Air Frame Icing Influences on the Risk of Loss of Control In-flight

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Although icing is covered in significant detail in flight training, often the subtle influences of icing on wing performance are not well understood in the world of commercial flight operations. In certain conditions, protection systems and escalating advisories to enhance stall prevention by the pilot can be reduced, or eliminated, due to the aerodynamic performance variations of the wing as a result of ice-altered angle of attack. In response to this unusual wing performance characteristic, the risk of loss of control in-flight (LOC-I) can be significantly elevated in certain conditions. With LOC-I continuing to consistently demonstrate itself as the leading lethal threat to air safety in aviation despite traditional unusual attitude training philosophies, associated procedures and regulatory requirements, the aviation training community must continue to evolve pilot knowledge, skill and awareness. The counter-intuitive nature of a meaningful all-attitude/all-envelope awareness, prevention and recovery skill development, to counter LOC-I conditions, poses training challenges as the industry looks to the future. This study will provide a brief outline of the aerodynamic influences of icing on airplane performance specifically related to angle of attack variations on jet and turbo prop airplanes. Performance charts will be presented to highlight the direct influence airplane icing has on reducing, in some cases eliminating, the pilots ability to be aware of an approaching stall and, at times, prevent the onset of the full stall in hazardous flight conditions. Mitigations will be outlined that allow pilots, through knowledge and skills training, to readily diagnose, prevent and, if necessary, recover airplanes from inadvertent upset and stall events due to reduced main wing angle of attack as result of icing conditions.

Nomenclature

AOA	=	Angle of Attack
C_D	=	coefficient of drag
C_L	=	coefficient of lift
L/D_{MAX}	=	point on the Lift vs. Drag curve with the most lift for the least drag
α	=	angle of attack
α_{stall}	=	the stalling angle of attack, also known as the critical angle of attack
FAA	=	Federal Aviation Administration
ICAO	=	International Civil Aviation Organization
LOC-I	=	Loss of Control In-flight: LOC-I is an extreme manifestation of a deviation from intended flight path.
UPRT	=	Upset Prevention and Recovery Training: The field of flight training dedicated to reducing LOC-I incidents and accidents as a result of specialized training specific to the nature and cause factors associated with historical LOC-I events

I. The Threat

"The warnings started to sound 'bank angle, bank angle' as we exceeded 60 degrees and my attitude indicator was rapidly turning more brown than blue. It finally flashed through my thick skull that no matter what the airspeed said we were in a full-on stall ..." – US Army Fixed Wing Pilot (Full story: http://tinyurl.com/usarmy-ice-upset)[1]

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Pilots are required to be aware of the weight, drag penalty and lift influences of main wing icing. However what is often missed, or perhaps even skipped as a feature threat in training for professional pilots, is the impact this type of icing can have on stall angle of attack (α_{stall}). Of critical operational importance to pilots, among other factors we will address, is that main wing icing tends to reduce the wing's stalling angle of attack. Fortunately, many advanced and commercial airplanes make a correction for calculated α_{stall} when anti-ice and/or de-ice systems are engaged, reducing the α required to trigger a stall warning. However, what if the icing condition is:

- Worse than anticipated by the system's correction,
- Not considered (i.e. no correction made) by our particular airplane's stall warning presentations and system, or
- Simply unnoticed (perhaps through pilot distraction, lack of attention or rapid accumulation than anticipated)?

Although not the leading cause of environmentally induced airplane upsets, airframe icing is most certainly one of the threats to our safety that can have the ugliest presentation of all … that is; little to no stall onset warning.

De-icing boots, weeping skins (TKS), and heated leading edges are great tools for removing or preventing ice from accumulating on the leading edges of airfoils (assuming those systems are used), but the remainder of the airframe remains susceptible to the accumulation of ice. Ice anywhere on the aircraft will obviously increase weight, but it also increases drag and, on the airfoil, decreases lift as well. In an icing encounter, these changes can happen rapidly. In some cases, α_{stall} can rapidly decrease to a point where the wing will stall before the stall warning system's trigger point is reached, whether or not that point is compensated for icing conditions. Here the aircraft will enter an actual aerodynamic stall without the buffer that the warning system normally provides and can catch the aircrew by surprise.

