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

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Advanced Air Transport Technology Program
High Aspect Ratio Wing Technical Challange

- 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 then 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

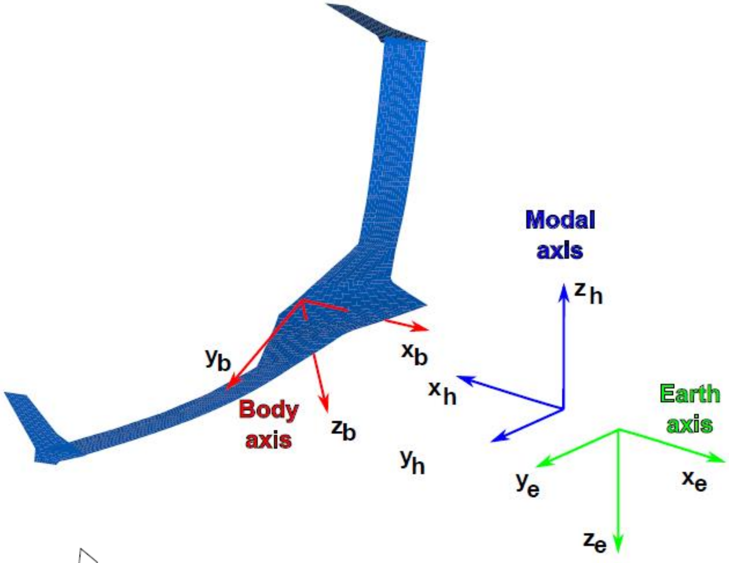
Coordinate Systems

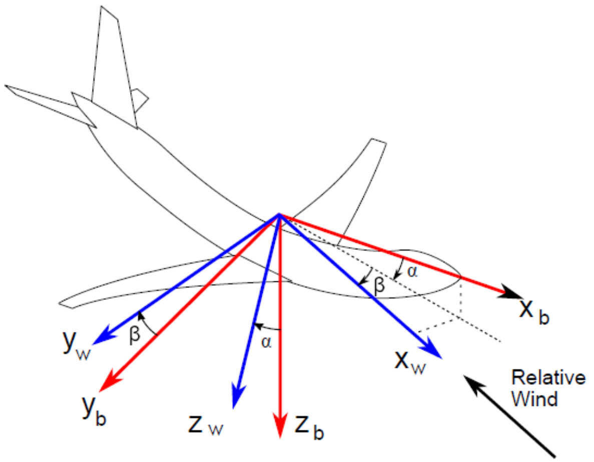
Earth Axis
- Flat earth and fixed (inertial) axis

