Generation and Calibration of Linear Models of Aircraft with Highly Coupled Aeroelastic and Flight Dynamics

Jeffrey Ouellette, Felipe Valdez

NASA Armstrong Flight Research Center

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High Aspect Ratio Wing Technical Challenge

- Configurations with higher aspect ratios, hybrid wing bodies
  - Increasing flying wing aspect ratio from 6 to 11
  - Increases loiter time from 28 to 40 hrs
  - Passive flutter margin requires ~25% increase in wing weight
- Advanced control techniques could avoid the penalty
  - Strong interactions between what the pilot sees (flight dynamics) and the structural dynamics
  - Actual gains can be less than predictions from rigid aircraft
- Specifically, how can we ...
  - Model lightweight flexible structures?
Flex/Rigid Coupling: Non-Traditional Flutter

Rigid Body/Flight Dynamics
- What the pilot typically observes
- Control laws normally operate in this bandwidth
  - Even load alleviation controllers

Structural Dynamics
- Pilot cannot control
- Normally passively stabilized
- Traditional flutter

Body freedom flutter is when these interact catastrophically
- Unconventional configurations
  - Flying wings
  - High speed aircraft (e.g. SR-71 or Concord)
- Fuselage/Body significant contribution to total aerodynamic forces
- Not easily testable in wind tunnels
  - Limitations in the mounting of the models
  - Limited data sets available for analysis
Objective

Generate/Integrate models useful for the design and evaluation of control laws for active structural control and flutter suppression that are able to accurately predict body freedom flutter.

For design
- Effects the form of the models
  - State-space models
  - Interpolation between flight conditions for full envelope design

For evaluation
- Uncertainty
- Piloted simulation

Prediction
- Physically based models
  - Using information typically available before flight
- Predictive accuracy has been insufficient/inconsistent
  - Based on our flight test experience:
    - How we generate models changed
    - What information we used did not change
Coordinate Systems

Earth Axis
- Flat earth and fixed (inertial) axis

Modal Axis (Aeroelasticity)
- Inertial axis
- Translates at fixed rate
- Orientation fixed relative to earth

Body Axis (Flight dynamics)
- Mean axis
  - Fixed at center of gravity
  - Moves relative to vehicle
- Orientation changes relative to earth

Wind Axis
- Orientation defined by wind direction
- Used to describe the body axis velocity
Model Elements

Aerodynamics
- Unsteady lifting surface (ZAERO)
  - Frequency domain (linear in time)
  - Potential flow (small disturbance from freestream)
  - Thin plates
- Augmented with steady CFD and wind tunnel
  - Higher fidelity
  - Incomplete information

Structural Dynamics
- Linear finite elements (NASTRAN)
- Assumed mode shapes
  - Mode shapes do not change with fuel
  - Aerodynamic coefficients are constant
  - Mass and stiffness matrices change instead of mode shapes
Differences in the Model Formulation

\[
\begin{align*}
\{ \dot{x}_{\text{rigid}} \} & = \begin{bmatrix} 0 & I & 0 & 0 \\
\cdots & \cdots & \cdots & \cdots \end{bmatrix} \begin{bmatrix} 0 & 0 \\
\cdots & \cdots & \cdots & \cdots \end{bmatrix} \{ x_{\text{rigid}} \} \\
\\{ \dot{v}_{\text{rigid}} \} & = \begin{bmatrix} 0 & 0 & 0 & I \\
\cdots & \cdots & \cdots & \cdots \end{bmatrix} \{ v_{\text{rigid}} \} \\
\{ \dot{x}_{\text{flex}} \} & = \begin{bmatrix} 0 & 0 & 0 & I \\
\cdots & \cdots & \cdots & \cdots \end{bmatrix} \{ x_{\text{flex}} \} \\
\{ \dot{v}_{\text{flex}} \} & = \begin{bmatrix} 0 & 0 & 0 & I \\
\cdots & \cdots & \cdots & \cdots \end{bmatrix} \{ v_{\text{flex}} \} \\
\{ \dot{x}_{\text{aero}} \} & = \begin{bmatrix} 0 & 0 & 0 & I \\
\cdots & \cdots & \cdots & \cdots \end{bmatrix} \{ x_{\text{aero}} \} \\
\{ \dot{v}_{\text{aero}} \} & = \begin{bmatrix} 0 & 0 & 0 & I \\
\cdots & \cdots & \cdots & \cdots \end{bmatrix} \{ v_{\text{aero}} \}
\end{align*}
\]

Flutter

Kinematics
Aerodynamics
Gravity

Typical
Integrated

Fully
Integrated

Flight
Dynamics
Aerodynamic Model Calibration

Aerodynamic Influence Coefficients
- How does motion of one panel, produce pressure on the others
- Input: Panel motion (downwash)
- Output: Pressure differential

Want to adjust to match CFD or wind tunnel data

Adjusting Steady Part of Inputs
- Boundary Layer
  - Change in effective shape
- Thickness
  - Deviation of local from freestream velocity

Extrapolation of corrections with frequency
- Effect of corrections decrease with frequency
Aerodynamic Correction Factors

AIC Correction factors are not new

- They are very problematic
- Primary issue is selection of parameters

Implemented a constraint on smoothness

- Limit changes between neighboring panels
- Helped to reduce excessive correction factors

Correction factors results

- Large error in nose
  - Center body thickness
- Slight correction at control surfaces
  - Boundary layer
Removing the Aerodynamic Frequency Dependence

AIC translated into a model with modes as input/output

Rational (Transfer) Function Approximation (RFA)
  - Similar to a typical Rogers method
  - Separating velocities and positions
    - Velocities are not derivatives of positions (non-inertial flight mechanics)
  - Matching Low Frequency
    - Forces at steady state (shape changes)
      - Common practice
      - Quasi-steady coefficients
        - E.g. constant pitch rate
        - Parameters taken from polynomial model

Polynomial Model
  - Fit by matching 8th order to 4 frequencies
    - Determined by examining convergence of coefficients
  - Only used for extrapolating RFA constraint
Comparing to Flight Data

Two methods used for comparing to flight data

Nonparametric Frequency Responses
- Single input to output response
- Corrected to give open loop

Low Order Equivalent System (LOES)
- Estimating open loop response
- 3 Modes (Pitch, Symmetric Bending, Symmetric Torsion)
  - \( H_{loes} = \frac{\sum_{i=1}^{6} n_i s^i}{\prod_{i=1}^{3} (s^2 + 2\zeta_i \omega_i + \omega_i^2)} \)
- Output error method
  - Both time and frequency domain have been used
Correlating Predictions to Flight

- Left top: Relative Frequency vs. Airspeed with Model and Flight Data.
- Right top: Damping vs. Airspeed with Model and Flight Data.
- Left bottom: Relative Frequency vs. Airspeed with Model and Flight Data.
- Right bottom: Damping vs. Airspeed with Model and Flight Data.
Accuracy of Frequency Responses

Low Speed

High Speed

Magnitude, dB

Phase, deg

Coherence

Frequency, Hz

1

0

0

1

Flight

Model

LOES

Short-Period

Bending

Torsion

Body Freedom Flutter

Torsion

Flight

Model

LOES