Identification of High Angle of Attack Aerodynamic Model Using Flight Data From Spin Tests

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Outline

• Introduction
• Aircraft tested & Instrumentation
• Spin test strip charts
• Flight path reconstruction
• System Identification
• Lessons learned
• Conclusions and Future Work
Introduction

- Define “high AOA model”: able to reproduce the spin maneuver.

\[ C_L, C_D, C_Y, C_{\ell}, C_m, C_n = f(\alpha, \beta, \omega, \delta_a, \delta_e, \delta_r) \]

Large aerodynamic look-up tables

- Typical sources of unsteady high AOA database:

  Rotary balance

  Forced oscillations
Introduction

- Typical sources of unsteady high AOA database (cont.):
  - Free-spin test
  - Free-flight test
  - Drop model
Introduction

• Advantages:
  • Build up approach;
  • Spin prediction in early phases of development.

• Disadvantages:
  • Dynamic scaling requirements;
  • Costs.

• What if I need the spin model of my actual aircraft (not a project)? (spin training)
  Maybe, the flight data from spin maneuvers could be used in the system identification process.
Aircraft tested

Embraer EMB-312 Tucano:

- Single engine
- Two-seat
- PT6A-25C (750 SHP)
- Average weight: 5,500 lbf (no stores)

Instrumentation:

- Air data boom (right wing tip);
- Accelerations and rotation rates;
- Euler angles ($\phi$, $\theta$, $\psi$);
- Body-axes angular rates ($p$, $q$, $r$);
- Linear accelerations ($ax$, $ay$, $az$);
- 32 Hz.
Spin test strip charts

First Problem:

- **True airspeed** \( (V) \): anemometric errors occur during the developed spin (high AOA and large sideslips).
At some points, very low values of dynamic pressure are measured, originating unrealistically high (or low) values of coefficients.
Filtering is not an option.
Other problems:

- **Heading angle ($\psi$):** derived from aircraft’s onboard compass, which experiences strong delay during very dynamic maneuvers.

If the heading values were true, we would have a pattern of straight lines, which means the aircraft is spinning at some constant yaw rate:
Other problems (Cont.):

• Pitch angle ($\theta$): If the aircraft reaches -85° (pitch down), the gimbal becomes locked at its physical limit.

The values are offset.

Recovering with $\theta = -20^\circ$.

• Roll angle ($\phi$): Coupled with $\theta$, i.e., a gimbal lock on pitch compromises roll measurements.

• Flow angles ($\alpha, \beta$): Calibrated for low AOA and sideslip, in steady-conditions. Not reliable for spins.
Flight path reconstruction (FPR)

- Euler angles ($\psi, \theta, \phi$): reconstructed by integration of $p/q/r$.

- Airspeed components ($u,v,w$): reconstructed by integration of $ax/ay/az$.

- Flow angles ($\alpha, \beta$): obtained from $u,v,w$.

- Altitude ($H$): reconstructed from Euler angles and $u,v,w$.

Approach adopted:

- Perform a FPR during the spin, in order to obtain the true airspeed and correct FTI limitations.
Spin test:
Spin test data:

- Velocity (V) vs. Time (s)
- Angle of Attack (α) vs. Time (s)
- Bank Angle (β) vs. Time (s)
- Angular Momentum (ψ) vs. Time (s)
- Height (h) vs. Time (s)
FPR results

- $V$ (m/s)
- $\alpha$ (º)
- $\beta$ (º)
- $\phi$ (º)
- $\theta$ (º)
- $\psi$ (º)
- $h$ (m)
Videos:

Original Data

Reconstructed Data
System Identification

- Local Model Networks
- Data Partitioning
- Parameter Estimation
Local model networks

- A nonlinear function can be modeled by a sum of simpler functions, which are valid only locally:

\[ C_L = \sum_{k=1}^{M} w_k(\alpha).C_{L_k}(\alpha) \]

- Smooth transitions: Weighting functions “w” are combinations of “tanh”.

- Example: 1-D domain
- Spin model: 6-D domain

\[ C_L, C_D, C_Y, C_{\ell}, C_m, C_n = f(\alpha, \beta, \omega, \delta_a, \delta_e, \delta_r) \]
Data partitioning

• The aircraft does not spin at all combinations of domain variables:

\[(\alpha, \beta, \omega, \delta_a, \delta_e, \delta_r)\]

\[-10^\circ < \alpha < 60^\circ\]  \[-15^\circ < \delta_a < 15^\circ\]
\[-40^\circ < \beta < 40^\circ\]  \[-20^\circ < \delta_e < 20^\circ\]
\[0^\circ / s < \omega < 250^\circ / s\]  \[-30^\circ < \delta_r < 30^\circ\]

• For example:
  • Full deflections of elevator and rudder only occur when AOA is beyond stall;
  • It is not possible to keep a high AOA without applying full aft elevator;
  • Partitioning AOA automatically represents subsets of elevator deflection.
Data partitioning

