Prediction of Icing Effects on the Coupled Dynamic Response of Light Airplanes

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AIAA Atmospheric Flight Mechanics Conference and Exhibit
Hilton Head, SC
August 21, 2007
Outline

• Concerns Regarding Aircraft Ice Accretions
• How This is Different from Previous Research
  ➢ Rudimentary, first-cut analysis
  ➢ Based on limited data
• Develop Aircraft Model and Test Methodology
  ➢ Validate and verify the model
  ➢ Several numerical examples
    ➢ System identification type maneuver “fully iced”
    ➢ Uneven ice distribution
• Conclusions and Recommendations
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 Configuration
  - 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

- Reduced longitudinal stability
  - $\downarrow C_L$, $\uparrow C_D$, $\downarrow C_{\alpha}$, $\downarrow C_{m\alpha}$

- Reduced lateral/directional stability

- Reduced aileron and rudder effectiveness

- Possible hingemoment reversal
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

• Sharma et. al, (2004)
  ➤ Pitch angle hold autopilot
  ➤ Envelope protection

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

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

\[ C_{(A)_{iced}} = (1 + \eta_{ice} k^s_{C_A}) \times C_{(A)} \]

Static effects on performance only
Objectives of This Work

• Develop a tool for studying and predicting icing effects on:
  ▶ Stability & control
  ▶ Performance
  ▶ Accident investigation
• Use only relatively simple, easy to obtain 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
- USAF Data Compendium (DATCOM) methods
- Propulsion model
  - Altitude and power effects
  - Table lookup
- Linear time invariant (LTI) state-space model
- Simulated in MatLab 7.0
- Longitudinal dynamics only
- Climb performance only
- Lateral/directional dynamics only
Coupled Aircraft Model – Longitudinal

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

\[ \dot{\alpha} = \frac{\dot{\theta}}{U_1} = (-g \sin \Theta_1 \cos \Phi_1 \theta - g \cos \Theta_1 \sin \Phi_1 \phi + Z_u u + Z_\alpha \alpha + Z_q q + U_1 q + Z_{\delta_e} \delta_e + Z_{\delta_T} \delta_T + Z_{\dot{\alpha}} \dot{\alpha}) / U_1 \]

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

\[ \dot{\theta} = -q \cos \Phi_1 - r \sin \Phi_1 \]

- Steady, level, 1-g trimmed flight in the stability axis
- \( P_1 = Q_1 = R_1 = V_1 = W_1 = \Phi_1 = 0 \)
Coupled Aircraft Model – Lateral/Directional

\[ \dot{\beta} = \left( Y_p p + g \phi \cos \Theta_1 \cos \Phi_1 + g \theta \sin \Theta_1 \sin \Phi_1 + Y_\beta \beta + (Y_r - U_1) r + Y_{\delta_A} \delta_A + Y_{\delta_R} \delta_R \right) / U_1 \]

\[ \dot{p} = L_\beta \beta + L_p p + L_r r + L_{\delta_A} \delta_A + L_{\delta_R} \delta_R + \frac{I_{xz}}{I_{xx}} \dot{r} \]

\[ \dot{r} = N_\beta \beta + N_p p + N_r r + N_{\delta_A} \delta_A + N_{\delta_R} \delta_R + \frac{I_{xz}}{I_{zz}} \dot{p} \]

\[ \dot{\phi} = p + r \cos \Phi_1 \tan \Theta_1 + q \sin \Phi_1 \tan \Theta_1 \]

\[ \dot{\psi} = r \cos \Phi_1 \sec \Theta_1 + q \sin \Phi_1 \sec \Theta_1 \]

- Steady, level, 1-g trimmed flight in the stability axis

- \( P_1 = Q_1 = R_1 = V_1 = W_1 = \Phi_1 = 0 \)
System Modeling Method

- **State-space representation**
  - Linear time invariant system (LTI)
    - \( \dot{X} = AX + BU \)
    - \( Y = CX + DU \)
  - \( X = [u \ a \ q \ \theta \ \beta \ p \ r \ \phi \ \psi]^T \)
  - \( U = [\delta_e \ \delta_T \ \delta_a \ \delta_r]^T \)

