Autopilot and Envelope Protection

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SMART ICING SYSTEMS Research Organization

Core Technologies

- Aerodynamics and Propulsion
- Flight Mechanics
- Control and Sensor Integration
- Human Factors/Cognitive Engineering
- Aircraft Icing Technology

IMS Functions

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

System Research/Integration

- Flight Simulation
- Flight Test
Typical Flight Envelope

- Aerodynamic Limits
- Thrust/Power Limits
- Structural Limits
- The flight envelope is primarily a function of load factor, velocity and altitude
- The *clean* aircraft flight envelope remains *constant*

Example of a Clean Aircraft Flight Envelope from Ramer 1989.
Envelope Protection for Commercial Jets

- Fly-by-wire system
- Pre-set limits
- Feel actuators
- Bank angle protection
- Stall protection
- Boeing: soft limits on control surface deflections
- Airbus: hard limits on the aircraft aerodynamic angles
Current System Limitations

- **Problem**: Limits change with level of ice accretion.

- **Solution**: In icing conditions the limits have to be determined and enforced *dynamically* during flight.

- **Problem**: Limits may be exceeded during maneuvers if only current sensor data is used to provide protection.

- **Solution**: System needed for *prediction* of future values from available sensor data including control positions.
Objectives

• Develop and analyze envelope protection techniques for operation in icing conditions

• Investigate standard autopilot behavior in icing conditions
Approach

• Prediction-based, dynamic, envelope protection
• Two modes: A/P off, A/P on
• A/P stability and performance characterization using robust control techniques
• Implement and test a ‘0\textsuperscript{th} order’ EP scheme for flight simulator: if $\alpha > \alpha_{\text{max}}$ generate warning
• Develop more sophisticated schemes based on prediction of future values
Why two EP schemes

- Current guidelines suggest A/P off under icing ⇒ ‘open loop’ EP necessary

- Future planes will rely heavily on automation ⇒ ‘closed loop’ EP is essential
Dynamic Envelope

• **The critical parameters:**
  - $\alpha_w$: Wing angle of attack
  - $\alpha_t$: Tail angle of attack
  - $\phi$: Roll angle

• Limits can be defined for these parameters as a function of ice accretion.
Angle of Attack Limiting

- $C_{l_{\text{max}}}$ vs $\Delta C_l$ fitted as linear functions for several AOA.
  
  $C_{L_{\text{max}}} = f(\Delta C_L (\eta_{\text{ice}}, \alpha))$

- The trim AOA used to find corresponding fit.

- The AOA corresponding to the $C_{l_{\text{max}}}$ is then set as the limit.
EP with A/P off

- **Limit detection**: Estimate limit boundaries using information from icing characterization

- **Prevention of limit violation**: Predict control limits and restrict the control deflection to safe values

- **Envelope Protection Interface**: Display limit information in the glass cockpit and use force feedback to avoid limit violation
Estimation of Safe Elevator Limits

- **Initialize the EP System:**
  The aircraft configuration and state at each time step is used to initialize the code.

- **Aircraft Model:**
  The iced non-linear aircraft model is used to calculate the force and moment coefficients within the code.

- **Calculate Elevator Limit:**
  The equations of motion are used to calculate the safe elevator limit.

- **Enforcing the Limit:**
  Pilot multipliers input “limited” by \( \Omega_{e,\text{limit}} \).
Simulation Results

Nonlinear Prediction of Angle of Attack Response

\[ \alpha_{\text{stall}} (\eta_{\text{ice}} = 0.1) \]

Pilot warned of limit violation

**FD Simulation**

**Predictive EP Algorithm**

*TIME (sec)*
Simulation Results

Linear Prediction of Elevator Limit

Simulation Results

Linear Prediction of Elevator Limit
Open Loop EP Conclusions

- The method developed to estimate the stall angle of attack showed promising results.
- Estimates based on limited airfoil data.
- Need to include 3-D wind tunnel or flight test data in order to improve stall estimates.
- Linearized $\Omega_{e,\text{limit}}$ predictions show encouraging results for cases tested.
- Explore nonlinear $\Omega_{e,\text{limit}}$ predictions.
EP with A/P on

- Pilot stick position dynamically affects control position
- EP continuously calculates limits on stick position and informs A/P

![Diagram of EP with A/P on system]
Closed Loop EP

- Monitor A/C state, A/P state and icing level
- Predict on-line future A/C state with current pilot input
- Adjust input based on prediction, inform pilot
- Same principle as open loop; different dynamical equations
Autopilots

- **Longitudinal Modes**
  - Pitch Attitude Hold (PAH)
  - Altitude Hold (ALH)

