Smart Icing Systems
Year 1 Interim Report

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K. Sivier, P. Voulgaris, C. Wickens

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1.0 Introduction

This report summarizes the current status of the research being performed by the University of Illinois on the Smart Icing Systems, SIS, concept under the first year of its NASA grant. This grant has completed its first year of funding and beginning the first year of a proposed 4-year extension. The core of the report is the summaries from the 5 groups conducting research to develop the technology for the SIS. To maintain a reasonable document length, the summaries from each group are relatively brief but give a reasonable review of the research in that area. More detailed information can be found on the SIS website (http://www2.aae.uiuc.edu/sis/) which is described briefly in Section 1.3 or from the research leaders in each area.

1.1 Objective

The objective of this research is to improve the safety of aircraft operating in atmospheric (including ground) icing conditions. The approach is to improve the ice tolerance of aircraft by developing autonomous systems which will sense changes in aircraft performance and handling qualities and respond in a human-centered fashion to enable the aircraft to maintain control and flight safety. UIUC is conducting the fundamental research necessary to develop such a smart icing systems concept.

1.2 SIS Concept

The fundamental principle behind the SIS 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 if the pilot/aircraft system can continue to maintain the desired flight path, with good flying qualities, and an acceptable safety margin, regardless of atmospheric icing conditions. The SIS approach adds another level of safety not currently available on aircraft.

The SIS concept will be implemented through the development of an Ice Management System, IMS, which is depicted in Fig. 1. Here the ice protection of a SIS equiped aircraft is shown in block diagram form.

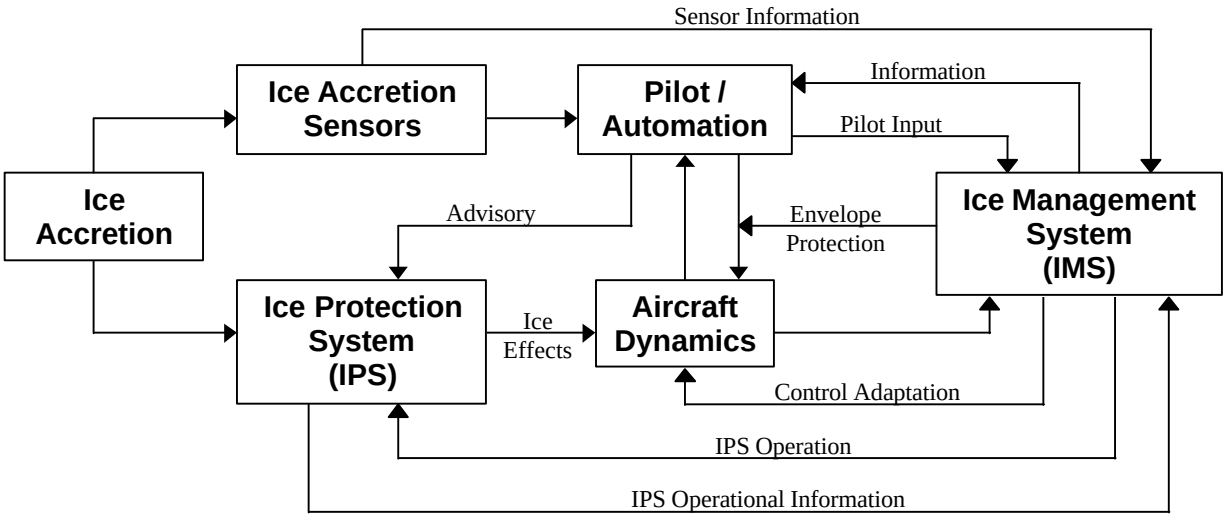


Fig. 1. Proposed new aircraft icing encounter model

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 four functions below:

1. **Icing Effects Characterization:** Sense the presence of ice accretion including its effect on measured aircraft performance, stability and control. Sense ice accretion and ice protection system performance and notify the pilot.
2. **Ice Protection System Operation and Monitoring:** 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. **Envelope Protection:** If the performance and control 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.
4. **Control Adaptation:** Modify the aircraft control laws to maintain clean-aircraft-like flying qualities to enable the aircraft to be safely flown within the reduced flight envelope. Notify the pilot of this action and maintain good pilot-automation coordination.

The research proposed here can be organized into three areas: Ice Management System (IMS) Research and Development, Flight Simulation, and the Safety and Economics Trade Study. Figure 2 depicts the organization of the research to develop the Smart Icing System and in particular the four functions of the Ice Management System. The five core technologies are shown in the top row of boxes and the four IMS functions are represented by the second row of boxes. Research is organized by the five core technologies, but focused on developing the technologies required in each of these areas to perform the four IMS functions. For example, Flight Mechanics supported by Aerodynamics will develop a nonlinear model of the aircraft forces and moments

including the effect of ice accretion. This will support the development of IMS functions 1, 2 and 4. Research in the other core technology areas will likewise support multiple IMS functions. We are not conducting original research in traditional Aircraft Icing Technology areas such as ice protection systems, etc. This research is being performed by other researchers and will be used in the SIS development when needed. Likewise, the IMS function *IPS Operation and Monitoring* has been developed and implemented to some extent by the industry. We are not conducting new research in this area although the function will be modeled in the Flight Simulation. The Flight Simulation will provide a research tool to integrate, develop and demonstrate the Smart Icing Systems technology and is shown at the bottom of Fig. 2.

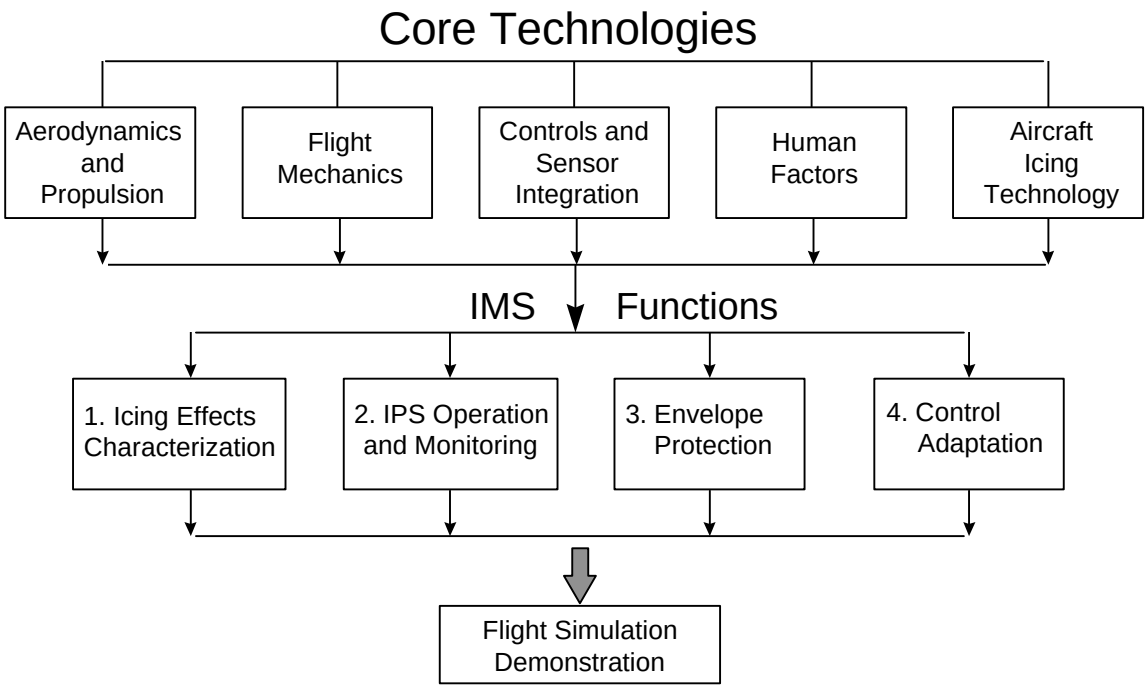


Fig. 2 Smart Icing Systems research organization.

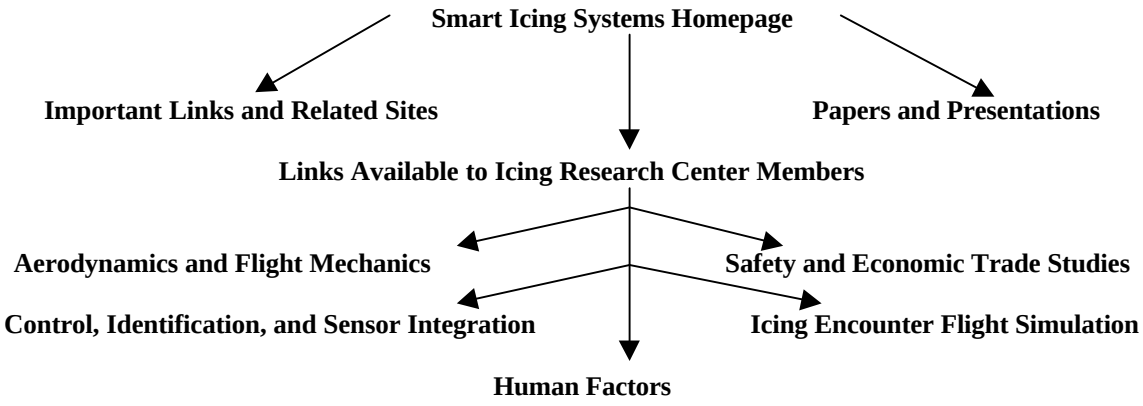
Therefore with the objective to improve aircraft safety through the development of Smart Icing Systems the following research areas are being pursued:

1. Aerodynamics, Flight Mechanics and Propulsion
2. Controls and Sensors
3. Human Factors
4. Flight Simulation
5. Safety and Economics Systems Study

These research areas are reviewed in section 2.1 to 2.5 in the following chapter.

1.3 SIS Website

The Smart Icing Systems Project is a product of five separate groups at the University of Illinois at Urbana-Champaign, which reside in different areas of the campus. To facilitate the continuous exchange of information between groups and to document and make available important findings, each group has its individual web page that is linked to a main Smart Icing Systems Project homepage. The main Smart Icing Systems homepage is located at http://www2.aae.uiuc.edu/sis/, and it contains links to the pages of the individual groups, along with relevant papers and general links. The basic structure of the website is shown below.



Since much of the Smart Icing System information is preliminary in nature, certain areas within the homepage will eventually be readable only by users in the uiuc.edu and nasa.gov domain.

2.0 Research Review

2.1 Aerodynamics, Propulsion and Flight Mechanics

The objectives for the first year were to formulate an approach to model the effect of ice accretion on aircraft performance and control as well as to determine the feasibility of a method to characterize ice accretion during steady flight.

This section is divided into 4 parts: Aerodynamic Effects, Initial Ice Accretion Effects Modeling, Quasi-Steady Ice Effects Characterization, and Computational Aerodynamic Modeling. A study on aerodynamic performance modeling using hinge-moment characteristics supported by the UIUC CRI grant is not included and can be found in an upcoming AIAA paper.[1]

2.1.1 Aerodynamic Effects of Ice Accretion

2.1.1.1 Objective

To develop a model to predict the effect of ice accretion on aircraft performance, stability and control based on icing cloud and aircraft parameters.

2.1.1.2 Approach

The icing effects are formulated using, the following equation

$$(C_A)_{iced} = (1 + h_{ice} k_{C_A}) C_A$$

Here η_{ice} is an icing severity parameter, and represents the amount and severity of the icing encounter, while k_{C_A} is a weighting factor that depends both on the degree of icing and the coefficient being modified. C_A is any performance, stability or control parameter or derivative that is affected by ice accretion.

In this preliminary formulation, the weighting factor, k_{C_A}, is assumed to be a function of several parameters:

$$k_{C_A} = f(\text{IPS, aircraft geometry and configuration, icing conditions})$$

where IPS refers to the status and activity of the Icing Protection System.

The icing severity parameter, η_{ice}, is also taken as a function of several parameters:

$$\eta_{ice} = f(n, K_0, A_c, E)$$

Where n is the freezing fraction, K_0 is the modified inertia parameter, A_c is the accumulation parameter, and E is the collection efficiency. In simplest terms, n is the fraction of water freezing at a point on a surface to the water impinging on the surface.

$$n = \frac{\text{mass of water freezing}}{\text{mass of water impinging}}$$

Inherent in the freezing fraction value is the type of ice that forms. A high freezing fraction, close to unity, indicates rime ice formation, while a lower n indicates glaze ice formation. The actual value for freezing fraction can be calculated at a representative aircraft location through a complex set of thermodynamic equations that take into account such things as airspeed, temperature, air and water density, pressure, viscosity, and several other variables. Hence, a *Mathcad* code is currently being developed to more easily calculate the freezing fraction at the stagnation point of a representative cylinder from given conditions.

The modified inertia parameter, K_0, is defined as follows:

$$K_0 = 18K\left[R_U^{-2/3} - \frac{\sqrt{6}}{R_U}\,\mathrm{Tan}^{-1}\left(\frac{R_U^{1/3}}{\sqrt{6}}\right)\right]$$

Where K is the inertia parameter, defined as:

$$K = \frac{\rho_d d_p U}{18c\mu}$$

and R_U, the droplet freestream Reynolds number is defined as:

$$R_U = \frac{\rho_\infty d_p U}{\mu_\infty}$$

For the inertia parameter and Reynolds number, ρ_d is the droplet density, d_p is the droplet diameter, U is the freestream velocity, c is the airfoil cord length, μ_∞ is the absolute air viscosity, and ρ_∞ is the air density.

The accumulation parameter, A_c, can be thought of as the length of ice growth in airfoil chords that would form on an imaginary flat plate placed perpendicular to the freestream flow for a time Δt, and it is defined as follows:

$$A_c = \frac{U(LWC)\Delta t}{\rho_{ice} c}$$

Where Δt is the time of exposure, LWC is the liquid water content of the freestream, and ρ_{ice} is the density of ice. One aspect of the accumulation parameter makes it particularly useful, and that is the ability of the parameter to account for exposure time through the Δt term. A_c also represents a nondimensional value which introduces the aircraft scale through the use of the characteristic length, c.

