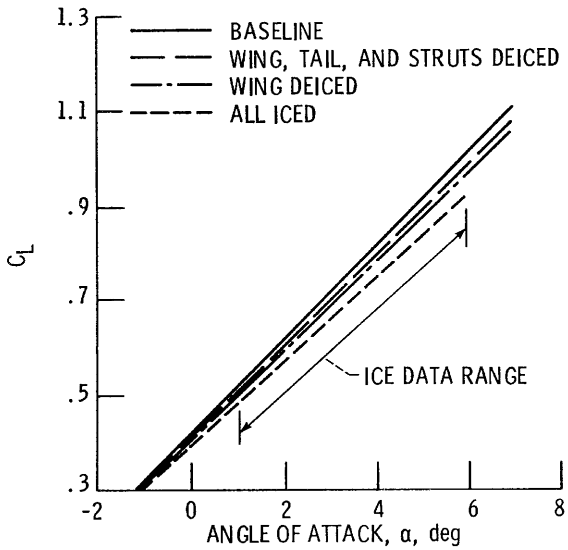

Fig. 4. Effect of glaze ice on lift curve for performance flight 86-21. (Ranaudo et al.[11])

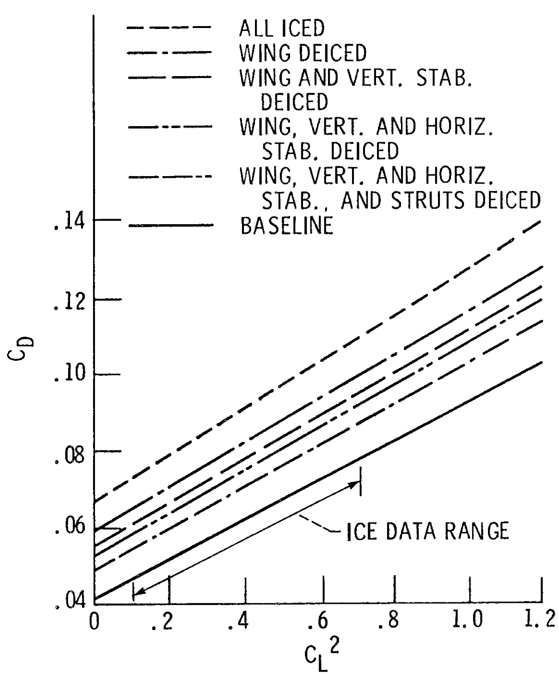

Fig. 5. Effect of glaze ice on aircraft drag for performance flight 86-21. (Ranaudo et al.[11])

In summary, ice accretion can seriously degrade aircraft performance. The exact amount of degradation is, of course, dependent on the aircraft, its ice protection system and the icing cloud conditions encountered. In terms of lift and drag, the most significant effects are the decrease in maximum lift and the increase in zero-lift drag. Measurable reductions in the lift-curve slope and increase in the drag due to lift (slope of the drag polar, dC_D/dC_L^2) have also been reported. Measurable and significant effects are seen even with the ice protection system operating on de-iced aircraft. This degradation in lift and drag can result in a severe loss in aerodynamic performance in all phases of flight.

3.2 Stability and Control

The most comprehensive data available on the effect of ice on aircraft stability and control is that reported by Ranaudo et al.[11-14] and Ratvasky and Ranaudo[15] from flight testing of the NASA Twin Otter aircraft. The data were acquired primarily with simulated ice but some natural icing conditions were also tested. Parameter identification methods were used to determine the stability derivatives of the aircaft with and without ice. Early research used the modified maximum likelihood estimate method, MMLE, and the subsequent data were reduced using modified stepwise regression, MSR. In both techniques, control inputs in the term of doublets were executed, and the inputs and aircraft response were recorded digitally. After several repeat runs the data were processed to determine the stability derivatives, when used in the equations of motion, that best predict the measured responses. The effect of power, landing flaps and angle of attack were studied to determine under what conditions the effect of the ice was most significant.