Current simulator models for icing may only provide an increase in aircraft weight with no penalties for drag, or for airfoil alteration. This is can be a poor representation of the true effects of airframe icing, and can produce negative training in both recognition of the problem and aircrew response. For an aircraft on a stabilized approach, with expected speeds and thrust set, drag begins to rise as lift decreases. If the aircraft maintains a steady speed while maintaining the desired approach path, the α required necessarily increases to maintain the required lift. With an increase in thrust, the aircraft slows due to increased drag, further increasing the α required to maintain lift. At the same time, lift available for a given α is likely falling due to aerofoil shape and efficiency variations, as is α_{stall}. These effects are not present in the static weight-only penalty of some simulator icing models. Further complicating the model is that, the longer the aircraft remains in the icing conditions, the worse the situation becomes. This is rarely reflected in many of today's simulator icing models.

Another threat that may not be reflected in simulator icing models is the potential for significant roll excursions and the loss of roll control effectiveness. The rolling moments can be significant and can potentially exceed the roll-control authority of the aircraft; especially with degraded control authority caused that may be caused by the accumulated ice affecting the ailerons. FAA Advisory Circular AC 91-51A states:

> "Another hazard of structural icing is the possible uncommanded and uncontrolled roll phenomenon referred to as roll upset that is associated with severe in-flight icing. Pilots flying airplanes certificated for flight in known icing conditions should be aware that severe icing is a condition that is outside of the airplane's certification icing envelope. Roll upset may be caused by airflow separation (aerodynamic stall) inducing self-deflection of the ailerons and loss of or degraded roll handling characteristics. This phenomena [sic] can result from severe icing conditions without the usual symptoms of ice accumulation or a perceived aerodynamic stall."[2]

Again, roll upset can present itself with little or no onset warning and without the triggering of the aircraft's stall warning system. Due to the lack of adequate simulation of the full effects of icing in many current icing models, aircrews may not be exposed to the possible insidious onset of these effects, nor do they typically experience the possibilities of their sudden manifestation and violent presentation. As such, current simulator models of icing can produce aircrew complacency and/or over-confidence with respect to the severe degradation in aircraft performance as a result of accumulated ice.

II. Understanding the Aerodynamics

To better understand the threat, and be able to more accurately model aircraft responses, a look at the aerodynamics is in order. As ice accumulates on an airfoil, it alters the characteristics of the airfoil. In essence, redesigning the wing. This often results in a "new wing" with a thicker camber and possibly a longer chord. This can happen even when using de-ice or anti-ice protection. Ice will typically accumulate aft of the protected area, particularly in severe icing conditions. As the ice accumulates, the aircraft becomes heavier. At the same time, the changing aerodynamics due to the ice results in changes to the coefficients of lift (C_L) and drag (C_D). Depending upon the severity of the icing encounter, the performance of the wing can change significantly in a short time period.

Considering the changes to C_D first, the accumulation of ice can impose a significant drag penalty. The presence of ice on the airfoil surface significantly affects the boundary layer airflow. Research conducted by the Department of Aerospace Engineering at Wichita State University (WSU) for the FAA showed increases in minimum C_D of over 3500% (See Table 1).[3] Additionally, several increases in C_D at 10 degrees and 15 degrees of over 300% were noted. As a consequence of drag alone, higher power settings are required to maintain airspeed. With the additional weight of the ice, more lift is required, requiring a higher α for the same airspeed, which in turn further increases drag. In portions of the flight envelope in extreme conditions, the total required power to maintain a level flightpath and constant airspeed may be more than the available thrust for the aircraft.

