Investigation of Asymmetric Thrust Detection with Demonstration in a Real-Time Simulation Testbed

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Outline

• Motivation and Background
• Asymmetric Thrust Detection Methods
• Results
• Conclusions
Motivation and Background

• Asymmetric thrust cited as cause of several loss of control aviation incidents and accidents
• Crew response may be inappropriate and exacerbate the situation
• Need recognition and response to unintended asymmetric thrust conditions
• Feasibility study initiated to evaluate three asymmetric thrust detection methods
Typical Sequence for Propulsion System Malfunction Plus Inappropriate Crew Response (PSM+ICR)

- Autopilot and autothrottle active
- Failure occurs
- Unintended asymmetric thrust occurs
- Control returned to flight crew
- Flight controls reach limits
- Automated flight controls manage asymmetry
- Limited time, control authority, information available
- Potential for inappropriate crew response and loss of control
Example PSM+ICR

Event #74 in PSM+ICR Report

- March 31, 1995, Flight 371 for Tarom Romanian Airlines (Airbus A310), departs Balotesti, Romania for Brussels, Belgium
- Autothrottle was engaged as the aircraft was ascending through 2,000 ft when the flaps were retracted
- With reduction in drag from flaps, the autothrottle moved to decrease power
- However, number 2 (right) engine throttle was stuck in the take-off throttle position
- To reduce airspeed, the number 1 (left) engine throttle was decreased until it went to idle developing an asymmetric thrust condition
- Asymmetric thrust was not apparent since the aircraft was in a left turn for a heading change
- Roll due to thrust asymmetry was not noticed until the pitch attitude suddenly dropped
- Aircraft continued to roll over and crashed with no survivors

Asymmetric Thrust Detection Methods

• Two methods based on estimated thrust for cross wing comparison of two engines
  – Kalman Filter
  – Table Lookup
Estimated Thrust: Kalman Filter Method

\[
\dot{\hat{x}}_{xq} = \left( A_{xq} - KC_{xq} \right) \Delta \hat{x}_{xq} + B_{xq} \Delta u + K \Delta y \\
\Delta \hat{y} = C_{xq} \Delta \hat{x}_{xq} + D \Delta u \\
\Delta \hat{z} = F_{xq} \Delta \hat{x}_{xq} + G \Delta u
\]

- \( x \) – state vector
- \( y \) – sensed output vector
- \( u \) – actuator command vector
- \( z \) – unmeasured output vector (net thrust)
- \( A,B,C,D,F,G \) – state space matrices
- \( K \) – Kalman gain matrix

- Piecewise linear model used to estimate non-measured parameters
- Kalman filter provides estimates that account for performance degradation over time
Estimated Thrust: Table Lookup Method

- Thrust tables calculated over entire flight envelope
  - Altitude
  - Mach
  - Fan Speed

- Thrust tables reduced through parameter correction to sea level conditions
  - Mach
  - Fan Speed
Thrust Estimation Asymmetric Detection Logic

<table>
<thead>
<tr>
<th>Engine 1</th>
<th>Estimated Corrected Net Thrust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine 2</td>
<td>Estimated Corrected Net Thrust</td>
</tr>
</tbody>
</table>

Absolute error

\[ |u| \]

Max Thrust

Absolute Percent error

\[ \times \frac{100}{\text{threshold}} \]

detection threshold exceeded?

\[ \text{yes} \quad \text{no} \]

persistance threshold exceeded?

\[ \text{yes} \quad \text{no} \]

Annunciate thrust asymmetry

No thrust asymmetry detected

\[ \text{yes} \quad \text{no} \]

Net Thrust

Yes

No

Annunciate thrust asymmetry

No thrust asymmetry detected

Annunciate thrust asymmetry
Asymmetric Thrust Detection Methods

• One method based on engine pressure ratio to compare commanded vs sensed signals for one engine
Engine Pressure Ratio Method and Detection Logic

- Engine Pressure Ratio (EPR)
  \[ EPR = \frac{\text{Engine Exit Pressure}}{\text{Engine Inlet Pressure}} = \frac{P_5}{P_2} \]
  - Commanded
  - Sensed

- EPR Method for Asymmetric Thrust Detection Logic
Results

• Asymmetric thrust detection sensitivity study
  – Accuracy of detection methods determined from Monte Carlo study to establish statistical baseline

• Piloted flight simulation evaluation
  – Real time demonstration of typical asymmetric thrust conditions
Linear Turbofan Engine Model Example

The asymmetric thrust detection methods were evaluated using the NASA Commercial Modular Aero-Propulsion System Simulation 40k (C-MAPSS40k) high-bypass turbofan engine model.