The effect of a simulated moderate glaze ice accretion attached to the horizontal and vertical tail was determined.[15] Figures 6 and 7 show longitudinal data with and without tail ice ($\delta_f = 0°$ and $C_T = 0.07$). The change in pitching moment coefficient with angle of attack, C_{m_α}, was negative for a statically stable aircraft. Adding tail ice for the no flap case at low power setting reduced the longitudinal static stability by increasing C_{m_α} by approximately 10%. This reduction in stability was true for all iced cases and rose to 17% for the flap deflected 10° case and no power. Figure 7 depicts the derivative which relates the effectiveness or power of the elevator in producing aircraft pitching moment, $C_{m_{\delta e}}$. As expected the presence of ice on the tail reduced the effectiveness of the elevator. A reduction of 12% is shown in Fig. 7 for the no flap case, which was shown to increase to 16% with 10° of flaps. While some change in the degradation of elevator power is seen in Fig. 7, this effect is not as large in the flapped data. The ice on the tail reduced the effectiveness of the tail and the static stability of the aircraft over the entire angle of attack range tested. This was thought to be due to the reduction in the tail lift curve slope caused by the ice. If conditions near tail stall had been tested, the effect of the ice may have been even more significant. The effect of ice on portions of the aircraft other than the tail can also affect longitudinal stability and control. Earlier measurements[11] in natural ice showed a 15% reduction in elevator effectiveness with all the aircraft iced, which reduced to about 9% when all but the tail was deiced. Thus the numbers quoted above may have been larger had simulated ice been used on the entire aircraft.

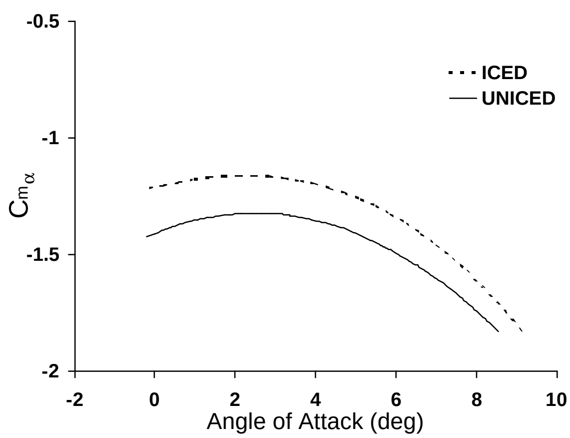

Fig. 6. Static longitudinal stability derivative. (Ratvasky and Ranaudo[15])

Control issues also arise due to the effect ice has on aerodynamic hinge moments and, therefore, stick forces for aircraft with unpowered controls.[7] Trunov and Ingelman-Sundberg[16] presented an excellent discussion of the role of the change in elevator hinge moment in the horizontal tail stall with icing accidents. Lower surface separation on the tail led to the loss of effectiveness and a large change in hinge moment which can overpower the pilot. This resulted from the downwash at the tail experienced with the use of high powered landing flaps. Brumby[13] described another icing or wing contamination control problem on swept wing aircraft during takeoff. Here, due to mistrim caused by the contamination, the pilot may over-rotate the aircraft resulting in wing stall and loss of longitudinal and lateral control.

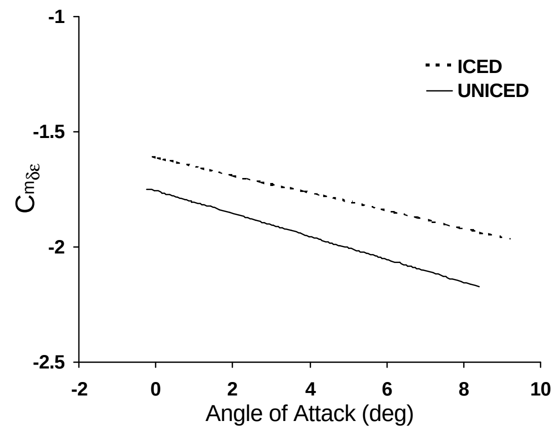

Fig. 7. Elevator effectiveness derivative. (Ratvasky and Ranaudo[15])

Lateral stability and control were also affected by ice and Ratvasky and Ranaudo[15] studied the effect of simulated tail ice on these parameters. Weathercock stability, C_{n_β}, was reduced, particularly at the no power condition. Rudder effectiveness, $C_{n_{\delta r}}$, was reduced by approximately 8% by the simulated moderate glaze ice tested on the tail surfaces.