With respect to lift, the presence of ice, in general, reduces C_L for a given α. For α ranging from 3 degrees to 15 degrees, the research at WSU noted decreases in C_L anywhere from 0% to over 85%. Additionally, the α for maximum C_L, also known as α_{stall}, generally fell with icing.[3] To compensate for this effect, aircraft manufacturers often reduce the α required to trigger stall warnings when the anti-ice system is on or when icing is detected. The provided compensation, however, may not be enough given the significant drop in α_{stall} under some icing conditions.

Configuration	$C_{L,stall}$	$\Delta C_{L,stall}$	α_{stall}	$\Delta\alpha_{stall}$	C_L at $\alpha = 13.8°$	ΔC_L at $\alpha = 13.8°$	$C_{D,min}$	$\Delta C_{D,min}$	C_D at $\alpha = 13.8°$	ΔC_D at $\alpha = 13.8°$
Clean	0.87	0.0%	13.8°	0.0°	0.87	0.0%	0.006	0.0%	0.147	0.0%
IRT-CS10	0.54	-37.9%	10.5°	-3.3°	0.56	-35.6%	0.072	1100.0%	0.209	42.2%
IRT-IS10	0.64	-26.4%	10.6°	-3.2°	0.59	-32.2%	0.047	683.3%	0.198	34.7%
IRT-SC5	0.90	3.4%	15.8°	2.0°	0.86	-1.1%	0.014	133.3%	0.172	17.0%
IRT-CS2	0.77	-11.5%	12.7°	-1.1°	0.76	-12.6%	0.018	200.0%	0.174	18.4%
IRT-CS22	0.06	-93.6%	6.0°	-7.8°	0.36	-58.6%	0.218	3533.3%	0.300	104.1%
IRT-IPSF22	0.53	-39.1%	10.5°	-3.3°	0.53	-39.1%	0.078	1200.0%	0.210	42.9%

Table 1: EFFECT OF IRT ICE SHAPES ON $C_{L,stall}$, α_{stall}, AND $C_{D,min}$; Re_{MAC} = 1.8×10^6; $\delta_A = 0°$ (Ref. 3)

Despite corrections to our protection systems, can main wing ice be a controllability concern? In Ref. 4, Crash During Takeoff in Icing Conditions – Challenger 601, Montrose, Colorado (November 28, 2004), we have the following excerpt:

> "Previous Safety Board investigations of takeoff accidents involving airplanes with contaminated upper wing surfaces have found that the presence of a small amount of surface roughness on the upper wing surface can reduce maximum lift by as much as 33 percent, depending upon the extent and level of roughness. Wind tunnel and flight-testing by the accident airplane manufacturer indicated that the presence of surface roughness equivalent to 40-grit sandpaper on a CL-600-2A12-type wing can reduce the stall AOA up to 7^O compared to the stall AOA of an uncontaminated wing. Once localized airflow separation begins on a portion of a contaminated wing, that wing can stall before the other one, which results in lift asymmetry and large roll rates that are not responsive to control inputs."

Considering α_{stall} is generally in the neighborhood of 12^O to 15^O for many airfoils, the 7^O impact of main wing icing referenced in the excerpt above is significant.

Even when ice protection systems are used, heated leading edges in particular, there is still likelihood that α_{stall} is decreasing in icing conditions. The cause of this phenomenon can be due to ice forming briefly on the heated surface, melting, then running back onto the non-heated wing surfaces and refreezing. These runback accretions create ridges aft of the heated area that disrupt the boundary layer flow, lowering C_L for a given α, as well as reducing α_{stall}. Fig. 1 shows data from an FAA sponsored study by the University of Illinois on the effects of these runback accretions on aerodynamics. The upper curves on the left-hand graph clearly show both C_L and α_{stall} decreasing as a result of the runback accretions.

