Prediction of Icing Effects on the Stability and Control of Light Airplanes

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Outline

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Problem and Significance

• Inclement weather
  ▶ Average of 19.6% of environment related reported general aviation (GA) accidents from 1998 to 2000

• Icing conditions
  ▶ 2.9% in 1997
  ▶ 2.4% in 1998
  ▶ 3.6% in 1999
  ▶ 2.7% in 2000
  ▶ 44.55% of these resulted in fatalities
Type of Ice Accretions

• Rime, glaze, and mixed ice
• Dependent on:
  ➤ Aircraft
  ➤ Airspeed
  ➤ Exposure time
  ➤ Atmospheric air temperature
  ➤ Liquid water content
  ➤ Median volumetric diameter
Separation Bubble

Schematic of Upper Surface Separation Bubble
Aft of Leading-Edge Ice Accretion
Basic Effects of Ice Accretion on Aircraft

- Possible separation bubble aft of ice ridge
- $\downarrow C_L$
- $\uparrow C_D$
- $\downarrow C_{L\alpha}$
- $\downarrow C_{m\alpha}$
- Possible hingemoment reversal
- Reduced longitudinal stability
- Reduced elevator effectiveness
Considerations

• Prediction and Analysis
  ➢ Wind tunnel testing with icing
  ➢ Flight testing with icing
  ➢ Sophisticated numerical analysis codes

• Limitations
  ➢ All of these techniques are costly
  ➢ Require full scale vehicles or wind tunnel models
  ➢ Require detailed data
Previous Research

• Bragg et. al, (1996-2004)
  ▶ Wing and airfoil
  ▶ Wind tunnel data
  ▶ Flight data
  ▶ Parametric models
  ▶ CFD code

• Broeren et.al, (2003, 2004)
  ▶ Inter-cycle ice accretions

• Lee et.al, (1999, 2000)
  ▶ Simulated ice on airfoils

\[ C_{(A)_{iced}} = (1 + \eta_{ice} k'_{C_A}) C_{(A)} \]
Objectives of This Work

• Develop a tool for studying and predicting icing effects on:
  ▶ stability & control
  ▶ performance
• Use only relatively simple data
• Inexpensive
• Leverage existing data/results as much as possible
• Extensible to similar configurations
• Accurate within limitations of data and results used
Scope

• Complete configuration
• DATCOM methods
• Propulsion model
  ▶ Altitude and power effects
  ▶ Installation effects
  ▶ Prop thrust, jet thrust, propeller thrust
  ▶ Table lookup
• Linear time invariant (LTI) state-space model
• Simulated in MatLab 7.0
• Longitudinal dynamics only
• Climb Performance only
Aircraft Model

\[
\dot{u} = -g \cos \Theta_1 \theta + (X_{T_u} + X_u)u + X_{\alpha} \alpha + X_q q + X_{\delta_e} \delta_e + X_{\delta_T} \delta_T + X_{\alpha} \dot{\alpha}
\]

\[
\dot{\alpha} = \frac{\dot{w}}{U_1} = (-g \sin \Theta_1 \theta + Z_u u + Z_{\alpha} \alpha + Z_q q + U_1 q + Z_{\delta_e} \delta_e + Z_{\delta_T} \delta_T + Z_{\alpha} \dot{\alpha}) / U_1
\]

\[
\dot{q} = (M_{T_u} + M_u)u + (M_{T_{\alpha}} + M_{\alpha})\alpha + M_q q + M_{\delta_e} \delta_e + M_{\delta_T} \delta_T + M_{\alpha} \dot{\alpha}
\]

\[
\dot{\theta} = q
\]

- Steady, level, 1-g trimmed flight in the stability axis
- \( P_1 = Q_1 = R_1 = V_1 = W_1 = \Phi_1 = 0 \)
- \( \Theta_1 = \text{constant} \)
System Modeling Method

- State-space representation
  - Linear time invariant system (LTI)
    - \( \dot{X} = AX + BU \)
    - \( Y = CX + DU \)
  - \( X = [u \quad \alpha \quad q \quad \theta]^T \)
  - \( U = \begin{bmatrix} \delta_e \\ \delta_T \end{bmatrix} \)
  - Discrete model
    - \( X(k+1) = \Phi X(k) + \Gamma U(k) \)
    - \( Y(k) = CX(k) + DU(k) \)

\[ \Phi = e^{Ah} \]
\[ \Gamma = \left( \int_0^h e^{A\tau} d\tau \right) B \]
Validation

- Check governing physics using a level acceleration maneuver
- Use available data for a Cessna 208B Super Cargomaster
- Check stability and controllability
- Simulation of discrete model
Validation Analysis