The final parameter is the collection efficiency, E, which is defined as follows:

$$E = \frac{\text{mass of water droplets impinging}}{\text{mass of water seen in the body projected area}}$$

The collection efficiency and K_0 will also depend on the aircraft scale and geometry assuring that η_{ice} is sensitive to the particular aircraft under consideration.

The complete formulation of the icing effects will produce a relationship for the icing severity factor, η_{ice}, as a function of freezing fraction (n), modified inertia parameter (K_0), accumulation parameter (A_c), and collection efficiency (E).

2.1.1.3 Results

In the intitial model model k_{C_A} will be taken as constant and derived from the NASA Twin Otter data. η_{ice} is a new concept and cannot be based solely on the Twin Otter data and sufficient data from a variety of aircraft are not available. For this initial estimate, the values for η_{ice} are based on airfoil ΔC_d data, which is more available than other icing data. Specifically, the data shown here were taken from Shaw, Sotos, and Solano.[2] After plotting the various points for the rime and glaze cases, a best case (quadratic) curve fit was performed to approximate a continuous ΔC_d. These curve fit equations, which relate ΔC_d to A_cE, are analogous to equations that would relate η_{ice} to A_cE. Hence, the curves and equations presented in Fig. 3 are part of the ongoing analysis to develop a relationship for η_{ice}.

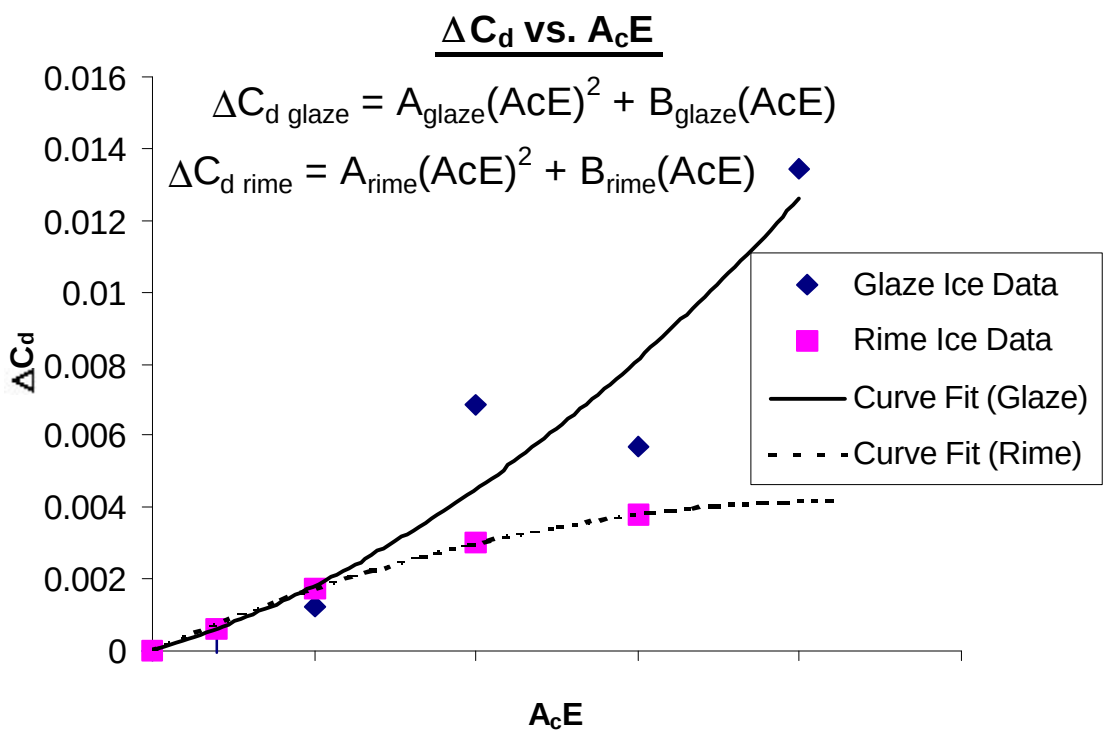


Figure 3 Airfoil drag rise for rime and glaze ice as a function of AcE.

The data in Fig. 3 show that these ΔC_d data can be reasonably represented by a second order polynomial in AcE with the coefficients of the polynomial a function of the freezing fraction (n) to account for the larger drag rise due to glaze ice. After examining all available data, a final relationship of this type will be formulated. η_{ice} will then be related to this function. It may be advantageous to consider the value of η_{ice} for any given aircraft in a standard icing encounter. For example this could be a corner of the

FAA part 25 Appendix C envelope. This would facilitate comparing different aircraft severity potential and provide a baseline useful in the formulation of the k_{C_A} terms. This formulation is still in process.

2.1.1.4 Future Research

Future research in this area during the next year will include:

- Complete the initial formulation of η_{ice} based on airfoil drag
- Find k_{C_A} values from the NASA Twin Otter data assuming they are constant
- Release the initial ice effects model
- Formulate k_{C_A} in terms of the effect of ice on the underlying aerodynamics and begin the development of a higher order model

2.1.2 Initial Ice Accretion Effects Modeling

2.1.2.1 Objectives

During the first year there were two main objectives:

- Determine a method by which the linear aerodynamic properties of an aircraft can be determined. Use this method to model the Twin Otter aircraft.
- Determine the performance, stability and control characteristics of an aircraft with and without ice from the linear model.

2.1.2.2 Approach / Methods

A simple linear model of the aircraft was formulated initially for use in developing the systems identification methods being developed for ice accretion effects characterization. This simple model is based on NASA Twin Otter data and is described below.

In order to achieve greater accuracy in the linear flight model, the NASA TND-6800 report[3] is being used. This report outlines the analysis of the longitudinal characteristics of a smaller twin engine aircraft. The reason to use this report is that it outlines the analysis, which includes many effects such as nacelle interference that are normally ignored. However, this report only allows the analysis of the longitudinal system. The NASA TND-6800 method requires detailed dimensions of the aircraft. We are currently in contact with NASA Lewis to acquire these data. The lateral system will be addressed once the longitudinal system is completed. DATCOM[4] or Advanced Aircraft Analysis[5] wil be used in order to accurately model the Twin Otter in the lateral mode.

The information about the aircraft's flight model will then be used in the analysis of its performance and stability. Using MATLAB and Simulink a configurable simulator has been developed. This will allow the flight model to be entered and simulated. The simulator is capable of computing all six degrees of freedom and returning any required information. However, it should be noted that this simulation is not real time do to the integration techniques used in Simulink. The primary purpose of these simulations is to

provide an analysis and diagnostic tool for the development of the aircraft models. These simulations will be used to show how the short period, phugoid, and how any performance information varies with ice accretion. This simulation will explore the accuracy of the models before they are used in the high-fidelity simulations to be developed. (see section 2.5)

2.1.2.3 Results

The current longitudinal model was taken from AIAA report 89-0754.[6] Where values were not available they were estimated. This information includes data for empty and gross take-off weights:

Using the information in Table 1 at gross weight, the iced and clean dimensional derivatives were calculated. This information is shown in Table 2.

In addition, the dimensional derivative formulas presented in Roskam[7] are to be used in the MATLAB code to allow for dynamically changing stability derivatives. Currently the MATLAB flight simulation code is being changed to allow for the computation of the individual stability derivatives as separate functions. By removing the functions from the main code, it will allow for a simple means by which to update dimensional formulas as improvements are made.

2.1.2.4 Future Research

Future plans include extending the current longitudinal analysis to the lateral case. In addition, research with the aerodynamics group will be undertaken to incorporate the next generation icing model where the k_{C_A} terms are calculated from the aerodynamics and information about the aircraft stability and control. These data will allow for a future analysis of the aircraft's flight envelope and how it changes with respect to the ice on the aircraft.

Twin Otter Aerodynamic Data				
		Empty	Gross	
Wing Area	S	39.02		m^2
Span	b	19.81		m
Aspect Ratio	AR	10		
Mean Aero Chord	cbar	1.981		m
Mass	M	4150	4600	kg
Interias	Ixx	21279	21787	$kg*m^2$
	Iyy	30000	31027	$kg*m^2$
	Izz	44986	48639	$kg*m^2$
	Ixz	1432	1498	$kg*m^2$
	Cz_{α}	-5.66		AIAA 89-0754
	Cz_q	-19.97		AIAA 89-0754
	$Cz_{\delta e}$	-0.608		AIAA 89-0754
	Cm_{α}	-1.31		AIAA 89-0754
	Cm_q	-34.2		AIAA 89-0754
	$Cm_{\delta e}$	-1.74		AIAA 89-0754
	C_{Do}	0.0415		AIAA 89-0754
	$C_{L\alpha}$	5.66		Equivalent to $-C_{Z\alpha}$
	C_{Lq}	19.97		Equivalent to $-C_{Zq}$
	$C_{L\delta e}$	0.608		Equivalent to $-C_{Z\delta e}$
	$Cm_{\alpha dot}$	-9		Estimate from Roskam[5]
	Cm_u	0		Roskam Eqn: 4.113
	Cm_1	0		Steady flight
	$Cm_{T\alpha}$	0		Roskam Eqn: 4.205
	Cm_{Tu}	0		Estimate from Roskam
	C_{Du}	0		Estimate from Roskam
	C_{D1}	0.0543		Based on C_L^2 Vs C_D baseline graph
	$C_{D\delta e}$	0		Estimate from Roskam
	C_{Tx1}	0.0543		Steady flight -- $C_{TX1}=C_{D1}$
	$C_{L\alpha dot}$	2.5		Estimate from Roskam
	C_{L1}	0.5		Based on lift = weight
	C_{Txu}	-0.0596		Estimate from Roskam
	$C_{D\alpha}$	0.2932		From $C_D = C_{Do} + k\ CL^2$ & $C_{D\alpha} = \partial C_D/\partial\alpha$
	C_{Lu}	0.02		Roskam Eqn: 4.109 estimation

Table 1 Twin Otter model

Twin Otter Stability and Control Information			
	Clean	Iced	Units
$\omega_{n\ \text{SHORT PERIOD}}$	3.631	3.405	/s
$\zeta_{\text{SHORT PERIOD}}$	0.771	0.803	
$\lambda_{\text{SHORT PERIOD}}$	-2.80 ± i(2.312)	-2.733 ± i(2.029)	/s
$\omega_{n\ \text{PHUGOID APPROX}}$	0.2137	0.2137	/s
$\zeta_{\text{PHUGOID APPROX}}$	0.0398	0.0377	
$\lambda_{\text{PHUGOID APPROX}}$	-0.00850 ± i(0.2135)	-0.00805 ± i(0.2135)	/s
M_δ	-10.45	-9.405	$/s^2$
Mu	0	0	/ft-s
Mq	-3.06	-3.06	/s
Madot	-0.804	-0.804	/s
MTu	0	0	/ft-s
M_α	-7.87	-6.69	$/s^2$
Z_δ	-40.33	-34.28	ft/s^2
Z_α	-379.03	-342.95	ft/s^2
Zu	-0.31	-0.31	/s
Zadot	-2.466	-2.466	ft/s
Zq	-19.7	-19.7	ft/s
X_α	13.72	13.91	ft/s^2
XTu	0.0149	0.0266	/s
Xu	-0.033	-0.0447	/s
Xd	0	0	ft/s^2

Table 2 Twin Otter dimensional derivatives

2.1.3 Quasi-Steady Ice Effects Characterization

2.1.3.1 Objectives

The objective of the research is to develop the method necessary to characterize icing and its effects on an aircraft by analyzing the quasi-steady in-flight aircraft data. A performance, stability and control, analysis of the steady state flight will be carried out to determine:

- The onset of icing on an aircraft (within a few seconds of accretion)
- Estimate the severity of ice accretion in terms of its affect on performance, stability and control
- Identify location of ice accretion on the aircraft and the potential safety hazards.

The research effort will concentrate on quasi-steady flight, which is characterized by control inputs and disturbances that are insufficient to excite the dynamic modes to the degree necessary to be identified using dynamic system identification techniques.

2.1.3.2 Approach

This section outlines the basic approach employed in the process of determining the effect of icing on the performance, stability and control of the aircraft in quasi-steady flight:

- Acquire flight data, using onboard sensors, for aircraft in icing conditions.
- Process aircraft data to obtain nondimensional parameters.
- Determine effect due to icing by comparing values obtained in flight to values obtained from the clean aircraft model, which includes dynamic effects. [i.e. $\Delta(P) = (P)_{iced} - (P)_{clean}$].
- Choose and set threshold values for icing determination and monitor trends of aircraft parameters to see if thresholds are crossed (implying onset of icing).
- Use the icing effects to determine the severity of ice accretion.
- Use the relative values of the icing effects to estimate the type and location of ice accretion and the potential safety hazards.

The equations of motion governing the aircraft flight are developed using Newton's 2nd law as shown by Roskam.[7] The aircraft is assumed to be a rigid body, with constant mass distribution, and the effect of ice accretion on aircraft mass is neglected. The X-Z plane of the aircraft is assumed to be symmetric i.e. $I_{xy} = I_{yz} = 0$. Changes in aircraft mass due to fuel burn will be taken into consideration over time periods greater than typical longitudinal dynamic modes. Using the above assumptions, the equations of motion for the aircraft are written for the rotating body-fixed system:

$$m(\dot{U} - VR + WQ) = -mg\sin q + F_{A_x} + F_{T_x}$$

$$m(\dot{V} + UR - WP) = mg\sin f\cos q + F_{A_y} + F_{T_y}$$

$$m(\dot{W} - UQ + VP) = mg\cos f\cos q_z + F_{A_z} + F_{T_z}$$

$$I_{xx}\dot{P} - I_{xz}\dot{R} - I_{xz}PQ + (I_{zz} - I_{yy})RQ = L_A + L_T$$

$$I_{yy}\dot{Q} - (I_{xx} - I_{zz})PR + I_{xz}(P^2 - R^2) = M_A + M_T$$

$$I_{zz}\dot{R} - I_{xz}\dot{P} + (I_{yy} - I_{xx})PQ + I_{xz}QR = N_A + N_T$$

2.1.3.3 Clean Aircraft Model

A clean aircraft model is developed to accurately determine C_D, C_L, C_M and C_h based on theoretical and empirical methods. The clean aircraft model allows for the comparison of values obtained during a flight with the model values. A discrepancy in the values beyond a certain threshold value will indicate the presence of ice accretion.