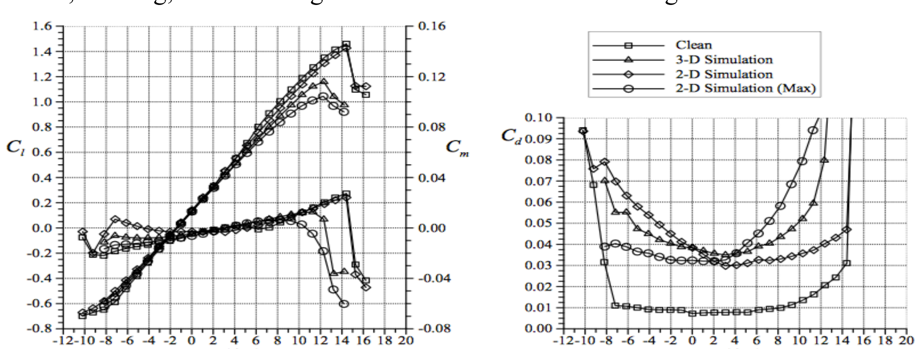

Figure 1. Comparison of the Effect of Geometrically Scaled, 3-D and 2-D Ice Shape Simulations for the Warm-Hold Case on the Lift, Drag, and Pitching Moment of NACA 23012 (Re=1.8x10^6, M=0.18) (Ref. 5)

So while the increase in weight due to the accumulated airframe ice requires a commensurate increase in lift, and therefore α, the amount of lift for a given α is decreasing, as well as α_{stall}. If α_{stall} has fallen below the trigger point of even the compensated stall warning trigger point, the aircrew can experience the full stall without any preceding stall indications or warnings. Complicating this issue is that the icing may not be uniform across the span of the wing. This would result in varying α across the span, with the potential for different portions of the wing being stalled and unstalled. If the distribution of stalled areas is not symmetric, the resulting rolling moments can be significant. This effect is in addition to any self-deflection induced by flow separation as previously mentioned. The loss of roll stability can be clearly seen in Fig. 2, which shows the rolling moments from American Eagle Flight 3008. This graph clearly shows the near instantaneous onset of roll upset coincident with the stall. This rapid onset of roll, even if preceded by a stall warning, would likely catch the aircrew off-guard.

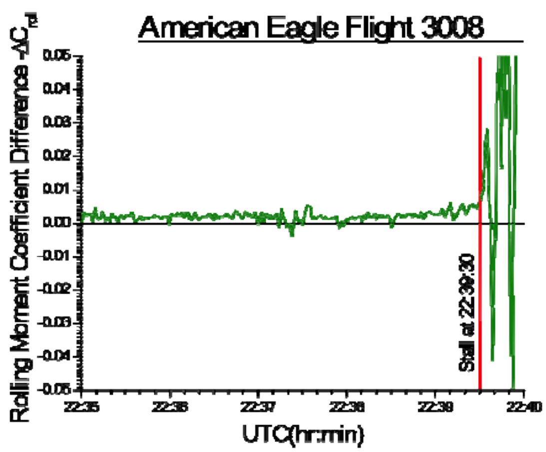

Figure 2. Excerpt showing aerodynamic degradation due to icing (American Eagle flight 3008 incident).[6]

Whether we have a dynamic calculation of predicted α_{stall} through the aircraft's on board systems or just a published 'stall speed' number firmly set in our mind's eye, each one of the above three conditions identified in the opening paragraph of this paper can significantly alter the approach to stall and the aerodynamic stall's sequence of anticipated precursor events and protections. In any of these cases, when the stall is encountered, it is often a full aerodynamic stall at or beyond α_{stall} and rarely ever responds favorably to the mindset of 'thrusting out' or 'minimizing altitude loss' as primary concerns. Most pilots are unaware that beyond α_{stall} the physics of flight are altered, in comparison to unstalled flight, due to the onset of negative stability and associated atypical control responsiveness - particularly roll control. Aggressive and correct α reduction as the first and most critical priority by the pilot and that action can literally make the difference between life and death. Historically, traditional stall training focused on minimizing altitude loss rather than α reduction to regain positive control of the airplane.

