Flight Test Research

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Sam Lee

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Edward Whalen
SMART ICING SYSTEMS
Research Organization

Core Technologies

- Aerodynamics and Propulsion
- Flight Mechanics
- Controls and Sensor Integration
- Human Factors
- Aircraft Icing Technology

IMS Functions

- Characterize Icing Effects
- Operate and Monitor IPS
- Envelope Protection
- Adaptive Control

Systems Integration

- Flight Simulation
- Flight Test
Flight Test

Goal:  Improve the safety of aircraft in icing conditions.

Objective:  
1) Acquire and analyze flight data to assist in the development of icing characterization
2) Evaluate characterization methods in flight.

Approach:  In cooperation with NASA acquire detailed flight dynamics data on the Twin Otter with and without ice. Use data to develop and test ID and characterization methods including the effects of dynamic input, sensor noise, repeatability, uncertainty, IPS detection, etc.
Smart Icing System Research

Smart Icing Systems Review, June 19-20, 2001

FLIGHT TEST GROUP

Aerodynamics And propulsion

Flight Mechanics

Controls and Sensors

Human factors

Characterization Of Ice Effects

Data Analysis

Flight Test Evaluation

Flight Simulation

Plan

Acquire Data

Sam Lee
Andy Broeren
James Melody
Ed Whalen

FLIGHT TEST GROUP
Outline

• SIS flight test Introduction
• Flight test data acquisition and reduction
• ID of flight test data
• Conclusions and Future Plans
SIS Flight Test Introduction

Michael Bragg
Sam Lee

University of Illinois
Outline

- Introduction
- Flight test matrix
- Data analysis plan
- Conclusion
Flight Test Overview

**First Phase – March 2001**
- Develop test plan and procedures
- Obtain initial clean and iced aircraft flight data for use in identification and characterization development

**Final Phase – Early 2002**
- Obtain more comprehensive clean and iced aircraft flight data
- Preliminary test of SIS system
Flight Test Philosophy

- Obtain clean data for baseline and to test ID methods
- Use doublets to ensure best chance of ID
- No-doublet data to provide most challenging ID cases
- Determine ability to identify onset and parameter changes
- No attempt made to identify throughout the entire aircraft envelope
# Flight Test Matrix

<table>
<thead>
<tr>
<th>Case</th>
<th>Flight Cond.</th>
<th>Doublet Mag.</th>
<th>Test Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Clear Air</td>
<td>0.25g</td>
<td>Baseline</td>
</tr>
<tr>
<td>1.2</td>
<td>Clear Air</td>
<td>0.10 to 0.50</td>
<td>Vary doublet magnitude</td>
</tr>
<tr>
<td>1.3</td>
<td>Clear Air</td>
<td>None</td>
<td>Standard maneuvers</td>
</tr>
<tr>
<td>1.4</td>
<td>Clear Air</td>
<td>None</td>
<td>Clear air turbulence</td>
</tr>
<tr>
<td>2.1</td>
<td>Icing</td>
<td>0.25g</td>
<td>Doublets during ice accretion</td>
</tr>
<tr>
<td>2.2</td>
<td>Icing</td>
<td>0.25g</td>
<td>Doublets with selective deicing</td>
</tr>
<tr>
<td>2.3</td>
<td>Icing</td>
<td>0.25g</td>
<td>Doublets with intercycle icing</td>
</tr>
<tr>
<td>2.4</td>
<td>Icing</td>
<td>None</td>
<td>Intercycle icing</td>
</tr>
<tr>
<td>2.5</td>
<td>Icing</td>
<td>None</td>
<td>Standard maneuvers</td>
</tr>
</tbody>
</table>
Clean Case 1.1

- **Objective:** Establish clean baseline and determine if effect of velocity and $\delta_f$ can be characterized.