As a result of the NASA Twin Otter research briefly reviewed here, it is clear that ice accretion affects the longitudinal and lateral static stability and control of the aircraft. This effect occurs even at low angle of attack and high power setting, conditions typical of cruise. A typical reduction in stability or control was 10%. Most of these data come from tail only simulated ice and the authors commented that these effects may be even more significant on other aircraft which do not have a large, oversized tail such as that on the Twin Otter.[15] There is also evidence that the effects of ice are more significant at large angles of attack near stall where significant early flow separation occurs due to the ice.[7,13,16]

3.3 Sensing Aerodynamic Effects on Wings

The aircraft performance, stability and control data reviewed in sections 3.1 and 3.2 above were primarily from flight at low angle of attack where flow separation was small. In this flow regime, the extent of separation was small and the aircraft aerodynamics can often be assumed to be linear. Figure 8 shows a possible C_L versus α curve for an aircraft with and without ice accretion. The linear range at low angle of attack is indicated on the figure. Also shown are typical aircraft cruise and climb lift coefficients. Note that the effect of ice on lift in these flight conditions is relatively small, although the reduction in maximum lift and, therefore, stall speed is much more significant. The angle of attack for maximum lift is also greatly reduced. The aircraft will be in the linear range during the majority of the flight and, therefore, this is the information that will be available to the IMS to evaluate the ice accretion effect. The challenge is how to sense the significant reduction in maximum lift in the nonlinear region of the curve with only data from the linear region. It may be possible to correlate changes in lift curve slope or the angle of attack for zero lift, but this would require very accurate measurement of these parameters. Another possible approach is to sense more detailed information about the flow over the aircraft in the linear range. Some approaches to acquire this type of data are reviewed below.

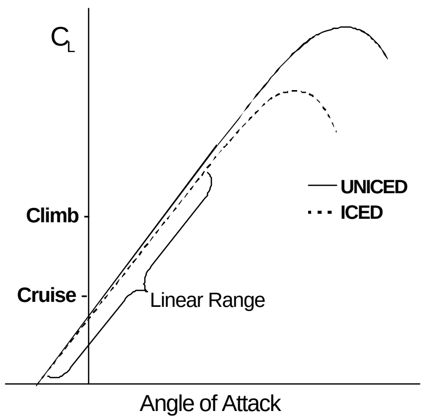

Fig. 8. Effect of ice on aircraft lift coefficient.

The flow over an iced surface has increased unsteadiness in comparison to that over a clean surface. This unsteadiness can be sensed by measurement of surface pressure or velocity fluctuations as a function of time. There are several systems under development that will monitor, and possibly predict, degraded aerodynamic performance due to airfoil contamination such as ice, by detecting the presence and extent of separated flow. One such sensing device is the Aircraft Icing Performance Monitoring System, AIMS, developed at Innovative Dynamics, Inc. (IDI) under the Small Business Innovation Research Program at NASA Lewis Research Center. Another system formerly owned by Jet Electronics and Technology, Incorporated (a unit of BFGoodrich Aerospace) and now under further development by Marinvent Corporation is the Stall Warning Plus, a stall warning and contamination advisory system. A third contamination detection product is the System for On-board Lift Analysis/AirSpeed Directional Indicator System, SOLA/ASDIS, being researched at AERS/Midwest, Inc.

AIMS was developed to detect the presence and extent of flow separation and potential stall on aerodynamic surfaces.[17] Non-intrusive surface sensors measure the pressure fluctuations on the wing's suction surface. The RMS pressure level and frequency content of the measured signals are used to determine the extent of the separated flow. Stall Warning Plus senses airfoil contamination by monitoring the turbulence intensity parameter, a ratio of the fluctuating and steady components of the local velocity.[18] Measuring both components enables the system to detect the onset of flow separation in addition to changes in the turbulent content of the flow. The SOLA/ASDIS system compares time-dependent pressure measurements of clean and contaminated airfoils by use of a non-dimensional pressure parameter to quantify airfoil lift capability.[19]

