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

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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

\[
\begin{align*}
\begin{cases}
\dot{x}_{\text{rigid}} \\
\dot{v}_{\text{rigid}} \\
\dot{x}_{\text{flex}} \\
\dot{v}_{\text{flex}} \\
\dot{x}_{\text{aero}}
\end{cases}
&= \begin{bmatrix}
0 & I & 0 & 0 \\
0 & 0 & 0 & 0 & I \\
\cdots (k) & \cdots (k) & \cdots (k) & \cdots (k) \\
\text{Flutter}
\end{bmatrix}
\begin{cases}
x_{\text{rigid}} \\
v_{\text{rigid}} \\
x_{\text{flex}} \\
v_{\text{flex}} \\
x_{\text{aero}}
\end{cases} \\
\begin{cases}
\dot{x}_{\text{rigid}} \\
\dot{v}_{\text{rigid}} \\
\dot{x}_{\text{flex}} \\
\dot{v}_{\text{flex}} \\
\dot{x}_{\text{aero}}
\end{cases}
&= \begin{bmatrix}
0 & I & 0 & 0 & 0 \\
0 & 0 & 0 & I & 0 \\
\cdots (k) & \cdots (k) & \cdots (k) & \cdots (k) & \cdots (k) \\
\text{Typical} \\
\text{Gravity}
\end{bmatrix}
\begin{cases}
x_{\text{rigid}} \\
v_{\text{rigid}} \\
x_{\text{flex}} \\
v_{\text{flex}} \\
x_{\text{aero}}
\end{cases} \\
\begin{cases}
\dot{x}_{\text{rigid}} \\
\dot{v}_{\text{rigid}} \\
\dot{x}_{\text{flex}} \\
\dot{v}_{\text{flex}} \\
\dot{x}_{\text{aero}}
\end{cases}
&= \begin{bmatrix}
\cdots & \cdots & 0 & 0 & 0 \\
\cdots & \cdots & \cdots & \cdots & \cdots \\
0 & 0 & I & 0 & 0 \\
\cdots (k) & \cdots (k) & \cdots (k) & \cdots (k) & \cdots (k) \\
\text{Fully} \\
\text{Integrated}
\end{bmatrix}
\begin{cases}
x_{\text{rigid}} \\
v_{\text{rigid}} \\
x_{\text{flex}} \\
v_{\text{flex}} \\
x_{\text{aero}}
\end{cases} \\
\begin{cases}
\dot{x}_{\text{rigid}} \\
\dot{v}_{\text{rigid}} \\
\dot{x}_{\text{flex}} \\
\dot{v}_{\text{flex}} \\
\dot{x}_{\text{aero}}
\end{cases}
&= \begin{bmatrix}
\cdots & \cdots \\
\cdots & \cdots \\
0 & \cdots (k) & \cdots (k) & \cdots (k) & \cdots (k) \\
\text{Flight} \\
\text{Dynamics}
\end{bmatrix}
\begin{cases}
x_{\text{rigid}} \\
v_{\text{rigid}}
\end{cases}
\end{align*}
\]
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 8\textsuperscript{th} 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

- Relative Frequency vs. Airspeed
- Damping vs. Airspeed
- Fuel % vs. Airspeed
- Fuel % vs. Airspeed

Model vs. Flight Data
Accuracy of Frequency Responses

Low Speed

- Magnitude, dB
  - Flight
  - Model
  - LOES

- Phase, deg

- Coherence

High Speed

- Magnitude, dB
  - Flight
  - Model
  - LOES

- Phase, deg

- Coherence

Frequency, Hz