- **Approach:** Obtain baseline data for steady flight at fixed VIAS and angle of attack.
  - 0.25g doublets
  - $V = 85, 110, 130$ KIAS
  - $C_t = 0.041, 0.05, 0.063$
  - $\delta_f = 0$ and $10$ deg
Clean Case 1.2

- **Objective:** Determine effect of doublet amplitude can be characterized
- **Approach:** Vary doublet amplitude at fixed conditions.
  - 0.10, 0.25, 0.50g doublets
  - $V = 130$ KIAS
  - $C_t = 0.063$
Clean Case 1.3

- **Objective:** Determine if standard maneuvers provide enough input for characterization.
- **Approach:** Transition from cruise to climbs, descents, standard turns.
  - $V = 85 \text{ and } 130 \text{ KIAS}$
  - $C_t = 0.041, 0.050, 0.063$
  - $\delta_f = 0 \text{ and } 10 \text{ deg}$
Clean Case 1.4

- **Objective:** Determine if effect of turbulence (noise and dynamic input) on characterization.
- **Approach:** Level flight with turbulence at fixed velocity and angle of attack.
  - $V = 110, 130$ KIAS
  - $C_t = 0.050$ and $0.063$
Iced Case 2.1

- **Objective:** Baseline iced characterization data. Determine how characterization changes with increasing ice accretion time.

- **Approach:** Perform doublets every 3 to 5 minutes during ice accretion without de-icing.
  
  \[ C_t = 0.063 \]
Iced Case 2.2

- **Objective:** Determine if characterization can be accomplished without doublets during accretion. Evaluate changes with selective deicing.

- **Approach:** Accrete ice without doublets and selectively deice aircraft with doublets.
  - Wing, horizontal tail, and Vertical tail and struts
  - Perform doublet after each component is deiced
  - $C_t = 0.063$
Iced Case 2.3

- **Objective:** Determine if effect of de-icing cycles can be characterized.
- **Approach:** De-ice aircraft at regular intervals and perform doublets before and after each de-icing cycle.
  - $C_t = 0.063$
Objective: Determine if aircraft icing and de-icing could be identified without doublets.

Approach: De-ice aircraft in icing at regular intervals.
- No doublets
- $C_t = 0.063$
Iced Case 2.5

- **Objective:** Determine if iced aircraft could be identified from standard maneuvers.
- **Approach:** Accrete ice without de-icing. Initiate climbs, descents, and standard turns from cruise in icing.
## Summary of Flights

<table>
<thead>
<tr>
<th>Flight No.</th>
<th>Date</th>
<th>Condition</th>
<th>Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2/23/01</td>
<td>Light Rime</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>2/23/01</td>
<td>Clear Air</td>
<td>1.1</td>
</tr>
<tr>
<td>3</td>
<td>2/26/01</td>
<td>Mod. Rime</td>
<td>2.2, 2.3</td>
</tr>
<tr>
<td>4</td>
<td>2/27/01</td>
<td>Clear Air</td>
<td>1.1</td>
</tr>
<tr>
<td>5</td>
<td>2/28/01</td>
<td>Clear Air</td>
<td>1.1, 1.2, 1.3, 1.4</td>
</tr>
<tr>
<td>6</td>
<td>3/2/01</td>
<td>Mod. Glaze</td>
<td>2.1 (2), 2.2</td>
</tr>
<tr>
<td>7</td>
<td>3/2/01</td>
<td>Mod. Glaze</td>
<td>2.2, 2.3</td>
</tr>
<tr>
<td>8</td>
<td>3/7/01</td>
<td>Heavy Rime</td>
<td>2.4 (2), 2.5</td>
</tr>
<tr>
<td>9</td>
<td>3/9/01</td>
<td>Clear Air</td>
<td>1.3, 1.4</td>
</tr>
</tbody>
</table>
Data Analysis Plan

- Obtain the flight data
- Use Matlab ID toolbox (SIDPAC) for identification of ALL S & C derivatives from clean aircraft data.
  - SIDPAC performance will be compared with that of H-infinity ID for icing characterization.
- Subsystem analysis
  - Analyze performance of parameter ID
  - Analyze performance of trim characterization
  - Analyze performance of hinge-moment characterization
Data Analysis Plan (cont’d)