Each of the systems monitors flow unsteadiness by measuring surface pressure fluctuations. A prototype of the AIMS system, tested on a NACA 0012 with simulated frost and ice, used environmentally hardened electret microphones to measure changing pressure over time.[17] Elevated RMS pressure levels, increased up to five times those of attached turbulent flow, were used to determine the onset of separated flow, and peak RMS levels occurred near the reattachment point. A change in shape of the power spectrum also provided an indication of flow separation and was used to determine laminar to turbulent transition. Stall Warning Plus also monitors pressure, in this case by use of high-frequency solid-state pressure sensors.[20] Evaluation of the system during Fokker F100 and Aerospatiale ATR 42 icing trials determined the turbulence intensity parameter viable at all tested flap settings. It was estimated that at peak performance, a minimum of two sensors per wing were required on the ATR 42. The optimum sensor position for measurement was 60 and 80 % chord aft of the leading edge and 1 to 3 % chord above the surface, but ultimately it depends on the stall and contamination characteristics of the airfoil.[20] The SOLA/ASDIS system collects pressure measurements by an array of differential pressure sensors generally arranged in sets of three, one near the stagnation point, and the others on the upper and lower surfaces within 10 % chord of the airfoil leading edge.[19] Up to four sets of pressure ports can exist on each side of the wing. Tests on an airfoil with simulated ice showed a 22 % reduction in values of the non-dimensional pressure parameter at 6° angle of attack, and a 40 % reduction at 10°. The results showed promise for the system to be used as a component of an eventual aircraft take-off performance monitor.[19]

Although the three systems described above essentially measure the same unsteady flow characteristics, each uses different instrumentation to collect the data and a unique parameter to monitor aerodynamic performance.

3.4 Future Research

In the aerodynamics and flight mechanics area additional research is needed to better understand the effect of ice on aircraft performance, stability and control. To accomplish the smart icing systems goals identified above through the development of an Ice Management System, IMS, the following issues need to be addressed:

- How can one develop an accurate time dependent model of aircraft performance, stability and control in icing conditions?
- How can nonlinear behavior be predicted from data in the linear range?
- If local aerodynamic state sensors are needed, what kind of sensors are required and where should they be placed.
- What maneuvers and flight conditions may lead to loss of performance and/or control, and which of these should be included in the envelope protection system which will be developed.

4. Identification and Control

Essential to reliable operation of the Ice Management System, IMS, are the development and testing of appropriate identification algorithms. These algorithms must identify aircraft performance, stability, and control parameters over time, based on measurements of the aircraft state variables and control input. Since icing safety problems can occur at any time from takeoff to landing, an effective identification algorithm must function in all phases of flight. The information that the algorithm provides, combined with that received from other aircraft sensors and systems, will provide the pilot and the IMS with an understanding of the degradation in aircraft performance due to icing.

4.1. System Identification Concept

A high-level block diagram of an icing identification system is shown in Fig. 9, which is a detailed representation of the IMS and Aircraft Dynamics blocks of Fig. 2. Specifically, we consider the aircraft flight dynamics, which can be characterized by some parameters, say χ. The identification algorithm seeks to identify these parameters by observing the system input and output, and computing an estimate, $\hat{\chi}(t)$, based on this available information. Given that ice accretion will cause variations in the system parameters, on-line detection of these variations provides information regarding the degradation of performance due to ice accretion. The IMS makes use of a detection criterion applied to the parameter estimates to trigger an indicator for the presence of icing. In addition, the IMS incorporates other available and pertinent sensor information, *e.g.*, local aerodynamic sensors, for corroboration of the icing indication. A positive indication of icing can result in modification of the flight envelope, notification of the pilot, and/or adaptation of the flight control system.

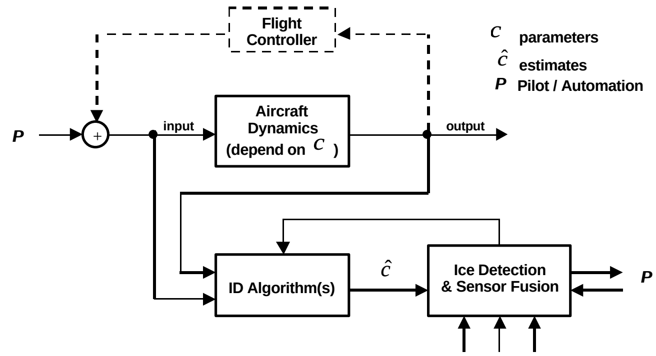

Fig. 9. Aircraft icing identification block diagram. Detailed representation of the IMS and Aircraft Dynamics block in Fig. 2.