### Sensor Measurements

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nf</td>
<td>Fan speed</td>
</tr>
<tr>
<td>Nc</td>
<td>Core speed</td>
</tr>
<tr>
<td>P2</td>
<td>Inlet total pressure</td>
</tr>
<tr>
<td>T2</td>
<td>Inlet total temperature</td>
</tr>
<tr>
<td>P25</td>
<td>HPC inlet total pressure</td>
</tr>
<tr>
<td>T25</td>
<td>HPC inlet total temperature</td>
</tr>
<tr>
<td>Ps3</td>
<td>HPC exit static pressure</td>
</tr>
<tr>
<td>T3</td>
<td>HPT exit total temperature</td>
</tr>
<tr>
<td>P5</td>
<td>LPT exit total pressure</td>
</tr>
<tr>
<td>T5</td>
<td>LPT exit total temperature</td>
</tr>
</tbody>
</table>

### Actuators

<table>
<thead>
<tr>
<th>Actuator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wf</td>
<td>Fuel flow</td>
</tr>
<tr>
<td>VSV</td>
<td>Variable stator vane</td>
</tr>
<tr>
<td>VBV</td>
<td>Variable bleed valve</td>
</tr>
</tbody>
</table>

### Inputs

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alt</td>
<td>Altitude</td>
</tr>
<tr>
<td>MN</td>
<td>Mach number</td>
</tr>
<tr>
<td>PLA</td>
<td>Power lever angle</td>
</tr>
<tr>
<td>dTamb</td>
<td>Ambient temperature deviation relative to standard day conditions</td>
</tr>
<tr>
<td>Det</td>
<td>Performance deterioration level</td>
</tr>
<tr>
<td>Noise</td>
<td>Measurement noise enabled or disabled (discrete input)</td>
</tr>
</tbody>
</table>
## Statistical Baseline

### Monte Carlo Simulation Results
- Based on data from commercial aircraft flight profiles
- 216 data sets of 10 minute segments of cruise condition flight data with no thrust asymmetry played back through C-MAPSS40k
- Simulated engine deterioration and sensor noise provided realistic variance in the data
- Establish common false positive rate of 2 per 216 trials

<table>
<thead>
<tr>
<th>Method</th>
<th>Threshold</th>
<th>Persistency</th>
<th>False Alarms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kalman filter</td>
<td>0.187 %</td>
<td>6.5 sec</td>
<td>2 of 216 trials</td>
</tr>
<tr>
<td>Table lookup</td>
<td>0.087 %</td>
<td>6.5 sec</td>
<td>2 of 216 trials</td>
</tr>
<tr>
<td>Sensed and commanded EPR comparison</td>
<td>0.95%</td>
<td>6.5 sec</td>
<td>2 of 216 trials</td>
</tr>
</tbody>
</table>
Monte Carlo Failure Simulation Results

- Uncommanded linear increase in PLA introduced to one engine
- Simulated engine deterioration and sensor noise provided realistic variance in the data
- Average percent of corrected thrust at time of detection calculated for all 216 trials

<table>
<thead>
<tr>
<th>Method</th>
<th>Average percent of corrected thrust asymmetry at time of detection</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kalman filter</td>
<td>0.9664%</td>
<td>2.7792%</td>
</tr>
<tr>
<td>Table lookup</td>
<td>0.7647%</td>
<td>2.1976%</td>
</tr>
<tr>
<td>Sensed and commanded EPR comparison</td>
<td>2.7672%</td>
<td>4.0936%</td>
</tr>
</tbody>
</table>
Flight Simulator

- In original configuration, the NASA Glenn flight simulator is a FAA approved Advanced Aviation Training Device (AATD)
- For this study, it was configured to operate the Transport Class Model (TCM) developed by NASA Langley with two copies of C-MAPSS40K developed by NASA Glenn
- Asymmetric thrust conditions were introduced with pilot-in-the-loop to examine pilot reactions and to visualize the dynamic effect on the aircraft
Flight Simulator Results

1. Engine 1 stuck throttle initiates at t = 15s

2. Absolute % Net Thrust Mismatch
   - Threshold: 10%
   - Estimated thrust mismatch exceeds 10%

3. Asymmetric thrust condition detected and confirmed after persisting for > 6.5 secs.
Conclusions

• Realistic asymmetric thrust events were successfully tested with the NASA Glenn flight simulator
• All three methods were capable of detecting the current industry standard of 10% thrust asymmetry
• Additional studies would need to investigate applicability and methods for annunciation of an asymmetric condition to the pilot
• Investigate a hybrid of two methods to provide detection and engine identification
Acknowledgements

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Backup Slides
Background

Fatalities by CICTT Aviation Occurrence Categories
Fatal Accidents | Worldwide Commercial Jet Fleet | 2004 through 2013

Statistical Summary of Commercial Jet Airplane Accidents, Boeing 2014