The development of the clean model is based on the methods outlined in NASA TN D-6800 (Ref 3) and is curently underway. The primary parameters modeled for the quasi-steady state are C_L, C_D, C_M, and C_h:

$$C_L = C_{L_{wfn}} + C_{L_{h(hf)}} + (\Delta C_L)_{dE} + (\Delta C_L)_{power}$$
$$C_M = C_{M_{wfn}} + C_{M_{h(hf)}} + (\Delta C_M)_{dE} + (\Delta C_M)_{tab} + (\Delta C_M)_{power}$$

$$C_D = C_{D_0} + (C_{D_i})_w + (C_{D_i})_h + (C_{D_i})_f + (C_{D_i})_n + (C_D)_{cooling\ system} + (\Delta C_D)_{power}$$
$$C_{h_{h(f)}} = (C_{L_{h(f)}})_{dtab=0} \frac{(x_{hinge} - x_{ac})_h}{\bar{c}_h} + (\Delta C_L)_{dtab} \frac{(x_{hinge} - x_{\bar{c}/4})_h}{\bar{c}_h} + (\Delta C'_M)_{dtab}$$

The clean aircraft model is tailored for the Twin Otter.

2.1.3.4 Icing Effects

The effects of icing on the quasi-steady flight are quantified by the changes between the icing flight values and the clean model values for α, δ_E, C_D, and C_h. As an example, the procedure for determining $\Delta\alpha$ during simple steady-state rectilinear flight in an unpowered glide is shown. An expression for α is obtained from the equations of motion in terms of stability derivatives.

$$a = \frac{C_{M_{d_E}}(C_L - C_{L_o} - C_{L_{iH}} i_H) + C_{L_{d_E}}(C_{M_o} + C_{M_{iH}} i_H)}{(-C_{L_{d_E}} C_{M_a} + C_{L_a} C_{M_{d_E}})}$$

Icing has a different effect on each stability derivative and this is accounted for using a icing severity factor, η_{ice}, and the sensitivity of the derivative to icing, k.

$$\left(\mathrm{C_A}\right)_{iced} = (1 + \eta_{ice} \mathrm{k}_{\mathrm{C_A}})\mathrm{C_A}$$

$\mathrm{k}_{\mathrm{C_A}}$ is a function of IPS activity, aircraft geometry, aircraft configuration, and icing effects.

Using this system, all the derivatives are a function of the icing severity factor, which is determined by the atmospheric conditions. The effect of ice on α is then calculated

$$\Delta a = a_{ice} - a_{clean}$$

and compared to a threshold value as are the other Δ's.

2.1.3.5 Results

Using the Twin Otter model derived from the NASA flight test data an example of the effect of ice accretion on the steady-state values can be determined. The effect of icing on the aircraft is presented in terms of $\Delta\alpha$, $\Delta\delta_E$, and ΔC_D, versus the non-dimensional icing severity parameter η_{ice}. Since η_{ice} for the available Twin Otter data is not yet available, the effects are formulated in terms of η_{ice} / η_{test} where η_{test} is the value of the icing severity parameter at the conditions the Twin Otter tests were conducted. The icing effects model then becomes

$$(C_A)_{ice} = C_A(1 + \frac{\varsigma_{ice}}{\varsigma_{test}} k_{C_A})$$

The variation of C_D, α and δ_E, with the non-dimensional icing severity (η_{ice}/η_{test}) is shown in Fig. 4.

The variation of C_D, α and δ_E are linear and the maximum variation occurs at η_{ice}/η_{test} = 1. The maximum changes due to ice accretion in C_D, α and δ_E are approximately 40%, 11% and 11% respectively. The values for the elevator deflection, δ_E, are negative in these calculations.

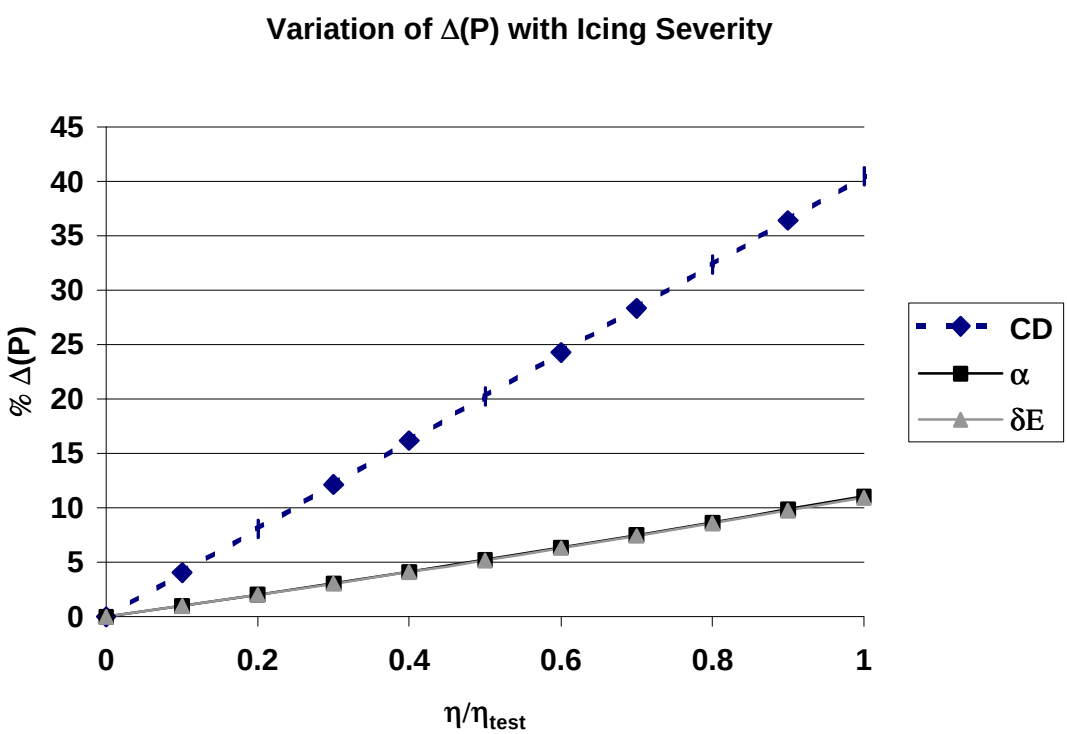


Fig. 4 Percentage Variation of Icing Effects with Icing Severity.

The main purpose in developing the clean model is to compare its values to the actual flight values, and thereby determine the effect of ice accretion. With the exception of the

drag, the effect of icing on the dimensionless parameters is typically within 10% of the clean values, and hence the accuracy of the clean model is critical. Developing a clean aircraft model that accurately predicts the non-dimensional parameters to the fidelity required is a significant task.

2.1.3.6 Future Research

The planned research tasks include:

- Incorporating the clean model into MATLAB and testing various scenarios.
- Compare model accuracy to values obtained from NASA Twin-Otter flights.
- Continuously upgrade model to match flight data.
- Once model matches real data, apply model to iced flight conditions.
- Compare the clean values (obtained from the model) to the iced values (obtained from flight test data).
- Use the discrepancies in the clean and iced values, and atmospheric conditions to determine severity of icing encounters.
- Determine the location of ice accretion if possible.

2.1.4 Computational Aerodynamic Modeling

Funding for computational aerodynamic modeling has not been provided up to this point from the SIS grant and is not scheduled to begin until year 2 of the 4-year extension. That means until November 2000. However research supported by other grants in this are is underway at UIUC. This section presents some information on the development of our CFD capability and briefly reviews plans for the research that will be supported by the SIS grant.

2.1.4.1 Objectives

In the previous year, the primary objective was to further the computational capability for predicting aerodynamics of iced airfoils.

2.1.4.2 Methods/Results

For the computational prediction of arbitrary ice shapes, we have continued to develop the NSU2D code[8] for key prescribed ice shapes determined from NASA and FAA technical suggestions. The steady RANS (Reynolds-Averaged Navier-Stokes) calculations methodology employs a robust turbulence model[9] along with an adaptive high-resolution unstructured grid methodology.[10] The calculations have been primarily steady-state RANS simulations and the results have shown good comparison with experiment up to (but not including) peak lift conditions. To improve the fidelity of the numerical approach for peak lift conditions, the code is currently being developed for unsteady RANS calculations by using an advanced multigrid implicit procedure.[11] This is intended to allow time-dependent computation of the low-frequency large-scale vortex

shedding phenomena noted to occur once large-scale separation regions are present on the airfoil.[12] Such unsteady features can result in significant hinge-moment fluctuations which can be associated with incipient stall and thus can be an important feature for characterizing the iced aerodynamics needed for IMS decision making.[1] Computations for both steady and unsteady RANS flows have been completed on the Cray Origin 2000 of NCSA (National Center for Supercomputing Applications) where Prof. Loth has an ongoing allocation for iced aerodynamic calculations. This parallel machine with 32 high-speed (MIPS R10000) processors that can allow high-resolution steady-state computations of thirty different angles-of-attack (to define a lift curve and drag polar) in less than one hour of CPU.

2.1.4.3 Plans for Future Research

Two CFD tasks will be undertaken to support the development of the SIS technology. The first task will be to develop a computational database to augment available experimental database for the purpose of developing a more sophisticated (neural-network) aircraft icing characteristics method for use by the characterization schemes and the flight simulator. The second task will be to explore and begin the development of a real-time prediction technology to be used for virtual-flight-testing of the IMS system.

The computations required to assemble the database will be made over the course of about one year and will use the NSU2D code[8] along with a range of prescribed ice shapes and airfoils determined from experimental icing encounters (including both flight-test and wind-tunnel data). The code will be run for both steady and unsteady RANS (Reynolds-Averaged Navier-Stokes) calculations.

Real-Time aerodynamic icing prediction methodology could provide the time-dependent aircraft icing shapes and resulting aerodynamic performance throughout a flight simulation (which can include the time-dependent test of the aircraft icing characterization methodology). Real time refers to the ability to calculate ice accretion and the resulting change in aircraft performance at a sufficient speed and accuracy to be used during a flight simulation. This technology would be extremely valuable and development will begin when the database method is completed. It is anticipated that this would be developed during the fourth year of the grant. These computations will be completed using the aerodynamic flow predictions of NSU2D coupled with the ice accretion physics of LEWICE. The use of LEWICE 2.0 allows for the state-of-the-art in ice accretion physics in a numerical package whose modular structure is intentionally suited for integration of an aerodynamics module such as NSU2D.[13] The challenges to this approach are significant with concerns ranging from accuracy of the codes to computational speed. Based on the computational resources anticipated by NCSA after the third year of this investigation (an eight-fold increase in the speed of the processors with 1024 available processors) a massively-parallel approach should allow moderate-resolution simulations which are temporally resolved to both the icing accretion time scale and the pilot input time scale.

2.2 Control, Identification, and Sensor Integration

2.2.1 Objective

In this first year of our study, our objective has been to demonstrate the feasibility of in-flight detection of icing using parameter identification techniques on the aircraft flight dynamics along with detection techniques applied to the resulting parameter estimates. In particular, we wanted to demonstrate that timely, accurate, and reliable indications of icing could be made available to the pilot and other flight systems. Moreover, we desired to merge an analytical framework with the particulars of the application into methods that would ultimately yield a useful and implementable detection algorithm.

2.2.2 Ice Detection Approach

Essential to reliable operation of the 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.

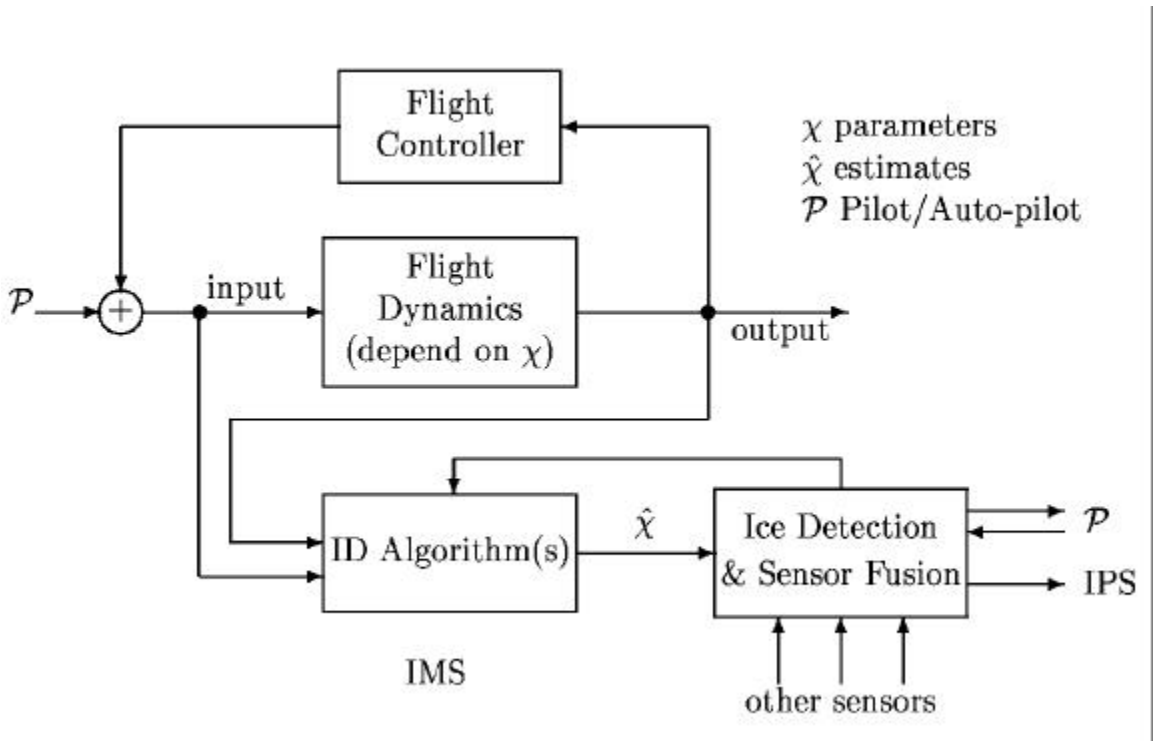


Figure 5: Aircraft icing detection block diagram.