The identification algorithm to be developed for this purpose must be able to accommodate two separate regimes:

(i) slow, small changes in flight characteristics at low to moderate angles of attack as ice is accreted on the aircraft, and

(ii) large, rapid, and nonlinear changes as the angle of attack is increased and flow separation occurs.

Accommodation of these two regimes leads in general to a two-phase identification algorithm. The *first phase* is geared toward sensing small changes, and it is natural here to consider a linearized version of the dynamics, with time-varying and nonlinear effects suppressed; a linear approximation to a nonlinear model may not, however, always yield successful results, and higher-order approximations may become necessary. The *second phase* is geared toward sensing larger changes, and here the system is considered in its original nonlinear and time-varying form.

It should be noted that research strongly related to this approach has been recently conducted in the context of the reconfiguration of the flight control system of fighter aircraft. Many current and future aircraft are open-loop unstable, and when some of the control surfaces are damaged, the remaining control surfaces may still be capable of controlling the aircraft if the controller is reconfigured quickly. In particular, current research efforts related to the new generation of tailless fighters are focused on the identification (ID) of the aircraft parameters when sudden changes due to failures and battle damage occur. The results of the ID are utilized to adjust the flight control laws in order to maintain, to the extent possible, the vehicle's stability and handling quality characteristics.

Preliminary results using linear and nonlinear models and modified least square ID algorithms, along with adaptation of inversion control laws, are very encouraging. Recent research[21-23] has described both the parameter ID algorithms and their successful application to aircraft reconfiguration. They also considered various important issues such as the trade off between using recursive least squares versus using batch algorithm on a moving window of data. Moreover, they discussed the issues associated with turning off the ID when insufficient excitation was present, and effects of damage occurring (jumps in parameter values) within a window of data.

4.2. Linearized Longitudinal Flight Dynamics Simulations

We have tested the feasibility of the phase 1 type identification philosophy introduced above on a simple model. The model was based on the inflight test data obtained from the NASA Twin Otter and discussed in Sections 3.1 and 3.2. Dimensionless stability and control derivatives for the longitudinal flight dynamics of the Twin Otter have already been estimated for both clean and iced conditions, and are available in the literature.[15] Using these estimates, we have simulated the linearized flight dynamics as a first test of the identification procedure. The system equations used for this purpose and the definitions of the dimensional derivatives are those given by Roskam.[24] It was assumed that icing affected only the M_δ, M_α, Z_δ, Z_α and X_α derivatives. The clean and iced values for these derivatives are given in Table 1. The resulting eigenvalues of the normal modes of the 4-dimensional linearized longitudinal dynamics are $\lambda = -2.75 \pm j\ 2.18$ /sec and $\lambda = -0.0065 \pm j\ 0.169$ /sec for the clean aircraft and $\lambda = -2.67 \pm j\ 2.00$ /sec and $\lambda = -0.00648 \pm j\ 0.169$ /sec for the iced aircraft. (In each case the first eignevalue represents the short period mode and the second the phugoid mode.) The striking fact of these results was that aircraft icing had only a small effect on the short period and almost no effect on the phugoid mode of the linearized system.

Table 1. Values of dimensional stability and control derivatives of the NASA Twin Otter that are affected by icing. Values are given for both the iced and clean conditions.

Derivative	Clean	Iced
M_δ (/s^2)	-10.44	-8.88
M_α (/s^2)	-7.86	-7.07
Z_δ (ft/s^2)	-40.30	-34.25
Z_α (ft/s^2)	-378.7	-342.5
X_α (ft/s^2)	13.71	13.90

The response of the flight dynamics to a 5° doublet elevator input over 10 seconds was calculated for both the iced and clean aircraft. Specifically, the elevator input was one period of a sine wave with an amplitude of 5° and a period of 10 seconds. The results of the simulation are shown in Fig. 10. As expected from the small modal variation due to icing, the calculated responses are relatively insensitive to the effects of icing. This insensitivity suggests that the linearized longitudinal flight dynamics do not capture icing effects, and that identification efforts based on this model will perform poorly. In fact, simulations of identification of stability and control derivatives have demonstrated this poor performance. A successful identification algorithm must be based on a representation of the system that is more sensitive to icing effects.

