Envelope Protection and Recovery Guidance for Upset Conditions

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Structure

- Introduction
- Estimation of the Safe Flight Envelope
- Envelope Protection including Concept Demonstration
- Ongoing research: Upset Recovery
Introduction

- Loss of control in flight remains the most frequent primary cause of accidents
- 40% of all accidents is LOC-I related and this category involves most fatalities
- Increasing trend over the last decades

Source: CAA global fatal accident reviews
Upset Prevention and Recovery

Research subtopics, based on CAST directives on safety enhancements:

1. **Upset prevention**
   - Adaptive safe flight envelope estimation
   - Autoflight trajectory prediction and alerting
   - Adaptive envelope protection

2. **Upset recovery**
   1. Stall recovery guidance
   2. Unusual attitude recovery

Upset recovery training aspect
Reconfiguring flight control

**Garteur:**

**EU-FP7:**
ADDSAFE (2009-2012)
RECONFIGURE (2013-2016)
ADFLICO (2012-2015)
ACROSS (2013-2016)

**NASA:**
IRAC (2006 – 2010)
VSST (2010 – 2014)
TASA (2014 – present)

Upset Prevention

**Algorithms**

- Envelope Estimation
- Aircraft model identification
- Manoeuvering envelope estimation
- Reachability analysis
- Flight plan & trajectory intent

**Flightdeck tools**

- Real-time updates to PFD limits
- Adaptive protections and haptic feedback
- Predictive alerts
- Predictive state and mode transition displays

**Introduction** – Envelope Estimation – Envelope Protection – Upset Recovery – Concept Demonstration
Estimation of the envelope boundaries
trim envelope

Trim envelope: all the sets of stable \((V,\gamma)\) for which \((\dot{V}, \dot{\gamma}) = 0\), where inputs \(\alpha_{\text{min}} \leq \alpha \leq \alpha_{\text{max}}\) and \(T_{\text{min}} \leq T \leq T_{\text{max}}\).

The nonlinear aircraft model is made affine in the inputs, which allows an efficient procedure for finding trim points analytically and checking their stability.

ACT Simulation Model at 15000 feet.
Estimation of the envelope boundaries
maneuvering envelope

Safe maneuverability envelope is defined as intersection between forward and backward reachable sets.

Robustness for model uncertainty included.

Based on ACT Simulation Model at 15000 ft.
Estimation of the envelope boundaries trim and maneuvering envelope variation

Nominal at 15000 ft.

Full Flaps at 15000 ft.

Nominal at 30000 ft.

Full Flaps, Gear, Spoilers at 13000 ft.

Estimation of the envelope boundaries
maximum bank angle

$L \cos \gamma \cos \phi = W$

maximum achievable bank angle at current airspeed and flight path angle before stall occurs

$V_{\text{IAS}} = 222$ kts, $\phi_{\text{max}} > 60^\circ$

$V_{\text{IAS}} = 161$ kts, $\phi_{\text{max}} = 45^\circ$

$V_{\text{IAS}} = 142$ kts, $\phi_{\text{max}} = 20^\circ$
Additional information provided to the pilot over the cockpit displays.
Experiment overview: Advanced Concepts Flight Simulator

• Objective
  Explore how crews manage their trajectory and energy state while interacting with flight-deck automation, both with and without new technology

• Overview
  – 10 commercial flight crews
  – 4 “challenging” descent and landing scenarios
  – NextGen compatible routes in Memphis airspace
  – Workload assessment, post run questionnaire, end of study questionnaire

• New technologies
  – Predicted trajectories displayed on the navigation display (ND) and a vertical situation display (VSD)
  – Maneuver envelope limits displayed on the primary flight display (PFD)
  – Predictive alerting (on EICAS and ND/VSD)
Experiment overview: Icing scenario

- Aircraft is initialized in an icing condition:
  modified flight dynamics: less lift, more drag, $\alpha_{\text{stall}}$ smaller
- Aircraft flies published profile (unless flight crew declares emergency)
- Larger than expected V overshoots during deceleration segments, potential stall, earlier than expected flap deployment needed
Results

Icing scenario

Impact of icing on the safe flight envelope

- Reduced lift capability, more speed needed to compensate for increased weight.
- Increase in drag, less net excess thrust available for climb.

Comparison of trim envelopes of the damaged and undamaged RCAM model:

- Original set.
- Set for damage.