III. Mitigation Through Flight Training

Fortunately, the FAA's recent Advisory Circular 120-109 issued in August 2012 gives pilots and training organizations fairly comprehensive guidance on the importance of α management (i.e. 'push' forward on the elevator control to reduce angle of attack below critical as the first priority).[7] With proper awareness, prevention and monitoring skills in place, the need to address an icing event with the application of the AC's stall recovery template should be minimized. However, due to the influence significant icing accumulation can have on α_{stall}, it is possible for a pilot to encounter a full stall without any of the typical pre-stall indications, warnings, stick shakers and even stick pusher activations as addressed in Section II.

The process of enhancing pilot knowledge, skills and attitudes associated with the airframe icing can be arranged within the three main categories of Upset Prevention and Recovery Training (UPRT):

1. Awareness Training,
2. Prevention Training, comprised of Recognition & Avoidance, and
3. Recovery Training, involving elements of both Recognition and Recovery.

Each of these categories are outlined below under the section on The Three Categories of Icing UPRT to assist the pilot and training mangers organize training interventions specific to the airframe icing threat. Before jumping into those three categories, let's briefly discuss the training phases and generalized competencies.

A. Academic Preparation

It is apparent from continued incidents of icing related loss-of-control mishaps that gaps exist in the academic preparation of pilots to effectively understand and counter icing events. These gaps in academics can be reduced by ensuring academic preparation establishes the foundation from which situational awareness, insight, knowledge, and eventually, skills will be developed. As in practical skill development, academic preparation should move from general to specific while clearly emphasizing the importance of basic concepts during each education phase. Although academic preparation is crucial and does offer a level of mitigation of icing-induced airplane upsets, the long-term retention of pertinent academic knowledge is best achieved when applied and correlated during practical hands-on awareness, prevention and recovery exercises.

B. Practical Skill Development

The development of practical skills can follow a variety of valid training paths. Today, most flight simulators attempt to model icing by only adding weight to the airplane. As we've discussed, the weight increase is just a portion of the issues the pilot will face in an icing-induced stall event in the real world. It is critically important that pilots clearly understand two essential concepts. First, that increased weight requires the wing to create more lift by operating at a higher angle of attack in order to maintain level flight at a given airspeed. Secondly, and perhaps less appreciated by many pilots, the stall angle of attack of the wing is being reduced by the presence of ice. If this reduction of α_{stall} exceeds the airplane's correction to the stall warning system's trigger point (if any) then the stall can happen without many or any of the typical cues pilots experience in training. The best training tools given existing simulator limitations are increased academic knowledge and practical hands-on stall recovery that is based on recognizing aerodynamic stall cues that are not often addressed or witnessed in typical stall training. A stall is characterized by any of the following individual factors, or any combined occurrence, of the following factors:

- Buffeting: Possibly heavy at times.
- A reduction or lack of pitch authority.
- A reduction or lack of roll control.
- Inability to arrest descent rate.

These factors are usually accompanied by a continuous stall warning. Once again, if α_{stall} is reduced below the corrected stall angle in the aircraft's software in an icing event, it is conceivable, if not likely, that the stall will happen without a stall warning. The pilot must know, understand, and be able to identify the above bulleted cues to initiate stall recovery actions per AC 120-109.[7] Also of significant importance is the elevated risk of asymmetric roll-off due to unbalanced ice accretion. In order to enhance retention and comprehension, the training organization should make every effort to ensure that academic preparation is presented prior to each practical training session in context that is directly relevant to the planned training event.

C. KSA Competencies and Competency-based Training

The application of competency-based training (CBT) methodologies has been introduced recently by ICAO in the training towards the MPL and for evidence-based recurrent training requirements in an FSTD, among other applications. The goal of competency-based training is different from traditional training programs that are designed so that the trainee meets the minimum skill, knowledge and experience requirements of the license, permit, certificate, rating or operational authorization being sought. In competency-based training, the training program focus is on trainees acquiring all the knowledge (K), skills (S) and attitudes (A), often referred to as KSAs, necessary to achieve the required competencies to perform their duties in a safe, efficient and effective manner.[8]