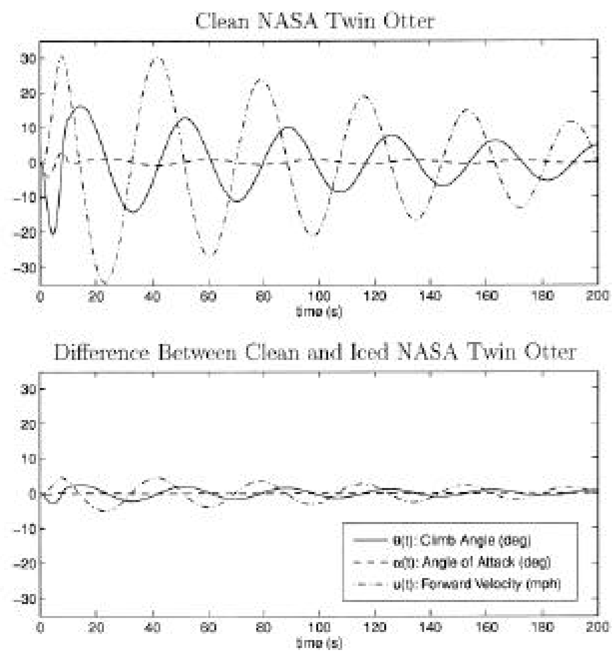

Fig. 10. Response of linearized longitudinal flight dynamics to a 5° doublet elevator input over ten seconds for the clean and iced NASA Twin Otter

4.3. Identification Algorithms for Nonlinear Dynamics

One approach to system identification is to use extended Kalman filter (EKF) state estimation techniques to identify the system parameters.[25] This approach is based on the assumption of time-invariant parameters, and often suffers from divergence of the estimated parameters from their true values. In addition to the standard EKF techniques, least-squares identification algorithms have been used to identify flight dynamics. Both the NASA Twin Otter MMLE and MSR algorithms[14,15] are based on least-squares identification techniques. It should be noted that the identification performed for the NASA Twin Otter is different from our application, in that for the Twin Otter the identification was performed after all of the data had been collected (that is, identification was a result of *batch processing* of the data), whereas in our case, the identification must occur in *real time* (and *on line*) in order to be useful. We are also utilizing at the present some of the algorithms developed in the context of nonlinear H^∞-based identification.[26] H^∞ methods provide an extension to least-squares identification in that they deliver a guaranteed attenuation level between system disturbances and parameter estimates. Unlike EKF methods, H^∞-based identification can make direct use of state time-derivative information. Finally, H^∞ methods apply to the case of time-varying parameters as well.

In the linear, slow-variation regime of ice accretion effects, the flight dynamics are essentially quasi-static and linear. Given the possible insensitivity of the linearized flight dynamics model to icing effects, consideration of the flight dynamics in this linear regime may be ineffective. Furthermore, each of the identification algorithms mentioned above has the characteristic that the rate of parameter convergence is related to the level of excitation of the system. Unfortunately, in this first regime of ice accretion effects, the aircraft will be operating primarily at a trim condition, and hence there will be little excitation of the flight dynamics, resulting in poor parameter convergence. Instead of identifying the linearized flight dynamics parameters (stability and control derivatives), another approach would be to take advantage of force equilibrium at the trim condition, and identify the rise in drag coefficient, change in airspeed, thrust setting and other trim conditions. This technique is particularly promising, since the drag is very sensitive to icing effects, as discussed in Section 3.1.

