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)

1. Autopilot and autothrottle active
2. Failure occurs
3. Unintended asymmetric thrust occurs
4. Flight controls reach limits
5. Automated flight controls manage asymmetry
6. Control returned to flight crew
7. Limited time, control authority, information available
8. 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

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

- **Piecewise linear model used to estimate non-measured parameters**
- **Kalman filter provides estimates that account for performance degradation over time**

\( x \) – 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
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

- Engine 1 Estimated Corrected Net Thrust
- Engine 2 Estimated Corrected Net Thrust

Absolute error $|u|$

Absolute Percent error $\times 100$

Detection threshold exceeded? yes

Persistency threshold exceeded? yes

No thrust asymmetry detected

Annunciate thrust asymmetry

No thrust asymmetry detected

No thrust asymmetry detected
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)**
  \[ EPR = \frac{\text{Engine Exit Pressure}}{\text{Engine Inlet Pressure}} = \frac{P5}{P2} \]
  - Commanded
  - Sensed

- **EPR Method for Asymmetric Thrust Detection Logic**

```
<table>
<thead>
<tr>
<th>Altitude</th>
<th>Mach</th>
<th>dTamb</th>
<th>PLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Logic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensed power setting</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absolute error</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Absolute Percent error</td>
<td></td>
<td></td>
</tr>
<tr>
<td>detection threshold exceeded?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>persistency threshold exceeded?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annunciate power mismatch in individual engine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No power mismatch detected</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No power mismatch detected</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

\[ \text{Absolute Percent error} = \frac{|u| \times 100}{\text{Absoulute error}} \]
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.

<table>
<thead>
<tr>
<th>Sensor Measurements</th>
<th>Actuators</th>
<th>Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nf</td>
<td>Wf</td>
<td>Alt</td>
</tr>
<tr>
<td>Fan speed</td>
<td>Fuel flow</td>
<td>Altitude</td>
</tr>
<tr>
<td>Nc</td>
<td>VSV</td>
<td>MN</td>
</tr>
<tr>
<td>Core speed</td>
<td>Variable stator vane</td>
<td>Mach number</td>
</tr>
<tr>
<td>P2</td>
<td>VBV</td>
<td>PLA</td>
</tr>
<tr>
<td>Inlet total pressure</td>
<td>Variable bleed valve</td>
<td>Power lever angle</td>
</tr>
<tr>
<td>T2</td>
<td></td>
<td>dTamb</td>
</tr>
<tr>
<td>Inlet total temperature</td>
<td></td>
<td>Ambient temperature deviation relative to standard day conditions</td>
</tr>
<tr>
<td>P25</td>
<td></td>
<td>Det</td>
</tr>
<tr>
<td>HPC inlet total pressure</td>
<td></td>
<td>Performance deterioration level</td>
</tr>
<tr>
<td>T25</td>
<td></td>
<td>Noise</td>
</tr>
<tr>
<td>HPC inlet total temperature</td>
<td></td>
<td>Measurement noise enabled or disabled (discrete input)</td>
</tr>
<tr>
<td>Ps3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HPC exit static pressure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td></td>
<td></td>
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<tr>
<td>HPT exit total temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LPT exit total pressure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LPT exit total temperature</td>
<td></td>
<td></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>
Statistical Baseline

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

- Engine 1 stuck throttle initiates at $t = 15\text{s}$
- Estimated net thrust (lbf)
- Absolute % net thrust mismatch reaches 10% threshold
- 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

This work was conducted under the NASA Aviation Safety Program, Vehicle Systems Safety Technologies Project
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