- Neural network information content analysis
  - ID
  - Trim characterization
  - Hinge-moment measurements
- Simulation of full IMS Neural Network
  - Neural networks trained on FDC data applied to flight test data
  - Neural networks trained on subset of flight test data applied to all flight test data
- Integration of flight test data with the flight simulator code
Future Work

• More extensive characterization analysis of flight test data
  – More clear air and iced case
  – Determine when ice accretion could be sensed
  – Determine if IPS activation could be sensed
• Use other characterization methods
  – Change in aircraft trim
• Solve problems encountered with Phase I test
• Phase II flight tests
  – More icing cases
  – Preliminary test of SIS system
Conclusion

- **Sam Lee** to talk on flight test data and initial SIDPAC analysis
- **Jim Melody** to talk on plans for H-Infinity ID of flight test data
- Flight test data analysis has just begun
SIS Flight Test Data and Characterization

Sam Lee

University of Illinois
Outline

- Icing research aircraft
- Flight test data
- System identification and characterization
- Conclusion
- Future plans
NASA Icing Research Aircraft

- Modified DeHavilland DHC-6 Twin Otter
- Instrumentation:
  - Measure icing meteorological conditions
  - Document ice accretion
  - Measure aircraft aerodynamics and control
Twin Otter Data Acquisition System

- Meteorological instrumentation
  - Particle sizing, cloud water content
  - Temperature, dew point
- Ice accretion documentation
  - Wing stereo camera (70 mm)
  - Digital video camera
  - Handheld 35 mm camera
Twin Otter Data Acquisition System (cont’d)

- Aircraft aerodynamics and control measurement
  - Engine performance measurement
  - Air data instruments
    - Pressure probe on nose boom
  - Inertial sensors
    - Accelerometers
    - Gyros
- Data acquired using SEA Lite 18 data acquisition system
  - 50 channels
  - 16 bit, 100 Hz
Sample Flight Data

- Sample data created using an elevator, aileron, and rudder doublet
- Clear air flight
  - VIAS = 130 kts
  - 0.25g
  - $C_T = 0.063$
- Represents 8 of over sixty parameters measured and calculated
Clear Air Flight Data

Elevator

Angle of Attack

$\delta_e$ (deg)

$\alpha$ (deg)

Time (sec)

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Clear Air Flight Data

Aileron

Bank Angle

\[ \delta_a \text{ (deg)} \]

\[ \phi \text{ (deg)} \]

Elevator Doublet

Rudder Doublet

Aileron Doublet

Elevator Doublet

Rudder Doublet

Time (sec)

Time (sec)
Clear Air Flight Data

Rudder

Sideslip Angle

δ_r (deg)

β (deg)

Elevator Doublet

Aileron Doublet

Rudder Doublet

Elevator Doublet

Aileron Doublet

Time (sec)

Time (sec)
Clear Air Flight Data

Lift

Drag

Elevator Doublet
Rudder Doublet
Aileron Doublet

Time (sec)

Elevator Doublet
Rudder Doublet
Aileron Doublet

Time (sec)
System Identification and Characterization

- Initial attempt at identification done using existing software
- System Identification Program for Aircraft (SIDPAC)
  - Developed by Dr. Gene Morelli – NASA Langley
  - Flight data used to generate linear stability and control derivatives utilizing least squares regression method
  - Matlab based with graphical user interface (GUI)
Stability and Control Derivatives

- Standard linearized model
  - Perturbation off of trim state
  - Subscript 1 denotes trim state

\[ C_x = C_{x,1} + C_{x,a}(a - a_1) + C_{x,b}(b - b_1) + C_{x,c}(c - c_1) + \ldots \]
Preliminary Identification Results

- Data from consecutive doublets
- Clear air (case 1.1)
  - $\text{VIAS} = 130$ kts.
  - $C_T = 0.063$
- Icing flight (case 2.2 before de-icing)
  - Moderate rime ice
  - $\text{VIAS} = 117$ kts.
  - $C_T = 0.063$
## Longitudinal Results