The general application of KSAs relates effectively and directly to many aspects of UPRT. As general listing of ICAO KSAs are as follows:

1. Application of Procedures
2. Communication
3. Aircraft Flight Path Management, automation
4. Aircraft Flight Path Management, manual control
5. Leadership and Teamwork
6. Problem Solving and Decision Making
7. Situation Awareness
8. Workload Management

The majority of pilot training today in both upset recovery and icing-mitigation training should address many of the eight KSAs primarily in the Awareness and Prevention phases of UPRT. Unfortunately, these same demonstrated competencies in the most severe phase of UPRT, Recovery Training, can rapidly breakdown. Simply put, the competencies a pilot demonstrates in training can quickly deteriorate in the situation of a real world upset. This is addressed in a 2012 AIAA Paper titled Unexpected Pilot Performance Contributing to Loss of Control in Flight (LOC-I).[9]

Essentially, real world competencies in UPRT, including icing-related stall events, benefit from comprehensive real-world training that includes on-aircraft training to ensure the psycho-physiological aspects of loss of control in-flight mitigation can be effectively managed by the crew.

V. Three Categories of Icing UPRT[10]

A. Awareness Training

The enhanced stall and airplane upset environment are often unfamiliar to pilots-in-training and can be further compounded by any icing event due to the lack of stall cuing, increased risk of roll-off and combination of lift, weight and drag variations. Elements of awareness development have a variety of applications within both the prevention and recovery training phases. This is particularly relevant when addressing icing-induced events. Through focus on the individual awareness elements of α, load, lift vector and energy management (and consequences of mismanagement) early in UPRT, the pilot-in-training is afforded an opportunity to gain trust and confidence in the training.

It is crucial that fundamental concepts are introduced in a non-threatening manner to enhance the pilot-in-training's situational awareness at a rate that can be internalized. Inappropriately subjecting a pilot in training to dramatic events beyond their ability to resolve correctly can have severe long-term negative consequences associated with their trust, overall maximum skill level, and ability to contain fear and stress-induced over-response. Reinforcing learning through positive experiences early in the training regime significantly impacts the pilot-in-training's overall capability to expand practical knowledge and skill in a short period of time.

B. Prevention Training: Recognition & Avoidance

As previously stated, the primary focus of all enhanced stall and upset recovery training programs and methodologies must be firmly and squarely placed on prevention through enhanced awareness. There are two general types of prevention training. One type is time-favorable and the other type is time-critical. Although thorough UPRT should address both, the latter time-critical component is often the most difficult to address for a variety of psycho-physiological reasons.

C. Level 1 Prevention: Time favorable intervention through Aeronautical Decision Making

This element of prevention revolves around the concept of effective aeronautical decision making (ADM) through analysis, awareness, resource management, and intercepting the error chain through airmanship and sound judgment. Typically on the time scale of minutes or hours, a common example would be a situation where the pilot assesses the conditions (such as icing) at an airport prior to descent and recognizes those conditions as being too severe to safely subject the airplane to that environment on approach. Although a very simple scenario, the process of using situational awareness to avert a potentially threatening flight condition is an example of prevention through effective ADM. In the preceding example, if the crew elected to continue to the planned destination as the conditions were not too severe to abandon the approach, an effective flight crew would brief their mitigation strategies, apply appropriate counter-measures (utilize weather radar, request updated weather information, apply increased approach speeds, etc.) and identify and narrow their approach targets (i.e. we will initiate a missed approach if we do not hit specific targets on approach). The latter scenario is a more comprehensive demonstration of how effective flight crews use time favorable prevention strategies to enhance loss of control in-flight threat mitigation.