- Cross-plots:

- Domain variables for partitioning: (only $\alpha$ and $\beta$)

  \begin{align*}
  0^\circ &< \alpha < 20^\circ & \quad & -25^\circ < \beta < -10^\circ \\
  20^\circ &< \alpha < 50^\circ & \quad & -10^\circ < \beta < 10^\circ \\
  & & \quad & 10^\circ < \beta < 25^\circ
  \end{align*}
Data partitioning

- 2-D weighting functions: $\alpha$, $\beta$

Region 1
$0^\circ < \alpha < 20^\circ$
any $\beta$

$w_1 = f(\alpha, \beta)$

Region 2
$20^\circ < \alpha < 50^\circ$
$-10^\circ < \beta < 10^\circ$

$w_2 = f(\alpha, \beta)$

Region 3
$20^\circ < \alpha < 50^\circ$
$-25^\circ < \beta < -10^\circ$ and
$10^\circ < \beta < 25^\circ$

$w_3 = f(\alpha, \beta)$
Data partitioning

• Example:

Region 1: \((C_{n\delta a})_1 = -0.3\)
Region 2: \((C_{n\delta a})_2 = 0.2\)
Region 3: \((C_{n\delta a})_3 = -0.1\)

\[C_{n\delta a} = \sum_{i=1}^{3} w_i \cdot (C_{n\delta a})_i\]

\[C_{n\delta a} = w_1 \cdot (-0.3) + w_2 \cdot (0.2) + w_3 \cdot (-0.1)\]
Parameter Estimation

• Classic approach:

\[ C_n = C_{n0} + C_{n\beta} \cdot \beta + C_{np} \cdot p + C_{nr} \cdot r + C_{n\delta_a} \cdot \delta_a + C_{n\delta_r} \cdot \delta_r \]

6 basic parameters

• For spin maneuvers:

\[ C_n = C_{n0}(\alpha, \beta) + C_{n\beta}(\alpha, \beta) \cdot \beta + C_{np}(\alpha, \beta) \cdot p + C_{nr}(\alpha, \beta) \cdot r + \ldots \\
C_{n\delta_a}(\alpha, \beta) \cdot \delta_a + C_{n\delta_r}(\alpha, \beta) \cdot \delta_r \]

\[ C_n = \left( w_1 \cdot C_{n01} + w_2 \cdot C_{n02} + w_3 \cdot C_{n03} \right) + \\
\left( w_1 \cdot C_{n\beta_1} + w_2 \cdot C_{n\beta_2} + w_3 \cdot C_{n\beta_3} \right) \cdot \beta + \\
\vdots \\
\left( w_1 \cdot C_{n\delta_{r1}} + w_2 \cdot C_{n\delta_{r2}} + w_3 \cdot C_{n\delta_{r3}} \right) \cdot \delta_r \]

6 basic parameters \times 3 partitions = 21 parameters
Parameter Estimation

• No general rule for data partitioning;
• Iterative algorithm:

  • **STEP 1:** For a pre-defined partitioning:
    • Arrange the regressors based on its relevance to the model;
    • Choose the most relevant regressors;
    • Define a model structure for each aerodynamic coefficient.

  • **STEP 2:** For this model structure:
    • Check the boundaries of the regions (partitioning):
    • If other boundaries provide a better model (smaller fit error and smaller standard deviations), use the new boundaries and go back to **STEP 1**, until convergence.
Parameter Estimation Results

“Good fit” does not mean “good estimation”.
Parameter Estimation Results

- Good regressor selection criteria (OLS);
- Low standard deviations of the estimates (not more than 10%, worst case);
- Low correlation coefficients between the regressors selected;
- Lift and drag curves make sense:

• All above indicates that this approach is valid (more analysis required).
Lessons learned

• Flight path reconstruction (FPR) is a very powerful tool for FTE’s:
  • Redundancy;
  • Calibration;
  • Overcome eventual FTI limitations.

• Local model networks allow to split a complex non-linear function into a number of simpler functions;

• Concatenation of a number of spin maneuvers, and low AOA maneuvers improves the model robustness and the reliability of FPR results.
Conclusions and Future Work

• If FTI is available, spin tests are a great source of high AOA data when compared to wind tunnels, because there are no model scaling problems;

• In this work, just three minutes of collected data were used, whereas several hours of wind tunnel testing would be required to achieve the simplest lookup tables for a simulator;

• Future work: more analysis on the data partitioning algorithm. Although the boundaries were variable, the number of partitions was fixed, for all aerodynamic coefficients;

• Estimate high and low AOA partitions simultaneously was difficult. Use the spins to develop a high AOA model from a simpler low AOA model previously identified (build up approach).
Acknowledgements

IPEV (Instituto de Pesquisas e Ensaios em Voo), through flight test instrumentation project and test vehicle operation; and

FINEP (Financiadora de Estudos e Projetos), under agreement 01.13.0518.00 for financial support.
Thank you!