<table>
<thead>
<tr>
<th>S&amp;C Deriv</th>
<th>Clean Doublets</th>
<th>Iced Doublets</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>$C_{L,\alpha}$</td>
<td>0.1057</td>
<td>0.1055</td>
</tr>
<tr>
<td>$C_{L,q}$</td>
<td>0.005</td>
<td>0.0051</td>
</tr>
<tr>
<td>$C_{L,\delta e}$</td>
<td>0.0101</td>
<td>0.0104</td>
</tr>
<tr>
<td>$C_{L,1}$</td>
<td>0.4407</td>
<td>0.442</td>
</tr>
<tr>
<td>$C_{m,\alpha}$</td>
<td>-0.0297</td>
<td>-0.0304</td>
</tr>
<tr>
<td>$C_{m,q}$</td>
<td>-43.0539</td>
<td>-43.561</td>
</tr>
<tr>
<td>$C_{m,\delta e}$</td>
<td>-0.0357</td>
<td>-0.0364</td>
</tr>
<tr>
<td>$C_{m,1}$</td>
<td>0.0009</td>
<td>0.0023</td>
</tr>
</tbody>
</table>
Summary of Longitudinal Results

<table>
<thead>
<tr>
<th>S&amp;C Deriv</th>
<th>Uncertainty *</th>
<th>Change Due to Ice</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{L,\alpha}$</td>
<td>2%</td>
<td>8%</td>
</tr>
<tr>
<td>$C_{L,q}$</td>
<td>2%</td>
<td>16%</td>
</tr>
<tr>
<td>$C_{L,\delta e}$</td>
<td>7%</td>
<td>14%</td>
</tr>
<tr>
<td>$C_{m,\alpha}$</td>
<td>2%</td>
<td>8%</td>
</tr>
<tr>
<td>$C_{m,q}$</td>
<td>4%</td>
<td>10%</td>
</tr>
<tr>
<td>$C_{m,\delta e}$</td>
<td>3%</td>
<td>7%</td>
</tr>
</tbody>
</table>

* Normalized differences between doublet 1 and 2.
Conclusion

• Repeatable stability and control derivatives obtained from flight test data
• Found significant differences in longitudinal values between clean and iced aircraft when doublets used for identification
$H_\infty$ Parameter ID Algorithm

Applied to Flight Test Data

James Melody
Parameter ID Block Diagram

Pilot

Flight Dynamics
(depend on $\chi$)

$\chi$ parameter

$\hat{\chi}$ parameter estimates

disturbance

measurement noise

$\hat{\chi}$

ID Algorithm

output
Parameter ID Review

\[ \chi := \left( C_{X_0}, C_{L_{\beta}}, C_{L_p}, C_{L_{\delta R}}, C_{M_\alpha}, C_{M_p}, C_{M_{\delta R}}, C_{N_\beta}, C_{N_p}, C_{N_{\delta R}} \right) \] are parameters to identify in the parameter ID form

\[
\begin{align*}
\dot{x} &= A(x, u)\chi + b(x, u) + d_p \\
y &= x + d_m
\end{align*}
\]

where \[ x = (V, \alpha, \beta, p, q, r, \phi, \theta, \psi) \] state

\[ u = (\delta_E, \delta_R, \delta_A, T) \] input

\[ y \] measured output

\[ d_p \] state disturbance (a.k.a., process noise)

\[ d_m \] measurement noise

- \( H^\infty \) algorithm in continuous-time form provides estimate \( \hat{\chi} \) according to

\[
\begin{bmatrix} \dot{x} \\ \dot{\hat{\chi}} \end{bmatrix} = \begin{bmatrix} 0 & A \\ 0 & H \end{bmatrix} \begin{bmatrix} \hat{x} \\ \hat{\chi} \end{bmatrix} + \begin{bmatrix} b \\ 0 \end{bmatrix} + \Sigma^{-1} \begin{bmatrix} I \\ 0 \end{bmatrix} (y - \hat{x}),
\]