- **Discrete model**
  - \( X_{k+1} = \Phi X_k + \Gamma U_k \)
  - \( Y_k = CX_k + DU_k \)
  - \( \Phi(h) = e^{Ah} \)
  - \( \Gamma = \left( \int_0^h e^{A\tau} d\tau \right) B \)
Validation

- Use available data for a Cessna 208B Super Cargomaster
- Check stability and controllability
- Simulation of discrete model
- Check governing physics using a ramp input aileron deflection
Validation Analysis – Longitudinal

Modal Composition

\[
\begin{align*}
\lambda_{1,2} &= -1.49 \pm 2.54 j \\
\omega_{sp} &= 2.94 \text{ rad/sec} \\
\zeta_{sp} &= 0.51 \\
\lambda_{3,4} &= -0.013 \pm 0.19 j \\
\omega_{p} &= 0.20 \text{ rad/sec} \\
\zeta_{p} &= 0.065
\end{align*}
\]

Controllability

\[
C = [B \ AB \ AAB \ AAAB]
\]

\[\text{rank (C)} = 5 \ ; \ \text{controllable}\]

Modal Coordinates

\[
\begin{align*}
X &= M\xi \\
\dot{\xi} &= M^{-1}AM\xi + M^{-1}BU \\
Y &= CM\xi + DU
\end{align*}
\]

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

Phugoid mode
pitch attitude angle, some angle-of-attack and pitch rate
Validation Analysis – Lateral/Directional

Modal Composition

\[ \lambda_{1,2} = -1.49 \pm 2.54 j \]
\[ \omega_d = 1.76 \text{ rad/sec} \]
\[ \xi_d = 0.21 \]
\[ \lambda_3 = -4.84 \]
\[ \tau_r = 0.21 \text{ sec} \]
\[ \lambda_4 = -0.016 \]
\[ \tau_s = 63.68 \text{ sec} \]

Controllability

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

rank \( (C) = 5 \); controllable

Modal Coordinates

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

Dutch roll
primarily yaw rate, some roll attitude angle

Roll mode
sideslip angle, some roll rate

Spiral mode
Roll attitude angle, yaw rate
Verification

• Ensure particular aircraft is correctly modeled

• Compare simulation to flight test data

• Simulation maneuver dictated by flight test data maneuver ensemble
  ➢ Elevator doublet
  ➢ Aileron singlet
    ➔ Both show good matching
Numerical Examples

- Conducted ~80 simulations
- 3 cases considered:
  - Parameter Identification – Fully Iced
  - Uneven Asymmetric Icing
    - Cruise
    - Right wing half fully iced
  - Uneven Asymmetric Icing
    - Climb
    - Right wing half fully iced
# Icing Factors Applied

<table>
<thead>
<tr>
<th>derivative</th>
<th>$-\Delta C_{L0}$</th>
<th>$-\Delta C_{L\alpha}$</th>
<th>$-\Delta C_{Lq}$</th>
<th>$-\Delta C_{L\delta e}$</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>$f_{\text{ice}}$ (%)</td>
<td>-20.0</td>
<td>-8.0</td>
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*Based on data from the DeHavilland Twin Otter from AIAA 2000-0360

\[
M_{\alpha_{\text{avd}}} = \frac{\bar{q}S C R^2 \left( 1 - 0.20 f_{\text{ice}} \right) C_{\text{mz}}}{I_{zz}}
\]
Fully Iced System Identification Style Maneuver
Longitudinal Responses

Flight Condition:
Altitude – 15000 ft
Airspeed – 113 kts
Dynamic Pressure – 30.6 lbs/ft²
(same for all responses)
Fully Iced System Identification Style Maneuver
Lateral/Directional Responses
Asymmetric Icing Climb Performance Longitudinal Responses
Asymmetric Icing Climb Performance
Lateral/Directional Responses
Conclusions

- Modeling and simulation methodology appears to be a promising tool for the scope of this research

- Evenly distributed ice cause aircraft to become less stable
  - Remains inherently stable

- Uneven ice accretion resulted in ice induced moments apparent within 50 seconds
  - Cruise case
    - 300 count drag increase
    - Time-to-Double=20 sec
  - Climb case
    - 400 count drag increase
    - Time-to-Double=20 sec
Recommendations for Future Research

• Simple, time dependent icing severity

• 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 maneuvers already analyzed
  ▶ Vary simulation ice accretion severity
Questions?