Modal Composition

\[ \lambda_{1,2} = -1.49 \pm 2.54 j \]
\[ \omega_{sp} = 2.94 \text{ rad/sec} \]
\[ \zeta_{sp} = 0.51 \]

\[ \lambda_{3,4} = -0.013 \pm 0.19 j \]
\[ \omega_{p} = 0.2 \text{ rad/sec} \]
\[ \zeta_{p} = 0.065 \]

Controllability

\[ C = \begin{bmatrix} B & AB & AAB & AAAB \end{bmatrix} \]

rank \((C) = 4 \); controllable

Modal Coordinates

\[ X = M\xi \]
\[ \dot{\xi} = M^{-1}AM\xi + M^{-1}BU \]
\[ Y = CM\xi + DU \]

Short period
primarily angle-of-attack, some pitch rate

Phugoid
pitch attitude angle, some angle-of-attack and pitch rate
Level Acceleration Time Histories

- Airspeed (ft/s)
- Angle of Attack (deg)
- Pitch rate (deg/s)
- Pitch attitude (deg)
- Airplane Lift Coefficient
- Airplane Drag Coefficient
- Elevator Position (deg)
- Altitude (ft)
Verification

• Ensure particular aircraft is correctly modeled
• Compare simulation to flight test data
• Simulation maneuver dictated by flight test data maneuver ensemble
  ➢ Elevator doublet

Cessna 208B Super Cargomaster
Elevator Doublet Verification Maneuver Responses

1. Airspeed (ft/s)
2. Angle of Attack (deg)
3. Pitch Rate (deg/s)
4. Pitch Attitude (deg)
5. Airplane Lift Coefficient
6. Airplane Drag Coefficient
7. Elevator Position (deg)
8. Altitude (ft)

Flight Test Data
Simulation
Numerical Examples

- Climb maneuvers: 15000ft to 17000ft
- 30 test cases run with various icing levels
  - Clean and iced cases compared
- 3 cases shown:
  - Aircraft 20% iced
  - Aircraft Fully Iced
  - Asymmetric Icing
    - wing 70% iced
    - horizontal tail 40% iced
# Icing Factors Applied

<table>
<thead>
<tr>
<th></th>
<th>$\Delta C_{z0}$</th>
<th>$\Delta C_{z\alpha}$</th>
<th>$\Delta C_{zq}$</th>
<th>$\Delta C_{z\delta e}$</th>
<th>$\Delta C_{m0}$</th>
<th>$\Delta C_{m\alpha}$</th>
<th>$\Delta C_{mq}$</th>
<th>$\Delta C_{m\delta e}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Iced</td>
<td>0.000</td>
<td>-10.000</td>
<td>-1.352</td>
<td>-9.539</td>
<td>0.000</td>
<td>-9.924</td>
<td>-3.509</td>
<td>-10.000</td>
</tr>
</tbody>
</table>

*Based on data from the DeHavilland Twin Otter from AIAA 2000-0360*
Aircraft 20% Iced Climb Performance Responses
Aircraft Fully Iced Climb Performance Responses

- Angular (°/min) vs. Time (s)
- Pitch (°) vs. Time (s)
- Airframe Lift Coefficient vs. Time (s)
- Elevator Position (°) vs. Time (s)
- Angle of Attack (°) vs. Time (s)
- Pitch attitude (°) vs. Time (s)
- Airframe Drag Coefficient vs. Time (s)
- Altitude (ft) vs. Time (s)

Legend:
- Clean
- Iced
Asymmetric Icing Climb Performance Responses

![Graphs showing performance responses to asymmetric icing conditions.](image)
Conclusions

• Simulation methodology appears to be an adequate tool for the scope of this research
• Rate of climb is sensitive to icing effects on elevator effectiveness
• Climb maneuver comparisons showed an adverse impact on climb performance
  ➢ 20% iced aircraft
    ➢ 80 count airplane coefficient drag increase
    ➢ 200ft commanded altitude undershoot
  ➢ Fully iced aircraft
    ➢ 280 count increase
    ➢ 1000ft undershoot
  ➢ Asymmetric Icing (wing 70% iced, horizontal tail 40% iced)
    ➢ 180 count increase
    ➢ 650ft undershoot
Recommendations for Future Research

• Improve simulation fidelity
  ➤ Continue aircraft model refinement
  ➤ Vortex lattice method code
    ➤ Model horn and surface roughness
    ➤ Extract stability derivative increments
  ➤ Compile a more complete ensemble of test cases
    ➤ Wide variety of altitudes
    ➤ Compare to climbs already analyzed
  ➤ Vary simulation ice accretion severity
Questions?