Another situation specific to icing UPRT is the pilot's awareness of an icing situation developing where he or she aggressively takes action to avoid letting the airplane's speed degrade into the slow flight region and avoiding situations requiring any significant increase in α. The pilot is aware of the α_{stall} variations and influence on airplane performance cause by increased weight, reduced lift and increased drag, and is taking early pro-active action to avert a stalled flight condition from developing. One such awareness point is airspeed stability. When operating at airspeeds above L/D_{MAX}, if power setting, airspeed, altitude, pitch, bank, and configuration are stable, minor excursions in speed tend to automatically correct themselves. The addition of airframe icing, however, will likely result in one or more parameters diverging from the stable point. For example; if pitch and power remain stable, increased weight and loss of life due to ice accumulation will result in altitude and airspeed loss. If the aircraft is on autopilot in an altitude hold mode, pitch will increase and speed will decrease. Add auto-throttles and power will increase in an attempt by the system to maintain airspeed as drag and α increase. A properly trained and aware pilot would be more likely to notice these indications as the result of ice accumulation (given icing conditions) and respond more quickly than a less aware pilot.

D. Level 2 Prevention: Time Critical intervention through Proportional Counter-Response

In simple terms, proportional counter response is the timely manipulation of flight controls and thrust, either singly or in combination, to manage an airplane flight attitude and/or flight envelope excursion that was unintended or not commanded by the pilot. The trained pilot is situationally aware and recognizes the developing threat. The time scale of this element of prevention is typically on the order of seconds or fractions of seconds with its goal being to recognize the development of a threatening condition and take proportional avoidance actions to preclude its development into an airplane upset. Due to the surprising nature of this level of developing upset, there is often a high risk of the pilot panicking and over-reacting to the event with the further risk of making the situation worse, unrecoverable or even generating structural failure in rare instances. The ability of the trained pilot to overcome surprise/startle factor can be significantly enhanced through exposure to similar time-critical events during training in combination with the pilot's enhanced skill set capable of resolving a flight condition beyond those experienced in day-to-day operations. Pilots who fly stick pusher equipped aircraft and who regularly receive stick pusher training may also need full stall training so they are familiar with potential aerodynamic stall cues. Remember that in an icing-induced event, the stick pusher may not activate due to the reduction in α_{stall}. For fly-by-wire airplanes with active flight envelope protections; this phase of time-critical prevention through proportional counter-response may be accomplished by the pilot allowing the automation to attempt to manage the time-critical disturbance in its entirety (if recommended by the manufacturer).

E. Recovery Training: Recognition & Recovery

Once an airplane's flight condition exceeds a certain level of severity, whether unintentional or uncommanded, the pilot must recognize the necessity of intervention and avert disaster through the pro-active application of effective upset recovery techniques. Early prevention through proportional counter-response in a developing airplane upset cannot be over-emphasized in UPRT, especially in icing encounters as mentioned in the Prevention section. However, once the flight condition has transitioned from the prevention phase and into the recovery phase, the pilot must recognize the transition and employ immediate corrective recovery action. Although definitions of an upset can vary, an airplane upset is typically defined as an unintentional flight condition that has deviated beyond established threshold values of pitch, roll, airspeed and/or α. For icing events, the unexpected pre-mature stall is likely the most significant threat due to lack of warning and higher risk of asymmetric roll-off. Remember, too, that the aircraft's stall warning system may not have been activated due to the reduction in α_{stall}. Forward control pressure must be increased until the stall characteristics (discussed above) go away, not just the stall warning (if any). Action must be quick and correct, as many aircraft, swept-wing jets in particular, can quickly progress to an unrecoverable condition.

One major deficiency in many UPRT programs is that the recovery phase of UPRT is often the primary, or exclusive, focus of training. On its own, recovery training does offer significant value on a variety of levels. The core element, however, of UPRT must again remain focused on prevention. The process of recovery training enhances the pilot's ability to contain startle factor, comprehend the primary and correct use of flight controls in the all-attitude all-envelope domain, and also enhances situational awareness. Similar to the overall concept of a building block approach to UPRT, the recovery phase is best served by following a similar process of awareness and skill development. The general sequence of imparting UPRT skills tends to follow the flow of:

1. Primary Control Strategies,
2. Alternate Control Strategies,
3. Secondary Flight Control Integration, and
4. Type/Class Specific Considerations.