A high-level block diagram of an icing identification system is shown in Fig. 5, which is a detailed representation of some of the functions 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 c . The identification algorithm seeks to identify these parameters by observing the system input and output, and computing an estimate, $\hat{c}(t)$, 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 and ice accretion sensors, for corroboration of the icing indication. Currently in our research, the detection of icing from the available data is accomplished with a neural network. Neural networks are ideal for this task because they can effectively handle the multiple inputs from sensors and parameter identification. 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.

The identification algorithm to be developed for this purpose must be able to accommodate two separate regimes of icing effects: 1) slow, small changes in flight characteristics at low angles of attack as ice is accreted on the flight surfaces, and 2) large, rapid, and nonlinear changes in the flight characteristics as the angle of attack is increased, or as the aircraft configuration is changed by the pilot, and flow separation occurs.

Accommodation of these two regimes leads in general to a two-phased 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 reconfiguration of the flight control systems of fighter aircraft.[14,15,16] Many current and future aircraft are open-loop unstable. When damage to some of the control surfaces occurs, 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 focussed on the identification of flight dynamics parameters when sudden changes due to failures and battle damage occur. The identified parameters are used to adjust the flight control laws in order to maintain, to the extent possible, the aircraft's stability and handling quality.

Preliminary results using linear and nonlinear models and static modified least-squares algorithms, along with the adaptation of inversion control laws, are encouraging. Recent research[14,15,16] has described both the parameter ID algorithms as well as their successful application to reconfiguration. They also consider various important issues such as the

tradeoff between using recursive least squares algorithms versus using static batch algorithms operating on a window of data. Moreover, they discuss the issues associated with turning off the ID when insufficient excitation was present, and the effects of damage occurring (*i.e.*, parameter jumps) within a window of data.

This study is similar to those reported,[14,15,16] insofar as we are also identifying flight dynamics parameters. However, in our study this identification occurs in the context of aircraft icing, where both the parameter variations and the excitation are usually small. With fighter aircraft control reconfiguration, the parameter changes are abrupt, and therefore are easier to recognize. Furthermore, excitation is generally larger for fighter aircraft than for commercial aircraft. Hence our study must focus on parameter convergence rates in the presence of smaller excitation.

2.2.3 Results

Investigations via simulation were performed for both candidate parameter identification algorithms and for neural network based icing detection. The parameter identification algorithms considered were a least-squares based batch algorithm and an H^{∞} recursive algorithm.

2.2.3.1 Parameter Identification Algorithms

The parameter identification algorithm simulations were performed for the linearized longitudinal flight dynamics model.

$$\begin{aligned}
\dot{u} &= -g\cos(q_1) + X_u u + X_{T_u} u + X_a a + X_{d_e} d_e \\
\dot{z} - U_1 q &= -gq\sin(q_1) + Z_u u + Z_a a + Z_{\dot{a}} \dot{a} + Z_a q + Z_{d_e} d_e \\
\dot{q} &= M_u u + M_{T_u} u + M_a a + M_{T_a} a + M_{\dot{a}} \dot{a} + M_q q + M_{d_e} d_e
\end{aligned}$$

The parameters to be identified, collectively denoted by c, are M_a, Z_a, X_a, M_{d_e}, and Z_{d_e}. Extensive simulation and analysis with the current Twin Otter model has shown that only M_a and M_{d_e} are useful for icing indication in a reasonable time frame; hence the estimates of Z_a, X_a, and Z_{d_e} are ignored. The linear longitudinal flight dynamics equations above are converted into the following form

$$\begin{aligned}
\dot{x} &= A(x,v)c + b(x,v) + w \\
y &= x + n
\end{aligned}$$

where $x = [q\ \theta\ \alpha\ u]^T$ is the state, $v = \delta_e$ is the input, y is the measured output, w is the state disturbance, and n is the process noise. Specifically, n(t) represents inaccuracies in the measurement, *e.g.*, instrument accuracy limitations, and w(t) represents unknown excitation of the flight dynamics, *e.g.*, turbulence, modeling error. These unknown

exogenous signals n(t) and w(t) will fundamentally limit the ability to accurately identify the parameters.

For the purpose of simulation, n(t) and w(t) are assumed to be zero-mean white Gaussian noise with each component independent, hence they are characterized by the variances of their components. The covariance of w was determined by considering w in the measurement of $\dot{x}$ (for the purpose of determining the covariance only) and assuming a SNR of 100 for each component of $\dot{x}$ for a 5° doublet over ten seconds. The variances of the components of n were taken to be the instrument resolution specifications for the NASA Twin Otter:[17]

$$\begin{array}{cccc} s_q & s_q & s_a & s_u \\ 0.0167°/\sec & 0.0293° & 0.003° & 0.076 knot \end{array}$$

The parameter identification simulations investigate the effectiveness of the candidate algorithms during a maneuver. In particular, we assume a period of steady level flight during which ice accretes but lack of excitation precludes parameter ID, followed by a maneuver during which parameter ID takes place. Consistent with this icing scenario, we begin the parameter ID algorithm simulation at the initialization of the maneuver, and the parameters are assumed to be constant over the maneuver. The maneuver is modeled as a doublet, and is thus characterized by its amplitude and length (*i.e.*, period). In order to easily evaluate the effectiveness of the candidate ID algorithms, we use a simple threshold that is the mean of clean and iced parameters. Finally, we also consider ID of the clean aircraft with small initial parameter estimate errors for ``false alarms''.

The Batch Least Squares algorithm collects measurements at several time instants into a batch and solves for the parameter estimate via matrix least squares. More specifically, at any time instant, t_m, the algorithm will concatenate the previous m measurements taken at a sample rate T. The resulting batch period, T_b, is thus mT . Hence the linear system of equations will take the form

$$\begin{aligned} A(x_{t_1}, v_{t_1})c &= \dot{x}_{t_1} - b(x_{t_1}, v_{t_1}) \\ A(x_{t_2}, v_{t_2})c &= \dot{x}_{t_2} - b(x_{t_2}, v_{t_2}) \\ &\vdots \\ A(x_{t_m}, v_{t_m})c &= \dot{x}_{t_m} - b(x_{t_m}, v_{t_m}) \end{aligned}$$

where $t_i = t_m - (n - i)T$, and x_{t_i} , $\dot{x}_{t_i}$, and v_{t_i} denote the respective values of the measurements at time t_i. For the sake of simplification, the equations above will be written as

$$Ac = \dot{X} - B$$

where the definitions of A, $\dot{X}$, and B are obvious. For the batch filter, both the state and the state derivative are assumed to be measured, hence $\dot{X}$, A, and B are known. The implementation of the algorithm is a matrix least squares solution

$$\hat{c} = \left[A^T A\right]^{-1} A^T \left(\dot{X} - B\right)$$

where an estimate $\hat{c}$ is produced every T seconds.

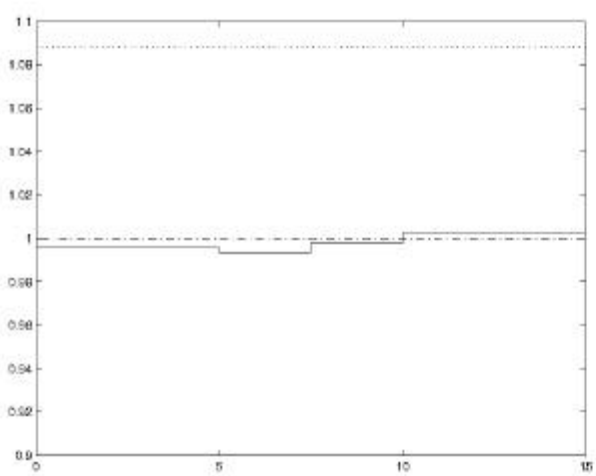
Simulations were performed for a batch period, T, of 2.5 s and a sampling rate of 80 Hz. The iced aircraft simulation results are shown in Fig. 6. Both parameter estimates, M_a and M_{d_e}, being well below the simple threshold, give strong indications of icing. The clean aircraft simulations are shown in Fig. 7. Again, both parameters estimates give an accurate indication of the clean aircraft, when evaluated with the simple threshold.

The H^∞-based ID algorithm is a recursive algorithm in that the parameter estimate at any time instant is a function of the entire history of information available (*i.e.*, not just the information at a batch of time instants). As such the H^∞-based ID algorithm is described by differential equations:

$$\begin{aligned}
\dot{\hat{c}}_g &= e^{-1} \Sigma_g^{-1} A(z,v)^T (z - \hat{x}) \\
\hat{x} &= A(z,v)\hat{c}_g + b(z,v) + e^{-1}(z - \hat{x}) \\
\dot{\Sigma}_g^{-1} &= \Sigma_g^{-1}\left[A(z,v)^T A(z,v) - g^{-2} Q(z,v)\right]\Sigma_g^{-1}
\end{aligned}$$

where $\gamma > 0$ is a scalar parameter, tightly lower bounded by a precomputable quantity γ^*.

M_a parameter estimates



M_{d_e} parameter estimates

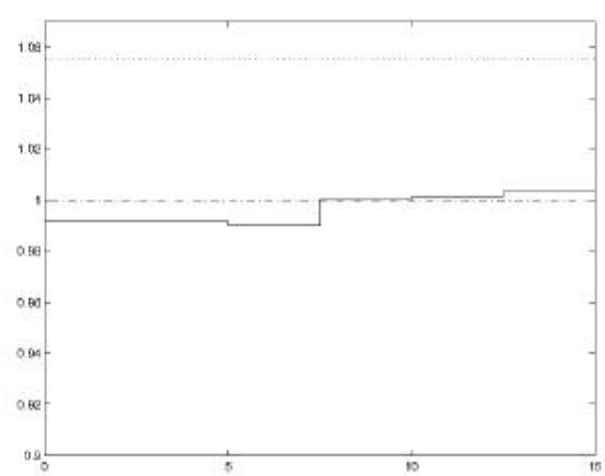


Figure 6: Parameter identification simulation results for the iced aircraft using the batch least-squares Algorithm with T = 2.5, a 5 doublet maneuver over 10 seconds and with process noise only. The estimates of M_a and M_{d_e} normalized to their actual (iced) values are plotted. The dotted lines represent the respective simple thresholds.

This is the NPFSI (noise perturbed full state information) algorithm.[18] As described in more detail in the reference, g is in fact the guaranteed disturbance attenuation bound:

$$\frac{\left\| c - \hat{c} \right\|_{Q(x,v)}}{\left(\left\| w \right\|^2 + \left| c - \hat{c}_{\circ} \right|^2 \right)^{\frac{1}{2}}} \leq g$$

where $\| \cdot \|_Q$ denotes L_2 norm with weighting function Q, and $\hat{c}$ is the estimate.

M_a parameter estimates $\qquad$ M_{d_e} parameter estimates

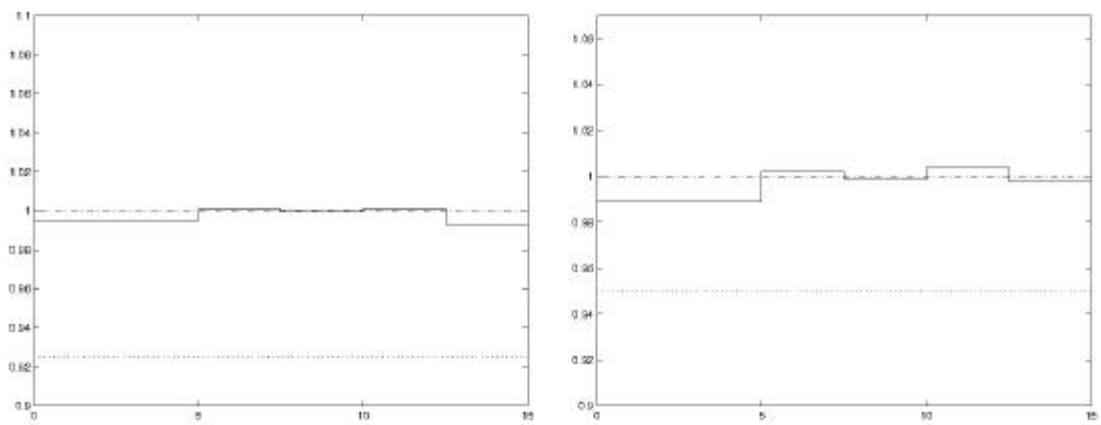


Figure 7: Parameter identification simulation results for the clean aircraft using the batch least-squares Algorithm with T = 2.5, a 5 doublet maneuver over 10 seconds and with process noise only. The estimates of M_a and M_{d_e} normalized to their actual (clean) values are plotted. The dotted lines represent the respective simple thresholds.

For the icing simulation, the natural choice of $Q(x, v) = A(x, v)^T A(x, v)$ was used, for which $\gamma = 1$.[18] In our simulations we took specific values γ of strictly larger than γ^*, and in particular $\gamma = 3$ and $\gamma = 4$. A doublet of 5° over ten seconds was used. The iced aircraft simulation results are shown in Fig. 8. Using the simple threshold, the ID algorithm gives an initial indication of icing in roughly 1 s and an unambiguous indication in under 5 s. Results pertaining to the more sophisticated neural network classifier are given in the following section.

In the case of the false alarm simulation, an initial parameter estimate error, $\tilde{c}(0)$, must be specified. (Note that this is not the case for the batch ID algorithm, since it is not recursive.) This initial parameter estimate error will in reality be due to state and process noises during the previous to the initialization of the maneuver, and to trim condition creep during steady level flight. Since these affects have not yet been well quantified, the simulations were performed for several $\tilde{c}(0)$. The results of these simulations for the

clean aircraft are given in Fig. 9. The M_a estimate yields a false alarm only for the largest $\tilde{c}(0)$, whereas the M_{d_e} estimate never gives a false alarm for the values of $\tilde{c}(0)$ simulated. As to be expected, the incidence of false alarms is less when the neural network classifier is used.