Comparison of trim envelopes of the damaged and undamaged RCAM model:

- Original set.
- Minimum airspeed increases further due to lower stall alpha.
- Set for damage.
Results

Icing scenario

Margins to limits for icing scenario

Margins to max & safe

Flap deployment strategy for icing scenario

Margins for all crews

flap deployment strategy

Implementation of the protections in the closed loop architecture

Protections are implemented in:

• Flight control laws
• Cockpit displays
• Haptic feedback

<table>
<thead>
<tr>
<th>Envelope boundary</th>
<th>Protection in controller</th>
<th>Displayed in PFD</th>
<th>Haptic feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>max bank</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>max alpha</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>min $V_{\text{CAS}}$</td>
<td>via max alpha</td>
<td>X</td>
<td>via max alpha</td>
</tr>
<tr>
<td>max load factor</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>min/max flight path angle</td>
<td></td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>
Implementation of the protections in the closed loop architecture

Implementation in controller

- nz loop
- α loop
- θ loop

longitudinal control

command filtering
reference model
roll control law

directional control

envelope estimation
FDIR

Envelope Protection
Implementation of the protections in the closed loop architecture

Cockpit displays

Haptic feedback

Increased stiffness for stall starts at --- in envelope

Introduction – Envelope Estimation – **Envelope Protection** – Upset Recovery – Concept Demonstration
Experiment method:
Simona Research Simulator

• Research hypotheses
  – Will envelope protection prevent loss of control and reduce workload?
  – Will modified PFD improve situational awareness about flying capabilities?
  – Will haptic feedback improve situational awareness about protective action?

• Overview
  – 7 commercial pilots, type rated for Airbus A330
  – 2 scenarios in approach:
    – Icing near Amsterdam Schiphol Airport
    – Windshear near Nice Côte d’Azur Airport
  – Workload and situational awareness assessment, post run questionnaire, end of study questionnaire

• New technologies
  – Adaptive envelope protection in flight control laws
  – Extended primary flight display
  – Haptic feedback on stick
Results: icing scenario

- Gradual ice accretion on the wings, starts around FL30
- Wind gusts make effect on envelope less obvious
- Speed and bank angle margins improve with new tech
- No increase in workload
Results: windshear scenario

• First downwash, followed by tailwind around WP3
• Envelope boundaries updated for windshear
• No noticeable difference in pilot performance
• Pilots stick to their windshear recovery procedure
Results: pilot feedback

- NASA TLX workload ratings:
  - Few confusion about envelope protection automation
  - Usefulness of indicators: V(PFD) – V(haptics) – nz(haptics) – φ(PFD) – Vz(PFD)
  - Awareness increase by new envelope limit indications
  - No fighting of the control system for icing as well as windshear
  - Good confidence about true envelope edges, based on information presented
Concept demonstration of envelope protection in Robotic Motion Simulator at DLR Oberpfaffenhofen.
Concept demonstration of envelope protection in Robotic Motion Simulator at DLR Oberpfaffenhofen
Conclusions of upset prevention and recovery

• Adaptive safe flight envelope estimation and protection algorithms have been designed and evaluated by several professional commercial airline pilots in various relevant simulation environments.

• Safe envelope bounds estimated in real time taking into account malfunctions and upsets, used for three kinds of protections:
  - Extended Primary Flight Display
  - Hard protections in the flight control laws
  - Haptic feedback on sidestick

• Significant performance changes detected in icing scenario, not so much for stabilizer misalignment or windshear.

• Observations with new technology:
  
  **ACFS experiments:**
  - pilots adapted strategy based on information
  - Icing scenario:
    - higher $V_{\text{min}}$
    - flap deployment for higher speeds

  **Simona experiments:**
  - larger safety margins to envelope boundaries prevent loss of control in off-nominal conditions,
  - reduced workload (objective and subjective ratings),
  - improved situational awareness (subjective ratings).
Upset recovery: stall recovery guidance

Strategy: exchange potential energy (altitude) for kinetic energy (speed), taking into account energy dissipation (drag) and energy inflow (thrust)

Constraints:
- Secondary stalls ($\alpha$)
- Structural loads ($n_z$)
- Pitching moment ($T_{\text{max}}$)

Pilot guidance through flight director ($\theta_c$) and throttle tape ($T_c$) in PFD
Thank you for your attention

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References

**Upset prevention**
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**Upset recovery**