It must be clear that type-specific considerations can be crucial to the effective implementation of recovery techniques and that the airplane manufacturer's recommended recovery methods always take precedence. This is particularly true in icing encounters as this situation is often assumed to be impossible to occur, not addressed or the manufacturer has not published type-specific icing stall recovery techniques.

The general building-block sequence addressing the recovery phase of skills training has been shown to impart long lasting skill sets to pilots while maximizing the understanding of prevention and recovery mitigation within the widest range of fixed wing airplane operations. The end result of a comprehensive upset recovery training program is to arm pilots with enhanced awareness and skills that are generally transferable and effective with due consideration for type-specific variations.

VI. Additional Considerations

A. Containing the Startle/Surprise Factor

Startle and surprise are without question significant factors in airframe icing events, upsets and associated stalls. Training programs must include and address startle/surprise factor. Imparting UPRT skill sets to pilots, without addressing startle/surprise factor, will not reliably enable the pilot to effect recovery during the mentally and physically demanding environment of an airplane upset. Although skill development should happen first to maximize the pilot's ability to integrate startle/surprise factor containment, the academic understanding of, and practical experience with, surprise/startle events are crucial in UPRT. Presently, the required magnitude, quality and relevance of startle/surprise factor, as it relates to UPRT awareness and skill development specifically, cannot be fully accomplished through ground-based simulation exclusively. The reality of the on-aircraft UPRT training process immerses the pilot within an augmented fidelity of the startle/surprise factor dynamic that is unique to the in-flight, real-world environment. Additionally, given the general technique of just adding weight to simulator models to replicate icing events can give the pilot a false sense of security as all the pre-stall and stall cues and presentation will be available during training. In the real world, none of these may be present.

B. Crew Resource Management and the Role of Pilot Monitoring

The CRM aspect of Upset Recovery Training is particularly challenging due to the widespread inconsistency of UPRT training in the commercial aviation industry. Although there is value in one crew member being comprehensively trained in the airplane upset/stall discipline, the presence of an additional crew member in the decision making process, as is the case in the CRM environment, can have dire consequences. Although the fundamental principles of enhancing situation awareness and promoting mutual decision making in the CRM environment is supportable, the timeline is intensely compressed. Given Boeing/NASA research[11] demonstrating the critical window of time necessary to resolve an airplane upset is often less than 10 seconds to initiate correct recovery action, the threat posed by interference from an untrained crewmember is severe. In general terms, the crew must (a) communicate and confirm the situation, (b) transfer control to the most situationally-aware pilot, and (c) work together through standardized interactions to mutually enhance awareness of the flight condition in order to manage stress between crew members and mitigate fear in a life-threatening situation. Effective application of KSA competencies is essential to upset and stall prevention. Due to the counter-intuitive nature of the UPRT environment, the untrained crewmember can be the most unpredictable element of the CRM-dependent airplane upset prevention and/or recovery scenario.

IV. Conclusion

In closing, icing can be dangerous for a variety of reasons, only some of which have been touched upon here. For example, discussions of configuration changes in icing conditions, flight control malfunctions to due ice interference and their associated influences on airplane control and performance are essential although beyond the scope of this paper. Hopefully, this short discussion on these unique stall-related phenomena was of value and perhaps even prompted a few readers to investigate further. Remember that, currently, simulators can provide an incomplete model of the effects of icing on aircraft performance. Severe airframe icing effects can reduce α_{stall} enough to preclude activation of the aircraft's stall warning and/or prevention systems, creating the situation where the aircraft enters a full aerodynamic stall without expected protection warnings. The stall may be accompanied by abrupt roll off and lack of roll control effectiveness. Pilots must know their pre-takeoff countermeasures, airborne mitigations and the airplane's performance limits. 'Preventing' a loss of control in-flight event is always preferred to getting to the point where 'upset recovery' is the only option. Prevention skills lie within the capabilities of the, competent, attentive, aware and appropriately knowledgeable pilot. Be prepared.

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