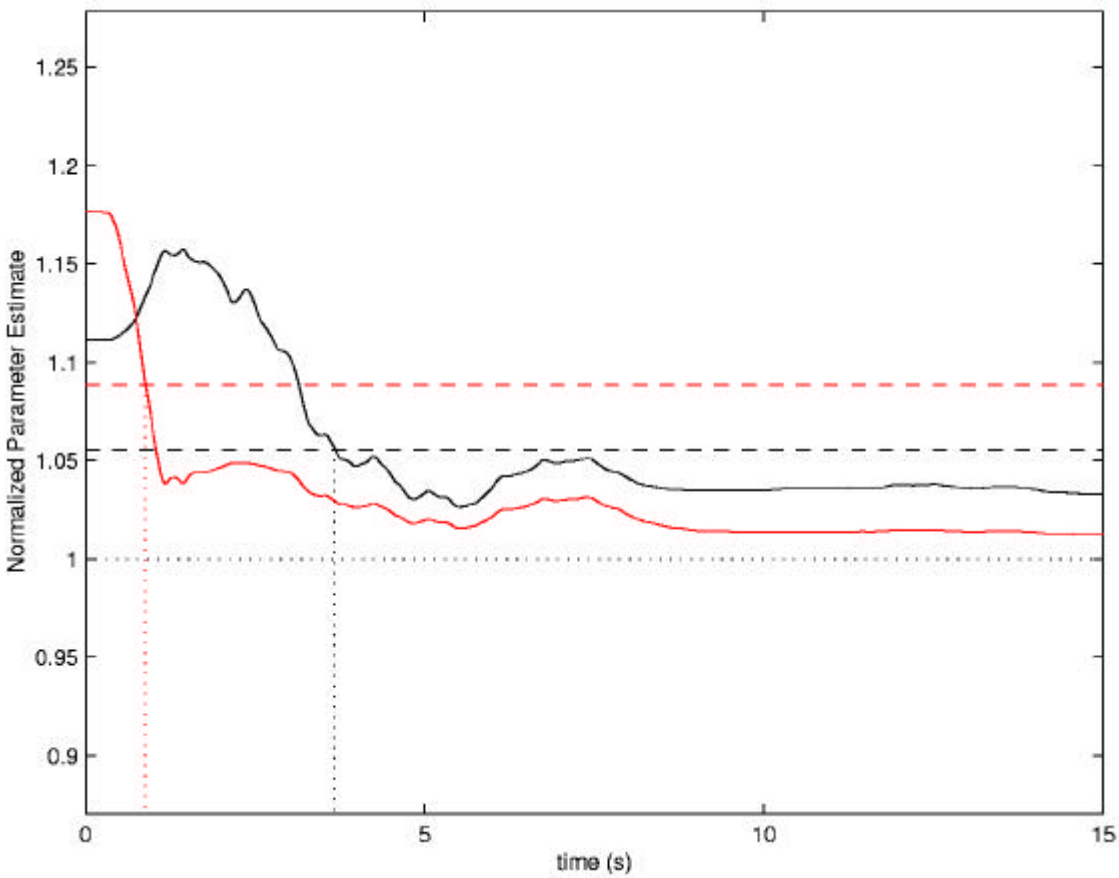
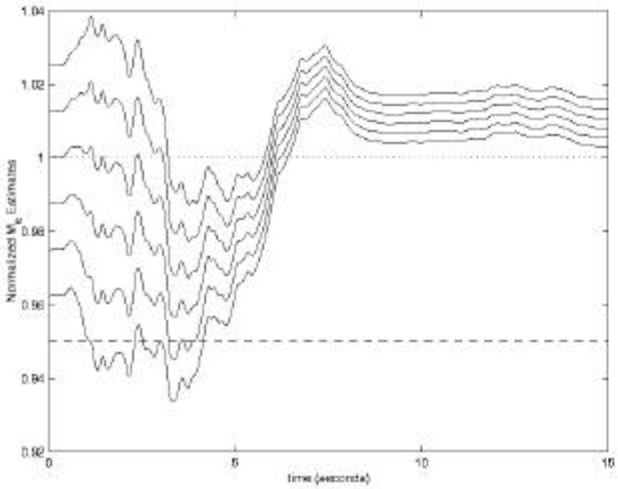


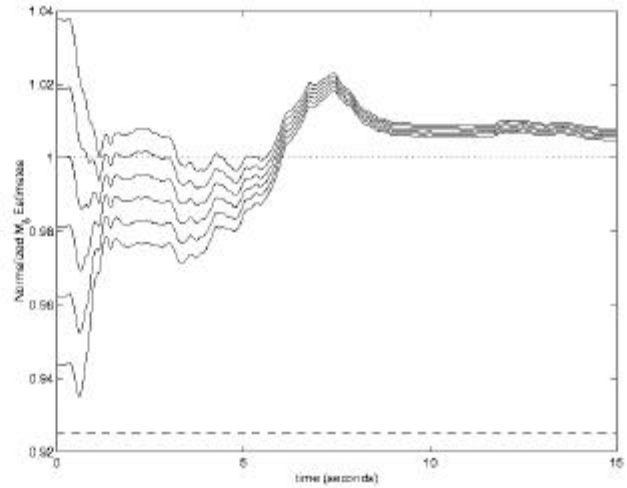
Figure 8: Parameter identification simulation results for the iced aircraft using the H^{∞} NPFSI Algorithm with $\gamma = 3$, a 5° doublet maneuver over 10 seconds and with process and measurement noises as above. The estimates of M_a and M_{d_e} normalized to their actual (iced) values are plotted. The dashed lines represent the respective simple thresholds, and the dotted lines indicate where the thresholds are initially crossed.

M_a parameter estimates



Notice: M_a gives false alarm for some initial error of < 3% of actual (clean) value.

M_{d_e} parameter estimates



Notice: M_{d_e} never gives false alarm for any initial errors of < 6% of actual (clean) value

Figure 9: Parameter identification simulation results for the clean aircraft using the H^∞ NPFSI Algorithm with γ = 3, a 5° doublet maneuver over 10 seconds and with process and measurement noises as above. The estimates of M_a and M_{d_e} normalized to their actual (clean) values are plotted. The dashed lines represent the respective simple thresholds.

2.2.3.2 Icing Detection Classifier

The classification and detection of icing using parameter estimates and available sensors can be accomplished through neural networks. Neural networks are adequate for the problem because they easily incorporate many different inputs and can account for nonlinearities between them. Currently, only estimates for the parameters M_{d_e} and M_a are used as inputs to the classification neural net. M_{d_e} and M_a are predominantly used because they converge relatively quickly and are indicative of tail plane icing.

Simulations were conducted and a neural net trained based upon sampled parameter estimates from the identification algorithm. The estimates of M_{d_e} and M_a were sampled every half second for five seconds after an excitation input occurred. Estimated M_{d_e} and M_a values were found for a variety of random inputs that consisted of doublets varying in amplitude and period. Two neural networks were then trained employing 300 of these random estimates. The networks were constructed to output -1 for a clean aircraft and +1 for iced. Testing was accomplished by estimating the parameters for many more random inputs and then using these estimates as input to the previously trained network. The

results are shown in Fig. 10. The left side of Fig. 10 portrays the results for a network that utilizes only estimated M_{d_e} and the right side gives the network for M_a. In both plots, each open circle represents a simulated classification of the aircraft condition. The individual classifications are plotted along the horizontal axis (*i.e.*, 600 on the horizontal axis label denotes the 600th classification simulation). The result of the classification is plotted on the vertical axis, where 1 indicates iced and -1 indicates clean. As can be seen, the neural networks accurately identify the clean and iced cases for many inputs.

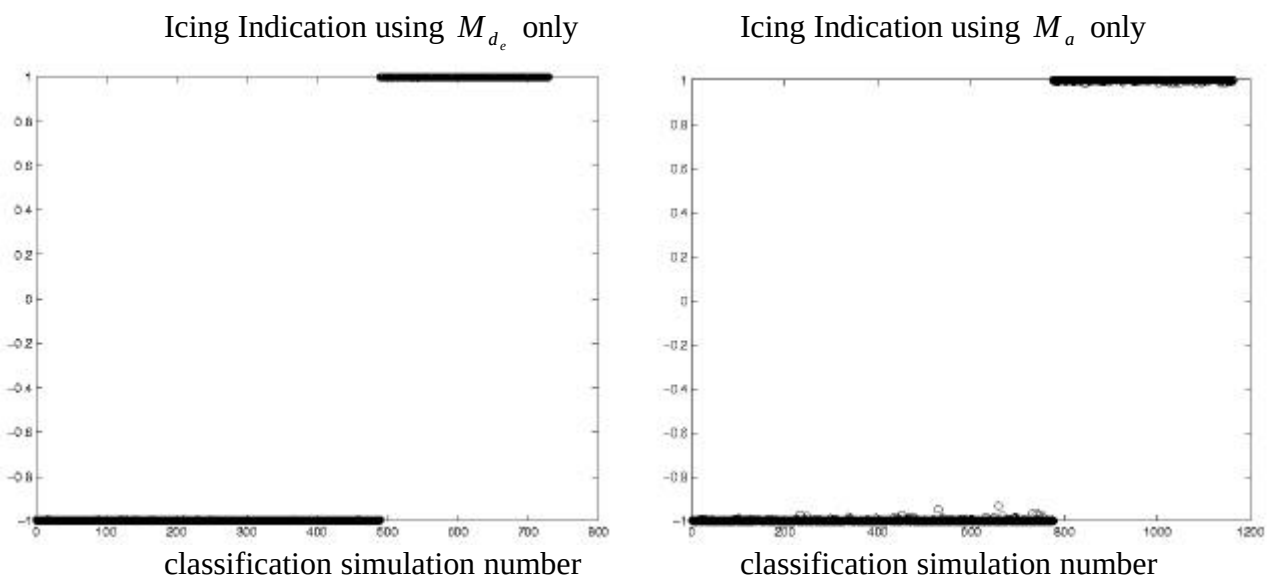


Figure 10: Neural network simulation results using parameter estimates from the recursive H^{∞}-based ID algorithm with $\gamma = 4$. Various doublet maneuvers with amplitudes from 0.5° to 10° and periods from 2 s to 15 s were used. For the clean aircraft, the initial parameter estimates were in the range of those used in Fig. 9. In both plots, -1 indicates clean and 1 indicates iced. In each case, detection is based on the first 5 s of parameter estimate information, beginning with the initialization of the maneuver.

2.2.4 Major Findings

The combination of parameter identification of the linearized longitudinal flight dynamics and neural network based detection provide a reliable, accurate, and timely (5 s after identification is initiated) indication of tailplane icing even during relatively small maneuvers (down to 0.5° doublets).

2.2.5 Future Plans

Having demonstrated feasibility of our icing classification approach in a relatively limited framework, our plans are to extend these promising results to more sophisticated icing scenarios based on more complicated flight dynamics and aircraft icing models.

Moreover, we plan to seek to further integrate our icing detection and characterization methods with information available from the steady-state icing characterization and other aerodynamic sensor. In particular, our future plans are given in the chronologically ordered list below.

1. investigate the tradeoff between neural network batch period, icing indication accuracy, and excitation level
2. incorporate other sensor information into the neural network classifier
3. investigate operation of the neural network classifier in detecting the transition from iced conditions back to clean conditions
4. investigate other candidate ID algorithms including extended Kalman filter algorithms and batch H^{∞}-based algorithms
5. investigate classification of icing severity and type of icing effect (*i.e.*, wing or tailplane icing). Requires incorporation of lateral-directional flight dynamics.
6. investigate feasibility of parameter ID based icing detection during "steady level" flight by taking advantage of state disturbance excitation.
7. implement parameter ID algorithms on more accurate time-varying and nonlinear flight dynamics models. Ultimately implement the ID algorithms on flight simulator with realistic interface with pilot and other flight systems.

2.3 Human Factors

2.3.1 Objectives

The objective of the human factors research activities is to design human-centered displays that a) inform pilots about the presence and (significant changes in) performance effects of icing conditions throughout the flight, b) communicate the status, activities, and limitations of the IMS to the flight crew in a timely and efficient manner, and c) provide pilots with advisory information that helps them handle inflight icing encounters safely and effectively.

2.3.2 Identification of Pilots' Information Requirements

One important step early in the design of any human-machine system is a thorough analysis of the operator's tasks and associated information requirements. This step serves to determine what information is critical to support operators in performing their tasks, and when and how this information should be presented. With this goal in mind, the human factors group has performed a number of activities throughout the first year of this project. The literature on in-flight icing from an operational perspective was reviewed. ASRS and NTSB reports on incidents and accidents involving icing-related problems were examined to identify what information might have helped the crew handle those situations more safely and efficiently. Finally, a small number of instructor and commuter airline pilots were interviewed to learn about their understanding and handling of icing conditions. These steps served to compile a preliminary list of likely information needs.

Based on this list, the group designed a survey of pilots' information requirements that consisted of three parts.

The first part served to gather information on the background of responding pilots. It asked about the pilots' current cockpit position, their number of flight hours, and the type of equipment they are currently flying. It also included questions about the type of anti-ice or de-ice equipment on their current airplane as well as their company's procedures and policies for operating this equipment. This background information is important to be able to interpret adequately pilots' responses to other parts of the survey.

The second part of the survey presented pilots with the above-mentioned list of possible information requirements and asked them to rate the importance of the various items on a scale from 0 to 3 (0 = 'not necessary at all', 1 = 'nice-to-have', 2 = sometimes important, and 3 ='necessary at all times'). Pilots were asked to provide ratings for all items independent of whether the information is currently available to them. They were also encouraged to explain their ratings, in particular in those cases where they indicated that the information is sometimes, but not always, important to them.