\[
\dot{\Sigma} = -\Sigma \begin{bmatrix} 0 & A \\ 0 & H \end{bmatrix} - \begin{bmatrix} 0 & 0 \\ A^T & H^T \end{bmatrix} \Sigma + \begin{bmatrix} I & 0 \\ 0 & -\gamma^{-2}Q \end{bmatrix} - \Sigma \begin{bmatrix} I & 0 \\ 0 & KK^T \end{bmatrix} \Sigma,
\]

with \( \Sigma(t) \in \mathbb{R}^{(n+r) \times (n+r)} \) and \( \Sigma(0) = \text{diag}(P_0, Q_0) \).

- Algorithm is discretized with \( 4^{th}-\text{order Runge Kutta method} \) for consistency with digital measurement information, and ultimately for digital implementation.
Modifications to ID Algorithm for Flight Tests

- 100 Hz sample rate in flight tests rather than 30 Hz sample rate in simulation

- Use total thrust measurement rather than engine power as input

- Use air density measurement directly, rather than calculating density from altitude as in FDC

- Use "calibrated" measurements, i.e., measurements corrected by Sam.

- Possibly include more S/C derivatives in parameter $\chi$, since even clean values are not necessarily well-known.
Regression-based identification in SIDPAC is a data smoothing operation, i.e., is used for post-processing of batches of data.

- uses a large set of measurements, many derived from raw measurements by Tom Ratvasky after flight tests
- not automated: requires interaction with operator, relying on operator’s expert judgment
- requires pilot test input for excitation
- not heavily model-dependent?
- not appropriate for real-time, in-flight identification

Our $H^\infty$ parameter identification is a recursive, online method

- uses a more limited set of measurements: 9 output + 4 input + $\rho$
- in general, can provide useful estimates even under excitation due to turbulence only
- gray-box identification: uses as much a priori knowledge of system as possible, separates uncertainty into unknown parameter $\Rightarrow$ model-dependent
- completely automated $\Rightarrow$ provides in-flight identification

Real-time identification is more difficult since it has less available information
Plan

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- Apply algorithm based on FDC model, but tuned on flight test data: $\gamma$, $Q_o$, constituents of $\chi$

- Apply algorithm based on model updated with flight test results: SIDPAC, mass/inertia information, sensor calibration, sensor accuracy. Compare with simulation results using updated model.

- Update model structure based on flight test results: longitudinal/lateral coupling, nonlinear aero coefficients, et cet.

- Apply full IMS designed on FDC data to flight test data

- Design and train full IMS on portion of flight test data, and apply to other flight test runs

- Investigate flight test data utility using NNet analysis as in FDC

- Incorporate algorithms into second phase of flight tests as real-time IMS
• Can SIDPAC ID results be considered as true model? More in depth statistical analysis of SIDPAC results is required. What about biases, systematic errors?

• Typical variations in S/C derivatives are 10% to 15%, not very substantial in the unpristine environment of flight tests.

• In FDC simulations, $H^\infty$ ID has been found to be fairly sensitive to model errors, given relatively small variations due to icing.

• Present $\eta$ “true value” may not suffice as a measure of icing degradation for training of NNet on flight test data.

• Need to understand effects of unmodeled dynamics in light of ID: nonlinearity, lat/long coupling, asymmetry, sensor offset, misalignment, distortion

• Need to collaborate closely with flight testing experts
Flight Test Waterfall Chart

Federal Fiscal Year

Planning

Flight Test

Data Analysis

Flight Test
Conclusions

- Flight test data of high quality
- Derivatives repeatable
- Significant effect of ice on derivatives
- H-infinity methods need to be adapted to flight data
Future Research

- Reduce flight data using both ID methods
- Study the effect of turbulence, sensor noise, IPS operation, icing onset detection, with and without doublet, etc.
- Apply old and new neural nets to flight data
- Prepare for second phase of flight testing