In the large-variation, nonlinear range of ice accretion effects, the system excitation should be sufficient. Furthermore, it is in this regime that the effects of icing on flight dynamics will be strong, since rapid and large changes are experienced in the flight dynamics. In this regime, detection of icing effects should be possible by identification of the flight dynamics. However, it is necessary to consider the dynamics as time-varying and nonlinear. Although this type of identification is more complex, the theoretical results for H^∞-based parameter identification can accommodate nonlinear systems that are linear in parameters.[26] In our study, both the EKF and H^∞ approaches are being pursued. The resulting algorithms are being evaluated in light of the two regimes of parameter variations discussed above. Of specific concern is the performance of the algorithms in terms of their rates of convergence and accuracy of the resulting parameter estimates in both the static and dynamic sense, possibly in the presence of unmeasured disturbances. Furthermore, the algorithms are being evaluated in terms of reliability and computational intensity.

5. A Human-Centered Design Approach In Support Of Pilot-Automation Coordination

In the preceding sections, the rationale for and the engineering approach to the design of a new Ice Management System (IMS) were laid out. This system represents a step towards higher machine intelligence and increased system autonomy and authority. One of the lessons learned from the development and introduction of similar systems in the past is that they are very beneficial in terms of an increased precision, efficiency, and reliability of operations. However, these benefits accrue primarily in situations where the automation acts on its own, without pilot involvement. When human and machine need to cooperate on a task, unexpected difficulties are being observed which are related to breakdowns in the communication and coordination between these two agents. In the aviation domain, for example, the introduction of advanced autoflight and flight management systems has created problems for pilots who sometimes find it difficult to keep track of the status and behavior of their automated counterparts.[27-30] As a result, they experience 'automation surprises' and a perceived and sometimes actual loss of control of the airplane.

While automation surprises have only recently become a major concern in the aviation industry, warnings of other potential problems with cockpit automation were voiced as early as the late 1970s.[31] These concerns have been fueled ever since by incidents and accidents involving automated aircraft,[32,33] by difficulties that pilots experience during training and line operations, [27,34] and by the results of empirical research looking at pilot-automation interaction. [28,30,35] Some of the major areas of concern have been the potential impact of automation on pilot workload, pilot error, trust calibration, and pilots' manual flying skills.[36-38]

More recently, a lack of mode awareness and resulting automation surprises have been added to this list. Mode awareness refers to the pilot's knowledge and understanding of the current and future status and behavior of the automation. A lack of mode awareness can lead to automation surprises when the pilot realizes that the behavior of the system does not match his/her expectations. These difficulties are not a pilot problem. Instead, they can be viewed as symptoms of a mismatch between the information needs and processing abilities of the human operator and the machine agent.[39] Past work has shown that automation surprises are most likely to result from (a) poor mental models of the functional structure of the automated system , and/or (b) low system observability (i.e., the cognitive work required to extract meaning from available data). They tend to occur in highly dynamic and/or non-routine situations.[29,40] Automation surprises have only recently emerged as a problem because they were not afforded by earlier flight deck systems which were, for the most part, reactive in nature. In contrast, modern automation technology can take action on its own without the need for explicit pilot commands and/or consent. This increased autonomy and authority of modern automated systems, in combination with low system observability, increases the likelihood of automation surprises as illustrated in Fig. 11.

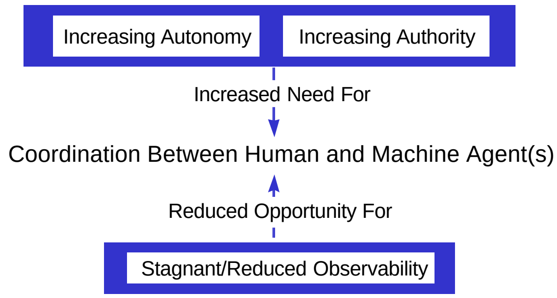

Fig. 11. Opposing trends in the evolution of modern technology and their impact on human-automation coordination

The envisioned Ice Management System, IMS, represents a step in the direction of increased system autonomy and authority. Not only will it provide pilots with new kinds of information such as sensed ice accretion and its effects on aircraft performance, stability and control. The system will also be capable of initiating steps on its own to counteract the detrimental effects of icing by modifying the flight envelope and by adapting the flight controls. The development of such a system is technologically feasible. Yet, its success will depend to a considerable extent on how well it is integrated with its human operators. This project will take a human-centered approach[41] to the design of the IMS to avoid peripheralization of the crew and resulting breakdowns in pilot-automation coordination.