The list of possible information requirements covers the following three areas: a) characteristics of the icing, b) aircraft configuration and performance, and c) information on the status and activities of icing-related onboard systems (IPS and IMS). The first category - characteristics of the icing - includes information regarding the location, shape, rate, amount, and type of ice accretion. We also asked about the importance of knowing the surface temperature of the aircraft and the outside air temperature (OAT). The second category covers information such as current flap and trim settings, implications of future configuration (i.e. flap and gear) changes, autopilot status (on/off) and active modes. With respect to aircraft performance, pilots were asked to rate the importance of items such as climb performance degradation, the degree of loss of lateral and longitudinal stability, stall margin or angle of attack (AOA), loss of airspeed, maximum safe bank angle, and the length of time the aircraft can maintain flight in current conditions. The last category - information on the IMS/IPS – asked about the perceived criticality of knowing the current status and current or planned actions of the IPS (Ice Protection System) and IMS (Ice Management System), the reliability of the IMS and its recommendations, and the reasoning behind those recommendations.

The survey was sent to 115 University of Illinois - Institute of Aviation Alumni who had graduated since 1988. This selection was made in an attempt to reach primarily those pilots who are currently flying for a commuter airline. Anyone graduating before 1988 is likely to fly for a major airline and thus on a large commercial transport aircraft with anti-ice equipment at this point. To date, we have received 23 completed surveys.

Before discussing the findings of the survey, it is important to note that the survey allows us to identify perceived, not necessarily actual, information requirements. It helps us understand what information pilots consider important, why they rate the information in certain ways, and it also allows us to identify possible misconceptions in pilots' understanding of icing conditions and effects which may indicate the need for additional

training in the future. The identification and consideration of perceived information requirements is important to ensure acceptance of a future design by its operators and to determine what information is meaningful to pilots. Still, it is only one of several sources of information and can not be relied on exclusively in the design of a system. For example, earlier research has shown that it is critical to keep pilots informed about the status and actions of their automated systems at all times. However, a lack of experience with such systems often leads pilots to underestimate the value of this information.

The following table shows pilots' median ratings of the various types of information included in the survey in descending order of importance:

Information Needed At All Times

Location / Rate / Amount of Ice Accretion
Outside Air Temperature
Stall Margin/Angle of Attack
IMS/IPS Status (On/Off)
Current IMS Actions
Reliability of the IMS and Its Sensors

Information Sometimes Important

Type of Icing
Current Flap Setting
Implications of Future/Planned Configuration Changes for Aircraft Performance
Autopilot Status (On/Off)
Active Autopilot Modes
Climb Performance Degradation
Excessive Elevator Trim Requirements for Given Configuration
Degree of Loss of Longitudinal Stability
Degree of Loss of Lateral Stability
Loss of Airspeed
Length of Time Airplane Can Maintain Safe Flight In Current Conditions
Maximum Safe Bank Angle
(Changes in) Engine Performance
Future/Planned IMS Actions

"Nice-To-Have" Information

Shape of Ice Accretion
Airplane Surface Temperature
Current Trim Settings
Reliability of IMS Recommendations
Reasoning Behind IMS Recommendations

In summary, most pilots rated information concerning characteristics of the icing – in particular, the location, rate, and amount of ice accretion – as most critical. This information is currently available to a limited extent only and only by means of visual inspection of the aircraft surfaces. The problem is that some critical surfaces (e.g., the tail section of the aircraft) are not at all visible from the cockpit, and ice accretion on any surface can be difficult or impossible to discern at night. Another piece of information that is not provided on most civilian aircraft – the stall margin/AOA - was rated critical as well. Finally, information concerning the IMS system such as its status, actions, and reliability were considered very important, probably reflecting a healthy sense of skepticism on the part of pilots.

In contrast, the shape of ice accretion obtained the lowest rating which may reflect either a lack of awareness of the importance of this parameter or pilots' acknowledgment of their inability to interpret this information in terms of its implications for aircraft performance. Other types of information received very low ratings even though they are considered important by pilots as indicated by their written comments (e.g., the reliability of and reasoning behind IMS recommendations). Pilots explained that they did not want this information displayed since they are concerned about possible information overload, especially in time-critical situations.

Some of the fairly low ratings for items related to aircraft configuration and performance need to be interpreted carefully since they may be due, in part, to a misunderstanding on the part of the responding pilots. Even though we stressed in our instructions that we were interested in the perceived importance of information regardless of whether it is available to them on their current flight deck, the comments by several pilots indicate that they missed this point and therefore assigned fairly low ratings to items they consider critical.

In response to two open-ended questions at the end of the survey, pilots overall expressed a positive attitude towards the proposed IMS system and its functionality. However, they were adamantly opposed to enabling the IMS to alter the flight envelope or adapt the flight controls when deemed necessary by the system. Instead, they preferred a less powerful system that would provide information and issue advisories or cautions only. Again, these data need to be interpreted in light of pilots' likely experiences with earlier advanced automation technology which, in many cases, is highly powerful and independent yet fails to communicate its intentions and actions to the flight crew. Thus, improved feedback design can be expected to increase the acceptability of proposed IMS functions.

2.3.3 Display Design In Support of Advisory Functions of the IMS

In addition to providing pilots with information that helps them detect and monitor changes in (the performance effects of) icing conditions, the IMS can also serve as an advisory system that helps pilots respond to critical icing encounters quickly and appropriately. While the ultimate goal of the IMS is to avoid such situations, they may

still occur when pilots miss available information or when a problem is masked by an autopilot for some time.

One situation that can cause considerable problems with potentially catastrophic consequences is the accretion of ice on the tailplane of the aircraft. Tailplane icing can occur independent of or in combination with wing icing. The two conditions require opposite pilot responses. Thus, the challenge for pilots is to diagnose the nature of the problem quickly and accurately and to respond appropriately, often in highly demanding circumstances such as a final approach.

To support pilots in this task, we are currently developing candidate displays that inform the pilot of the location of the ice accretion (status display) and/or the appropriate responses (such as changes in power or flap settings) to the icing encounter (command display). Command displays eliminate the cognitive step and thus reduce the potential for errors associated with moving from a diagnosis of the situation to the response selection. However, in cases where system recommendations are not completely reliable and accurate, the use of command displays can be problematic. In those situations, pilots have been shown to be less likely to reverse their course of action even if it does not have the desired and anticipated effects. This phenomenon, excessive trust in and over reliance on automation, has been observed with many earlier systems. Attempts will be made to exploit the benefits of command displays while minimizing their potential negative effects by providing information about the reliability of system recommendations.

2.3.4 Plans for Future Research

In early 1999, a slightly revised version of the information requirements survey will be distributed to all commuter pilots who are currently members of the airline pilots' association ALPA. Revisions of the survey are necessary to eliminate the observed misinterpretation of instructions and thus gather more valid and reliable data from a much larger sample of pilots flying different types of aircraft.

In Spring/Summer 1999, proposed command and status displays will be evaluated in the context of a medium-fidelity simulation of a twin-engine commuter-type airplane. Instructor pilots from the Institute of Aviation will serve as subjects. Their performance with these different displays will be compared across several scenarios that vary in terms of time criticality, reliability of system recommendations, and the modality of system commands.

2.4 Safety and Economics Trade Study

2.4.1 Objectives

As part of the smart icing systems (SIS) research, a systems study is being performed to evaluate the effects of the safety and economic factors of smart icing systems on the U.S. air transportation system (ATS). As part of this systems study, an overall picture of the

role that aircraft icing has on the transportation system is being developed. The study also takes into account past events and errors in evaluating the smart icing systems.

Specifically, the purpose of the systems study is to evaluate the impact of smart icing systems on the safety and economics of turboprop commuter aircraft in today's domestic air transportation system. A secondary goal is to estimate the impact on the smart icing system of future changes in the transportation system. To accomplish this, the systems study has the following objectives.

- Determine if, and to what extent, smart icing systems will increase the safety of turboprop commuter aircraft.
- Evaluate new technology developed to increase safety.
- Compare costs to determine the cost effectiveness of new systems.
- Compare the impact of smart icing systems to that of existing ice protection systems as well as to systems currently in research and development.

2.4.2. Progress and Results

There are two primary components of this systems study. The first component is a review of icing and the domestic air transportation system. Aircraft icing accidents and incidents are a necessary resource in this study. To complete the overall picture, details of IPS systems, such as problems and advantages, and of the certification of said systems must be collected. The other component to the systems study is a technology trade study. The trade study will use ACSYNT, an aircraft conceptual design program, to predict costs of IPSs on aircraft. For the systems study, costs refer to costs in weight, costs in performance, and monetary costs.

2.4.2.1 A Review of Icing and the Domestic Air Transportation System

To increase ATS safety, smart icing systems must solve the past and current problems of IPSs as well as future problems. Criteria for evaluating new systems can be developed from the study of the problems and advantages of past and current IPSs. In order to do an accurate study, both existing and new concepts must be considered. Information on new technology and new concepts is being gathered from leading IPS companies, airlines, and aircraft manufacturer's as well as from *Aviation Week & Space Technology* (AW&ST) and from compilations of abstracts like the *International Aerospace Abstracts*.

Airlines and aircraft manufacturers are often approached for funding to develop an IPS concept, or to commit to a concept being proposed. Therefore, consideration must be given to why the airlines use an IPS (e.g., to meet regulations, to decrease the number of canceled flights, to increase the number of tickets sold). Their reasoning can be applied to the evaluation of the new concepts considered for this study, in order to get an idea of

the interest expected from the airlines. This information will help in the overall objective of cost effectiveness.

2.4.2.1.1 Aircraft Icing Accident/Incidents Statistics

The U.S. air transportation system has had a large impact on the trends in aircraft design and the development of aircraft components. Growing concerns with aviation safety are reflected in the statistics that over one-half of the 803 accidents involving icing between 1975 and 1988 resulted in fatalities.[19] The ATS has responded with new FAA regulations and investments in new ice protection systems.

Aircraft accidents and incidents give prime examples of the impact of icing on the ATS. An analysis of how icing effected the situation, which led to the accident/incident, is being performed. The NTSB reports also contain information on whether or not an IPS was used and if so, how it factored into the accident. The problems encountered by the aircraft in these accidents/incidents must be solved and the solutions implemented in the SIS. If no IPS was used and could have been useful, the reasoning behind the lack of use will be used in the design of the SIS or in the training on the use of the equipment.

Using the NTSB web site search engine,[20] aircraft accident and incident reports involving icing from January 1, 1983 to present (information listed through August 1998) can be found. The report summaries listed on the web site are only for the cases where the investigations are completed. Therefore, the cases available to look at are not a complete listing of all accidents/incidents involving icing during this particular time period. Pertinent information such as aircraft type, passengers aboard, injury status, and a short description of the situation can be found for each accident/incident listed. Of the 41,206 accidents and incidents listed for the time period investigated, there are a total of 1197 accidents and 24 reported incidents, which involve icing. This includes all aircraft classes. The breakdown for aircraft engine type, excluding the general aviation class (which experienced 1111 accident and 3 incidents), is shown in Fig. 11.

Table 3 Turboprop Aircraft Icing Accident/Incident Causes

Flight Crew	13
Weather	13
Airplane – manufacturer	6
Airplane/systems failure	2
Maintenance	0
Airport/ATC	0
Other	4

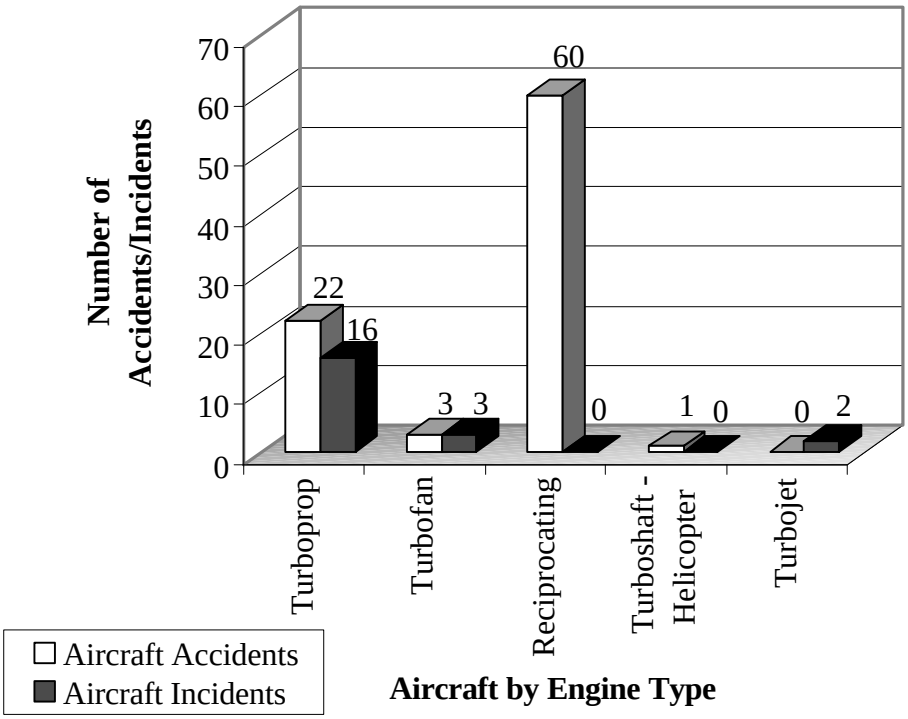


Figure 11 Aircraft Accident/Incidents Involving Icing January 1983 – August 1998

For the present study, only turboprops are taken into consideration. As Fig. 11 shows, turboprops make up 3.6% of the icing accidents/incidents analyzed, including general aviation. Of the 38 turboprop accidents/incidents analyzed, Table 3 shows their main causes. Of those accidents, ten were fatal, yielding a total of 104 deaths.

This study is continuing and recently obtained results from the ARAC committee and other sources are being analyzed to improve this analysis.

2.4.2.1.2 Ice Protection Systems and Components

There are many ice protection systems on the market today, ranging from deicing boots to electrothermal deicers. Information on IPSs has been collected from the major IPS companies in the industry. These are BFGoodrich Aerospace, Rosemount Aerospace, Incorporated, and Cox & Co. The smart icing system is most likely to work in conjunction with other IPSs. A few of the protection systems that are commonly used today are:

1. **Pneumatic Boot Deicer**
   Currently, the most-popular IPS is the pneumatic boot deicer. It has been the standard ice protection method since the 1930's.[21] With the option of either chordwise tube or spanwise tube deicing boots, one must consider that chordwise

tubes have lower drag, but chordwise tubes may present a manifolding complication. The main advantage of pneumatic boots is that they have been used successfully for many years. This provides for a large amount of experience in making repairs, maintenance checks, and replacements.