- **Lateral Modes**
  - Roll Attitude Hold (RAH)
  - Heading Hold (HH)
Block Diagram for PAH

\[ \theta_{ref} \rightarrow K_{\theta} \rightarrow \frac{K_i}{s} \text{ (integrator)} \rightarrow + \rightarrow + \rightarrow \text{Actuator Dynamics} \rightarrow \delta_e \rightarrow \text{A/C Dynamics} \rightarrow \theta \rightarrow q \]

\[ K_q \]

PAH
A/P Performance in Clean Conds

• Gains are scheduled on A/C speed

• Local designs exhibit good performance and stability margin properties

• Overall A/P performs well over the operational envelope of Twin Otter for clean conditions
Closed Loop PAH in Icing Conds

• The closed loop model is affinely dependent on the icing parameter $\eta$, i.e.

$$ \frac{dx}{dt} = A(\eta)x $$

$$ A(\eta) = A_0 + \eta(t)A_1 $$

where $\eta \in \Delta$, with $\Delta = [0, \eta_{max}]$

• Is iced closed loop stable?
Quadratic Stability

• Stability condition in terms of two LMIs

\[ A(\eta=0)^T K + KA(\eta=0) < \gamma I \]

and

\[ A(\eta=\eta_{\text{max}})^T K + KA(\eta=\eta_{\text{max}}) < \gamma I \]

where \( \gamma < 0 \) and \( \eta(t) \in [0, \eta_{\text{max}}] \)

• Above can be checked with LMILAB
Stability Analysis

- Pitch Attitude hold A/P maintains stability under icing for all icing conditions.

- There is a small degradation in the guaranteed stability level.

- Nonlinear phenomena not captured.
PAH A/P with EP Module

Pilot input ($\theta_{ref}$) → Command limiter → Limited $\theta_{ref}$ → Closed Loop PAH dynamics → x, Aircraft States

$\theta_{ref}$ limits

Reference Command limit Calculation

Limit Calculation

$\alpha_{stall}$

$\eta$
Envelope Protection for PAH Autopilot

PROBLEM: Insure for all time

$$\alpha(t) < \alpha_{\text{max}}(\eta(t))$$

APPROACH: Modify accordingly $$\theta_{\text{ref}}(t)$$
Envelop Protection Scheme

- Look at step pilot inputs
- Look at steady state response of the angle of attack

<table>
<thead>
<tr>
<th>Step Response</th>
<th>Envelope Protection System</th>
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<tbody>
<tr>
<td><img src="image1" alt="Step Response Diagram" /></td>
<td><strong>Steady State Estimation</strong></td>
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<tr>
<td></td>
<td>LIMIT DETECTION – Estimate value of limited parameter in steady state</td>
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<tr>
<td></td>
<td>LIMIT AVOIDANCE – Find control value that causes the limited parameter to reach envelope limit in steady state</td>
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Data Generation

- Data is generated by issuing a range of reference pitch commands at different flying conditions

\[ V_{\text{trim}}, \theta_{\text{ref}}, \eta \rightarrow \text{Closed loop PAH dynamics} \rightarrow \alpha_{ss} \]

- Steady state angle of attack values corresponding to trim state values of \( V, \eta \) and \( \theta_{\text{ref}} \) are recorded
EP Module Coding Scheme

EVERY 5 SECONDS

- Treat the state reached as a trim state
- Use the data generated to obtain maximum allowable \( \theta_{\text{ref}} \) (\( \theta_{\text{max}} \)) at that state

\[
\alpha_{ss} = f(V, \eta, \theta_{\text{max}}^{\text{ref}}) \approx \alpha_{\text{stall}}(\eta)
\]

- Compare \( \theta_{\text{ref}} \) at the current point with the \( \theta_{\text{max}}^{\text{ref}} \) value and pitch down if necessary
Simulation Results: $\eta$ Fixed

- A/C trimmed at $V = 60$ m/s with $\eta = 0.06$ at $H = 2300$ m
- A pitch up command of 7.6 degrees issued
- $\alpha_{\text{stall}} = 11.4$ degrees
η Fixed continued...
A Time Varying $\eta$ Case

- A pitch up command of 7.6 degrees with $V=60\,\text{m/s}$ is issued and ice starts to build and grows from $\eta=0$ at $t=0$ to $\eta=0.06$ at $t=50\,\text{s}$. 
Varying $\eta$ Continued...
Closed Loop EP Conclusions

• The pitch command inputs need to be reduced in case of icing to stay within the prescribed limit

• The EP module works well with varying stall angle limits due to ice accretion
Summary

• Developed prediction based EP methods for AoA limiting in icing conditions that show great promise in preventing envelope excursions
• Established stability of standard PAH schemes in icing conditions
• Demonstrated that standard PAH schemes can be safe if combined with appropriate closed loop EP modules
• Full scale development of prediction-based EP modules and validation of AP schemes is needed to establish full confidence