The basic premise of human-centered automation design is that pilots must remain in command and control of their flight. In order to achieve this goal, the pilot must be actively involved in and informed about ongoing activities and events in a meaningful and timely manner. The automation must be predictable for the pilot, and both human and machine agents must know each other's intent.[41]

With these goals in mind, the first step in designing the interface for the envisioned Ice Management System will be to determine the information requirements of the crew and examine different forms of information representation as well as the benefits and disadvantages of different protocols for human-computer cooperation. Some of the issues that need to be addressed in this context include:

- Of all the data that can be made available by the IMS, what subset will be relevant and meaningful for the flight crew? (How) Do information requirements change across different flight tasks and contexts?
- When should the crew be informed about sensed ice accretion and its effects on aircraft performance? Should this information about current status and trends be provided at all times, or should information become available only when the system determines that a certain level of criticality has been reached?
- In what form and where should icing-related data be presented? Should the new information be integrated with existing flight deck displays to avoid imposing new cognitive demands on the crew? Or should the information be presented on a dedicated display which may be difficult given the limited real estate on most flight decks?
- Should the pilot have the option to dynamically adjust the amount and nature of information? Or should it be predetermined by the system designer?
- How can the three-dimensional development, extent, shape, and characteristics of inferred icing conditions be visualized for the crew?

In addition to supporting the timely and efficient exchange of information between pilots and the IMS, the human factors experts involved in this project will also play an important role in the development of the proposed envelope protection functions of the IMS. Envelope protection functions associated with existing flight deck systems (e.g., stall and overspeed protection functions on several 'glass cockpit' aircraft) have sometimes led to confusion among the flight crew when the automated system took an unexpected and ill-understood action in response to sensor input rather than pilot commands. To avoid that similar difficulties are experienced with the envisioned IMS system, a number of questions need to be addressed in the design process. Some of these questions can be answered based on existing operational experience; others, however, will require prototype evaluations to assess the potential costs and benefits associated with different design implementations. One important question in this context is whether the envelope protection function should involve a 'hard limit' (i.e., one that does not allow for pilot override) or a 'soft limit' (one that informs the pilot of approaching the limits of the envelope but still allows the pilot to exceed those limits if considered necessary). Both approaches are currently being used on modern aircraft built by different manufacturers. To date, however, there is little empirical evidence for the effectiveness and desirability of either approach for different task and flight contexts. Another question is how transitions between pilot- and IMS/FMS-controlled flight can be managed in a seamless manner. Should these transitions require pilot consent, and how can we ensure that the pilot stays informed about these events?

Human factors considerations and iterative evaluations of proposed system solutions will be an integral part of the overall IMS development to ensure the early detection and correction of difficulties with human-automation coordination. In that sense, this project represents one of the first attempts at a predictive human-centered and integrated approach to system design.

6.0 Summary and Conclusions

A smart icing system has been proposed based on the ability to sense the effect of ice on the aircraft performance, stability and control. This system would add an additional level of safety to supplement the current avoidance and ice protection concepts while implementing pilot-automation coordination to ensure the pilot's ability to operate the system safely. The system would sense ice accretion and its effect on aircraft performance and control, and automatically operate ice protection systems, provide aircraft envelope protection and, if icing is severe, adapt the flight controls.

To develop such a system, an interdisciplinary research program is required and has in fact been initiated at the University of Illinois at Urbana-Champaign. The key research issues discussed in this paper were:

- Ice accretion results in flow separation and nonlinear aerodynamic behavior at large angles of attack and control deflections. These conditions must be better understood and mathematical models developed to aid in the use of local aerodynamic sensors or identification procedures to detect these conditions in flight.
- Adaptive flight envelope protection beyond the current simple angle of attack based systems currently in use must be developed.
- System identification algorithms must be developed and tested which are capable of detecting ice accretion and potentially dangerous control and performance problems in both the low-alpha range where ice usually accretes and dynamic high-alpha flight where flow separation and large effects are experienced.
- Human-automation issues must be addressed in parallel with the above technical issues. What information the flight crew needs, when and in what format it should be presented, and how the crew will interact with the automation must be determined early on for the system to be successful.

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