2. Hot Air Systems

Both anti-icing and deicing hot air systems are available for ice protection. As all "thermal" systems, the hot air system uses the application of heat to protect against ice.[21] Hot air systems are common IPSs, so it is well known for ease of repair and other maintenance concerns. There is reduced engine efficiency and can cause runback icing or refreezing of water on unheated areas that can result from the use of these systems.

3. Electrothermal Systems

Both anti-icing and deicing electrothermal systems are currently used. An advantage of the electrothermal system is that it does not use engine bleed air for operation. Some bleed air systems can cause a severe performance penalty for extraction of an adequate amount of bleed air. However, the electrothermal system does have a weight penalty for the extra electrical generator. Large electric-power requirements and weight penalties are some major disadvantages to this system. The advantage or disadvantage of the electrothermal system over a bleed air system due to power requirements is engine dependent. A comparison of whether the engine performance degradation outweighs the electric-power requirements should be made. Another disadvantage of the electrothermal system is runback icing. Therefore, the systems may be required to heat a larger area or run evaporative resulting in greater costs.

4. Electromechanical Impulse System

A deicing system gaining popularity is the electromechanical impulse system. This IPS cracks the ice, and separates the ice from the surface that is protected. The ice is then removed with the help of the flow over the surface. This system uses small electrical impulses, therefore very low amounts of power are required. There are no aerodynamic penalties to the system, because it is located within the wing. However, there are complex design requirements to install this system. Another advantage to the system is that no runback icing occurs. Although this system shows real promise in ice protection, it is still new and quite expensive.

Icing sensors or detectors are an integral part of many IPSs. There are many types of icing sensors on the market, including both primary and advisory. Most IPSs implement an ice detector as part of their design to help the crew detect the icing condition as quickly as possible. Ice detectors are lightweight and relatively inexpensive. Most sensors consist of a small probe, which sticks out from the surface of the aircraft. Although the sensor is small, there is danger of foreign objects striking the probe and damaging the sensor.

A study of the effects of current and proposed certification and operational regulations is very important to getting any IPS on the market. A significant part of the price of any IPS is the certification costs; hence, a thorough examination is needed. For older IPSs, this entails finding the costs of certification. For new concepts, a study of what is involved in getting certification along with the costs must be considered. The FAA Aircraft Icing Handbook and the FAR-25 regulations are sources for the existing certification and regulations. The latest advisory circulars are a source of the more current regulations. Information on new certifications is also available from the Regional Airline Association (RAA) and Aircraft Owners and Pilots Association (AOPA).

2.4.2.2 A Technology Trade Study

The principal element of the systems study, is a trade study that will evaluate and compare the smart icing system and other new IPS concepts with current systems. These evaluations are made in terms of costs and safety. To form the metrics for the trade study, a preliminary study utilizing the design tool was performed.

2.4.2.2.1 Baseline Study

The first task is to carry out a baseline study to establish a reference point for the trade studies to follow. It is also necessary to establish the forms of measurement (the metrics) that will be used for the evaluations and comparisons. The safety metrics can be based upon a calibration of statistics for current IPSs. Cost metrics refer to the usual economic costs such as IPS acquisition, installation, operation and maintenance as well as the IPS effects on aircraft performance, including fuel consumed.

The cost studies are being carried out using ACSYNT, a robust program for the conceptual design of aircraft. ACSYNT, which stands for AirCraft SYNThesis,[22] can be used for performance and economics analyses and is well suited for trade studies.

The preferred baseline aircraft for this study is a 70-passenger, turboprop commuter. This class of aircraft is believed to be a good representation of the turboprops used in today's ATS. However, there is no aircraft of that class, for which the required detail of data are available. The best data available is for a 35-passenger turboprop, the Fairchild F-27.[23] Therefore, the Fairchild F-27 was selected as the current baseline aircraft. The search for a more representative aircraft is on going and once acquired will be added to the study.

The F-27 has a gross takeoff weight of 37,500 lb and is powered by two Rolls Royce Dart 7 Mark 528 turboprop engines. Reference 23 gives the F-27's cruise performance as 1000 nmi at 32,200 ft and 227 kts. This cruise performance is not typical of aircraft and missions being considered for this study, but it was used for the preliminary studies discussed here. A more reasonable altitude of 10,000 ft to 20,000 ft and a reduced range will be used later in the study.

For the initial studies performed, a standard mission of a 1000 nmi cruise at 32,200 ft and 227 kts was chosen. The mission profile is shown in Fig. 12.

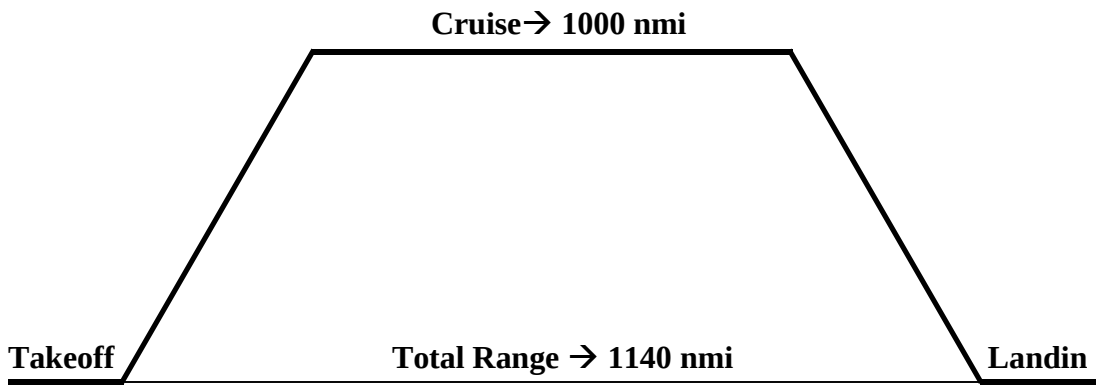


Figure 12 Mission Profile for Sensitivity Studies

For these studies, the cruise segment altitude and airspeed and the approximate gross takeoff weight were specified. ACSYNT determined everything else about the mission from takeoff to landing. Specifically, it calculates the fuel used for each mission segment as well as the total mission fuel.

The main interests for the initial study are fuel and cost sensitivities. For example, how much more fuel will be used to perform the same mission (altitude and range) at a slightly higher weight, perhaps due to adding additional equipment.

The weight sensitivity study consists of varying the gross takeoff weight of the baseline aircraft. This was done to approximate the weight of safety systems that might be added to an aircraft and to establish the associated fuel penalties of such systems. The cruise altitude was held constant at 32,200 ft. The gross takeoff weights were varied between 35,764 and 38,634 lb, the estimated gross takeoff weight range of a 35-passenger aircraft. For these tests, the geometry of the aircraft was held fixed.

Figure 13 shows the results of the weight sensitivity study. This figure shows a weight sensitivity of 19%; for every pound of equipment added, an additional 0.19 pounds of fuel must be added.

The purpose of the altitude study was to quantify the relationship between the fuel consumption and cruise altitude for fixed aircraft weight. These studies simulate a situation in which the aircraft flies the entire mission range at a different cruise altitude to avoid a weather system, such as an icing condition. The cruise altitude for the baseline aircraft was varied from 19,000 ft to 33,000 ft. The results showed an overall best fuel consumption altitude of about 24,000 ft (see Fig. 14).

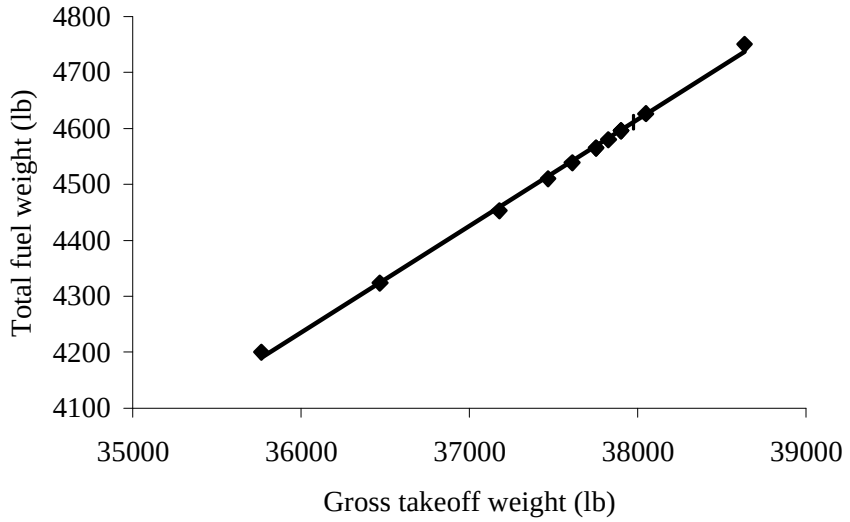


Figure 13 Total Fuel Weight versus Gross Takeoff Weight

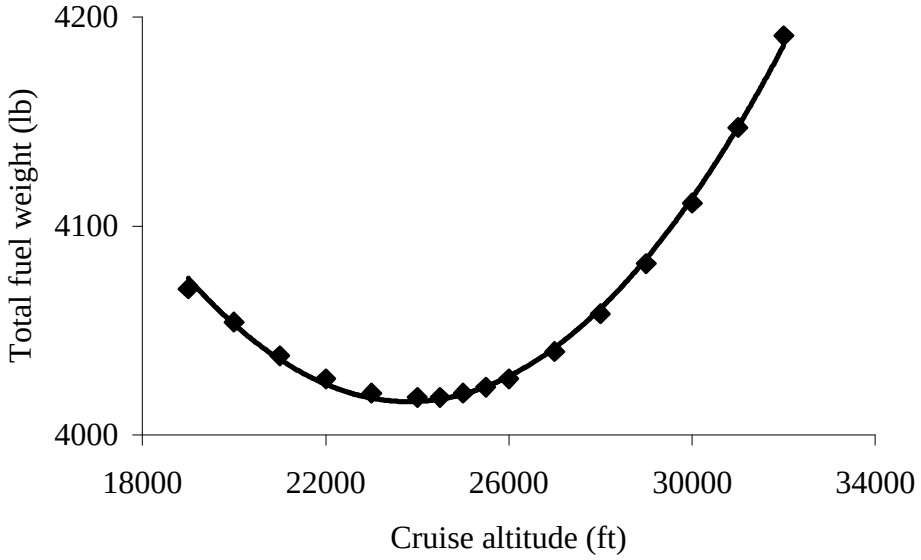


Figure 14 Total Fuel Weight versus Cruise Altitude

As mentioned previously, the cruise altitudes tested are high for the normal, regional, turboprop commuter. Additional tests will be performed for more reasonable cruise altitudes between 10,000 ft and 20,000 ft.

2.4.2.2.2 Trade Study

To obtain a statistical view of improvement, if any, over the years, past and current IPSs are compared. To perform this part of the systems study, a list of ice protection systems and devices has been developed. Table 4 shows the IPSs and sensors for which data have been found.

Table 4 Ice Protection Systems and Sensors

Ice Protection Device	Manufacturer
Primary Icing Sensor	Rosemount
Advisory Icing Sensor	Rosemount
HALO-Ultrasonic Sensor	Rosemount
Magnetostrictive Ice Detector	Rosemount
Heat of Transformation Ice Detector	Rosemount
SMART-BOOT Ice Detector	BFGoodrich
Standard Pneumatic Impulse Deicer	BFGoodrich
Silver Tube Pneumatic Deicer	BFGoodrich
Small Tube Pneumatic Deicer	BFGoodrich
Pneumatic Impulse Ice Protection	BFGoodrich
Electromechanical Impulse System	BFGoodrich
Electrothermal System	BFGoodrich
Electro-Expulsive Deicing System	Data-Products New England

The results of the comparisons are to provide validation and calibration of the analysis method for newer systems by comparing the results of the newer systems with known experience. With the results of the new concepts and the smart icing system, prediction of the effects upon the aircraft can be made, based on the previous calibration involving the past systems.

2.4.3 Future Research

As stated previously, the preferred aircraft for this study is a 70-passenger aircraft, because it would better represent the current ATS. Currently, the F-27 model is being scaled up to a 70-passenger aircraft. The scaling of the F-27 is being performed with the use of the design features of ACSYNT. Bombardier has been consulted about obtaining information on their de Havilland Dash 8Q-300 (50-passenger) and 8Q–400 (70-passenger) turboprop regional aircraft. The small amount of data received for the 8Q-400 is being used to guide the F-27 scale-up process. The baseline aircraft model, the F-27, will continue to be used throughout the rest of the study including the technology trade study. Any aircraft models added to the study later will be put through the same test runs as the F-27 for comparison purposes. If other aircraft models are added, the study will contain a broader sense of icing effects on the ATS.

Another challenge within this study has been to obtain system costs needed for analysis purposes. The information obtained from the manufacturers and several AIAA papers on IPSs do not contain cost information. Therefore, there is a continuing effort to find costs of acquiring the IPSs as well as operational costs. Once the previous statistical and calibration tests are completed, all systems are to be compared. The comparisons are to include aerodynamic data, weights, and overall monetary costs of the aircraft. The safety aspects found from different articles or the accident/incident reports will also be incorporated into this part of the study.

2.5 Icing Encounter Flight Simulation

Although NASA funding for the icing-encounter flight simulator has not begun, considerable development work has already been performed under other funding sources. Briefly, through past funding from the USA-CERL (Champaign, IL) and current funding from the Navy (San Diego), work to date has focused on developing a training simulator for pilots flying the 450-lb Pioneer unmanned aerial vehicle (UAV), which is primarily used for reconnaissance missions flown off Navy vessels.

2.5.1 Background

As shown in Fig 15, the Pioneer is sometimes recovered in a net onboard the deck of the ship - a maneuver that must be performed by a skilled and confident pilot.

Fig. 15 - Shipboard landing of the Pioneer into the capture net while being flown remotely by a pilot on ship deck (actual photo).

Initiation of the simulator development was motivated by the desire to train pilots using a low-risk simulator approach rather than actual aircraft aboard the ship. Figure 16 shows a view of the Pioneer from the simulator.

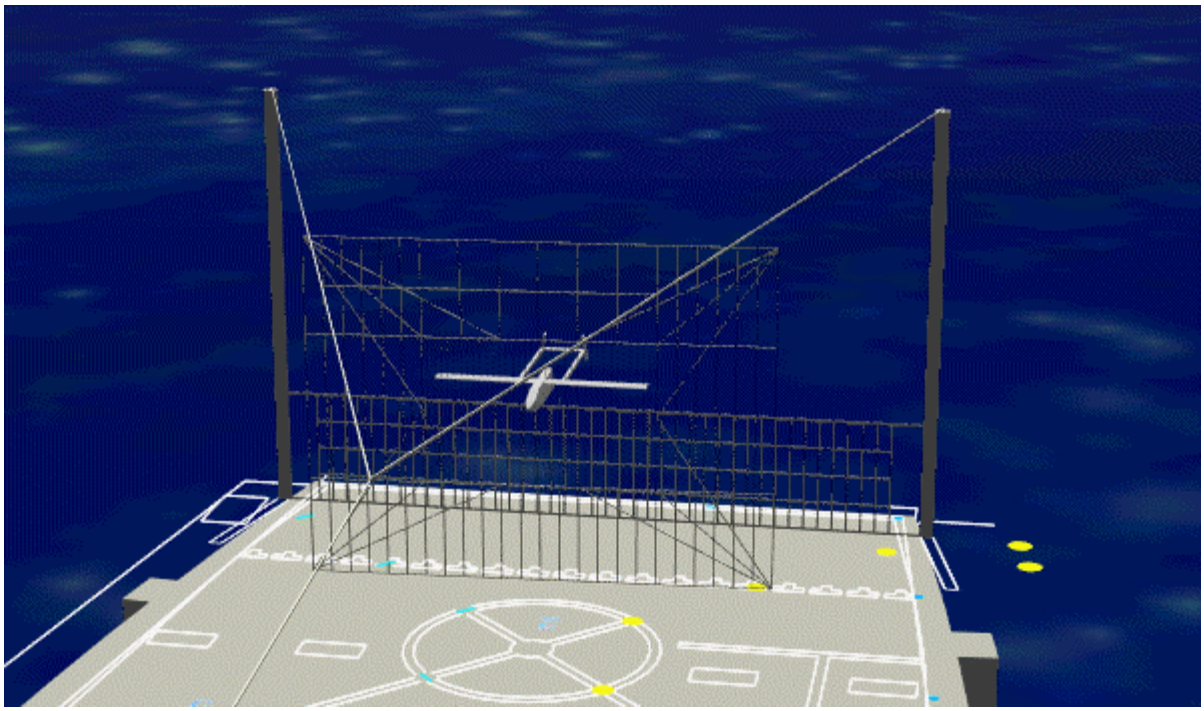


Fig. 16 - Simulator view of the shipboard landing (SGI Indigo2 rendering).

Recent UIUC efforts have focused on developing a PC-based version of the simulator for greater ease of model development in a collaborative environment. Also, separate programs - a map birds-eye-views and a telemetry program - were written to initiate the development of an interactive distributed simulation environment. These programs interact and display data from the simulator using computers over the network. Also, in support of Navy needs a turbulence model and a ground-handling model were integrated into the simulator.

Regarding the PC-based simulator, two views are currently implemented. The 3D view shown in Fig. 17 is used for the external pilot simulations (Navy effort), and the instrument view, Fig. 18, is a prototype for use in the human-factors research. With the current Pioneer aircraft model, some of the instrument displays are not currently active (e.g., the "IMS" display and "cabin pressure").

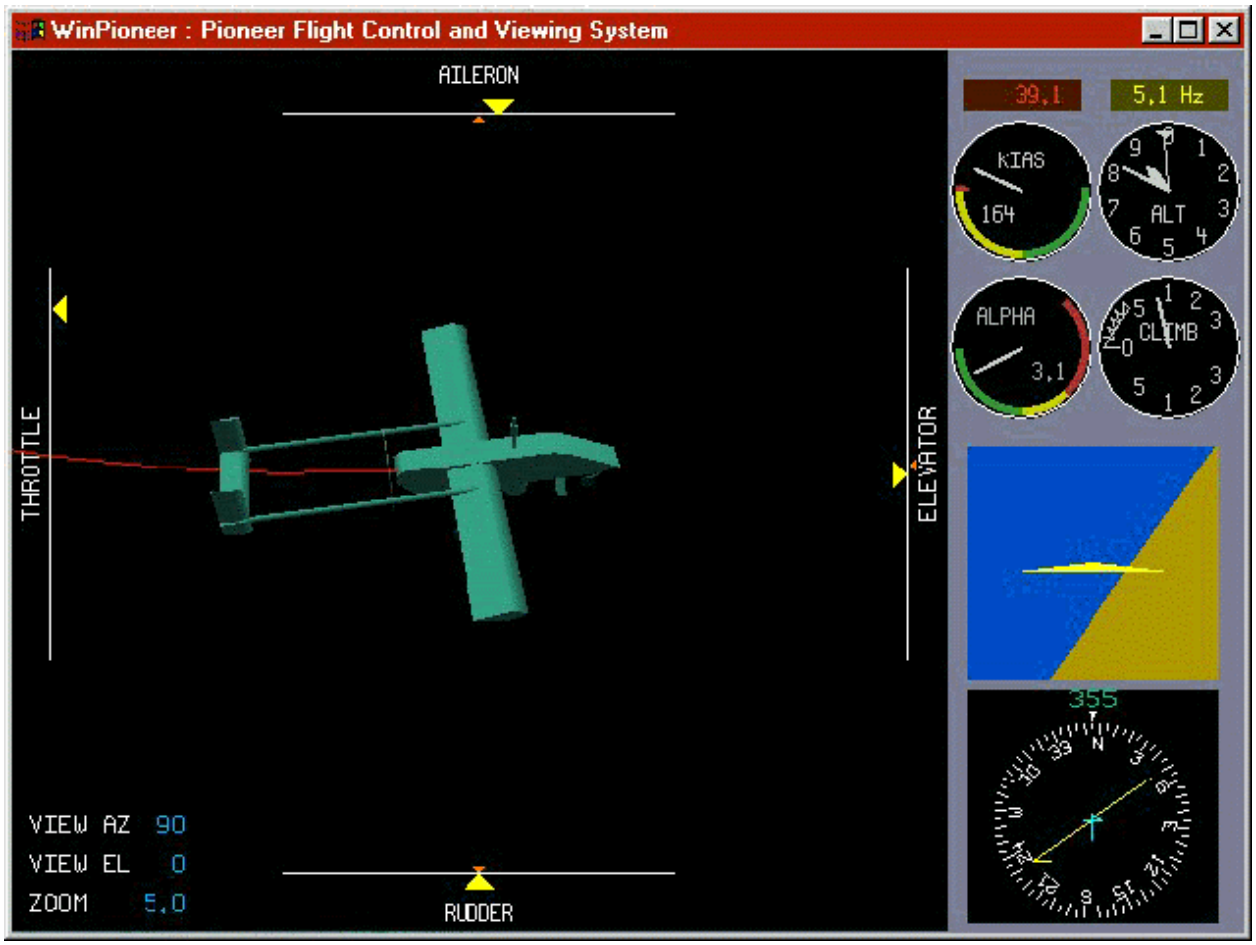


Fig. 17 - 3D view of the PC-based simulator for use in Navy external pilot training.

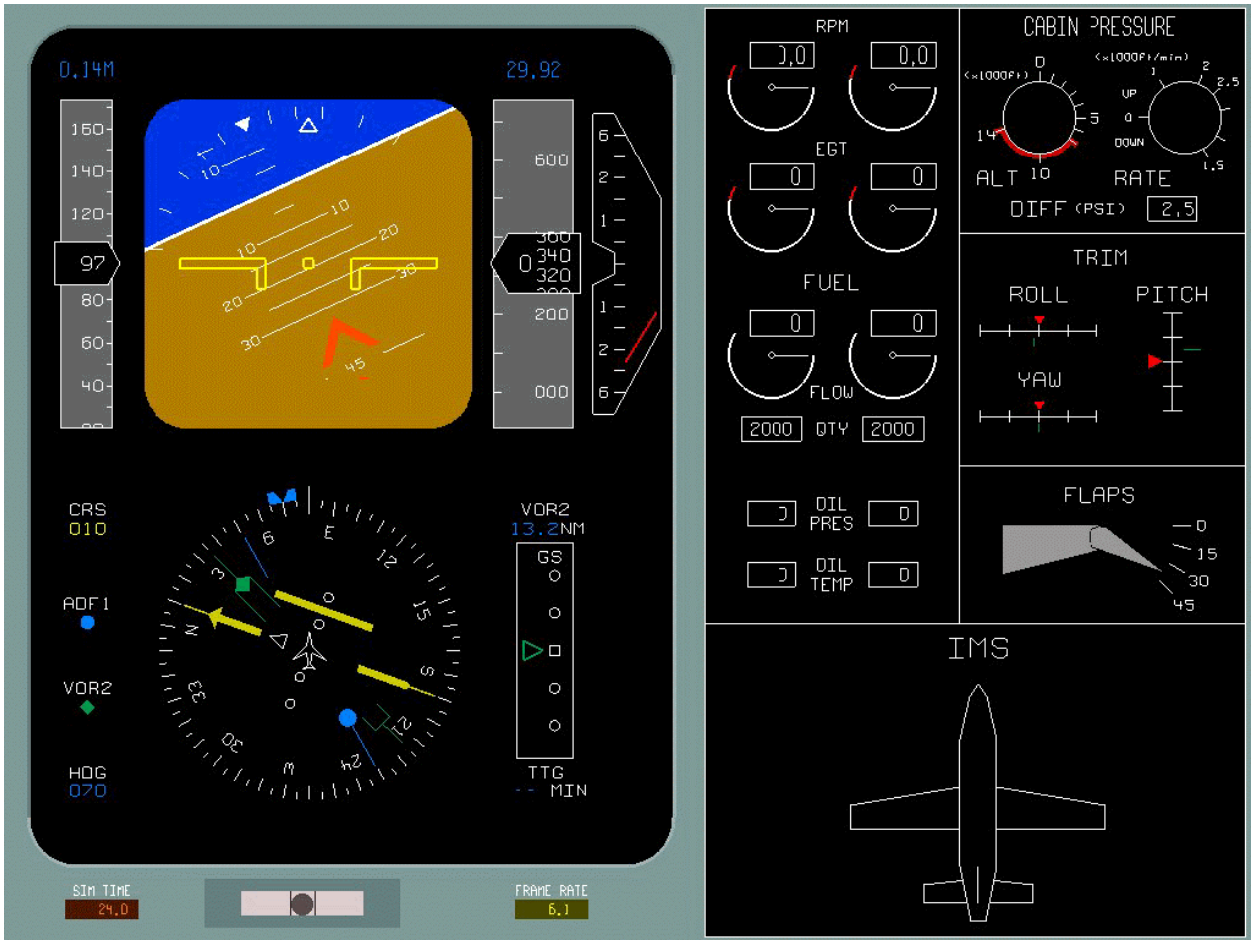


Fig. 18 Instrument view of the PC-based simulator for initial human-factors research.

2.5.2 Future Research

Finally, under NASA funding, the simulator activities in the first year of the 4-year extension will focus on the following five topics:

1. Integrate the aerodynamics model of the target baseline aircraft into the simulator (to replace the Pioneer)
2. Implement icing models into simulator for the target aircraft
3. Re-write the core flight vehicle model part of the C/C++ code so that it can be more easily adapted for use by the other groups (Controls and Human Factors)
4. Modify the flight-deck display (IMS display and instruments) in coordination with Human Factors research area
5. Begin to incorporate a flight control system into the simulator flight vehicle

3.0 Summary

The research conducted in the first year of NASA grant on Smart Icing Systems (SIS) has been presented in this report. More complete information can be found from the SIS web site at http://www2.aae.uiuc.edu/sis/. Summarized below are some of the major accomplishments and challenges.

One of the primary objectives of the first year was to determine the ability of the proposed methods to characterize the icing effects on the aircraft. Using the NASA Twin Otter as a model, batch least squares and H^{∞} system ID methods have been explored with good success. Combining these with a neural network method as a "ice detection classifier" has resulted in good detection performance. Within 5 seconds of starting the detection the method has converged with only small elevator input. Quasi-steady-state methods are being developed that compare the iced steady state values to known clean values. This method has promise for the situation where the more powerful system ID methods do not have enough dynamic content to function properly. One of the significant challenges is to develop an accurate and robust iced aircraft dynamic model to be used to test and validate the characterization methods. An iced aircraft model for the linearized dynamic case has been proposed and work is progressing to develop this model. The limited amount of Twin Otter iced aircraft data forces us to rely on 2-D data to help formulate this method. This area will continue to be challenging throughout the development of SIS.

Human factors researchers are well underway toward the goal of designing a human-centered display for the wealth of information that will become available to the pilot in an SIS-equipped aircraft. Initial results from a survey of pilot's information requirements in icing have been quite informative and point out many instances where pilots are not knowledgeable concerning icing. This survey has served to refine a larger effort that will gather data from a large number of commuter pilots.

The Safety and Economic Trade Study has spent much of this year gathering data and building and refining their analysis tools. It has been challenging to find accurate, baseline aircraft data, cost data, etc. However, most of these challenges have been overcome and safety and cost analysis data should be available soon.

Two areas are discussed in the report that have not yet received NASA SIS funding. Computational methods are being developed under a FAA grant and with other funding to analyze airfoils with ice accretions. To date results compare well to experiment except near maximum lift. An unsteady method is being developed to improve the code performance in this area. These methods will be applied starting in about a year to help augment the available experimental data to build better iced aircraft models. The second area is the Icing Encounter Flight Simulation research. A flight simulator is already operational at UIUC based on research funded by DOE. Good results have been obtained with this simulation tool on the UAV project. In the coming year this simulation will be updated to include the turboprop aircraft model and other improvements.

4.0 References

4.0 References

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