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

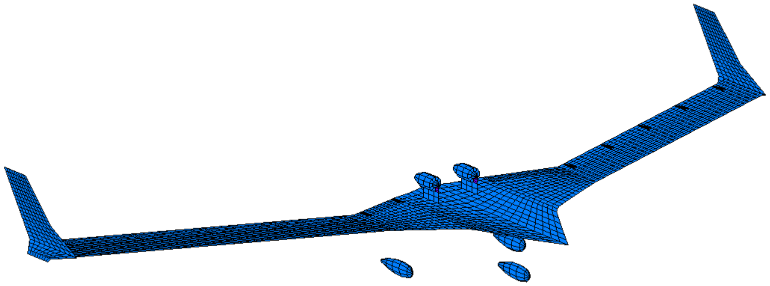




Model Elements

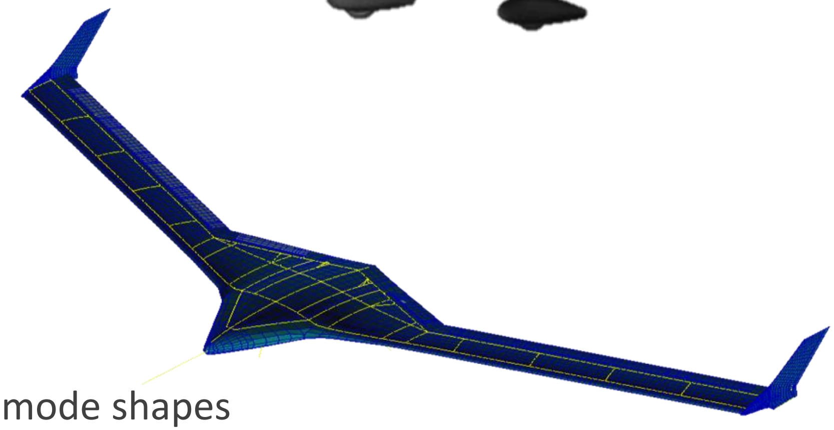
Aerodynamics

- 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

$$\begin{Bmatrix} \dot{x}_{rigid} \\ \dot{v}_{rigid} \\ \dot{x}_{flex} \\ \dot{v}_{flex} \\ \dot{x}_{aero} \end{Bmatrix} = \begin{bmatrix} \mathbf{0} & \boldsymbol{I} & \mathbf{0} & \mathbf{0} & \\ [\cdots](k) & [\cdots](k) & [\cdots](k) & [\cdots](k) & \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{I} & \\ [\cdots](k) & [\cdots](k) & [\cdots](k) & [\cdots](k) & \\ & & & & \end{bmatrix} \begin{Bmatrix} x_{rigid} \\ v_{rigid} \\ x_{flex} \\ v_{flex} \end{Bmatrix}$$

Flutter

$$\begin{Bmatrix} \dot{x}_{rigid} \\ \dot{v}_{rigid} \\ \dot{x}_{flex} \\ \dot{v}_{flex} \\ \dot{x}_{aero} \end{Bmatrix} = \begin{bmatrix} \mathbf{0} & \boldsymbol{I} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ [\cdots] & [\cdots] & [\cdots] & [\cdots] & [\cdots] \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{I} & \mathbf{0} \\ [\cdots] & [\cdots] & [\cdots] & [\cdots] & [\cdots] \\ \mathbf{0} & [\cdots] & \mathbf{0} & [\cdots] & [\cdots] \end{bmatrix} \begin{Bmatrix} x_{rigid} \\ v_{rigid} \\ x_{flex} \\ v_{flex} \\ x_{aero} \end{Bmatrix}$$

Typical Integrated

$$\begin{Bmatrix} \dot{x}_{rigid} \\ \dot{v}_{rigid} \\ \dot{x}_{flex} \\ \dot{v}_{flex} \\ \dot{x}_{aero} \end{Bmatrix} = \begin{bmatrix} [\cdots] & [\cdots] & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ [\cdots] & [\cdots] & [\cdots] & [\cdots] & [\cdots] \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{I} & \mathbf{0} \\ \mathbf{0} & [\cdots] & [\cdots] & [\cdots] & [\cdots] \\ \mathbf{0} & [\cdots] & \mathbf{0} & [\cdots] & [\cdots] \end{bmatrix} \begin{Bmatrix} x_{rigid} \\ v_{rigid} \\ x_{flex} \\ v_{flex} \\ x_{aero} \end{Bmatrix}$$

Fully Integrated

$$\begin{Bmatrix} \dot{x}_{rigid} \\ \dot{v}_{rigid} \\ \\ \\ \end{Bmatrix} = \begin{bmatrix} [\cdots] & [\cdots] & & & \\ [\cdots] & [\cdots] & & & \\ & & & & \\ & & & & \end{bmatrix} \begin{Bmatrix} x_{rigid} \\ v_{rigid} \\ \\ \\ \end{Bmatrix}$$

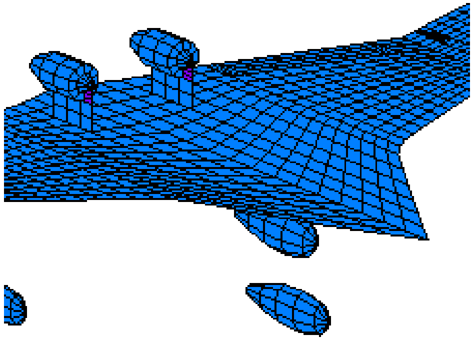
Flight Dynamics

Kinematics
Aerodynamics
Gravity

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

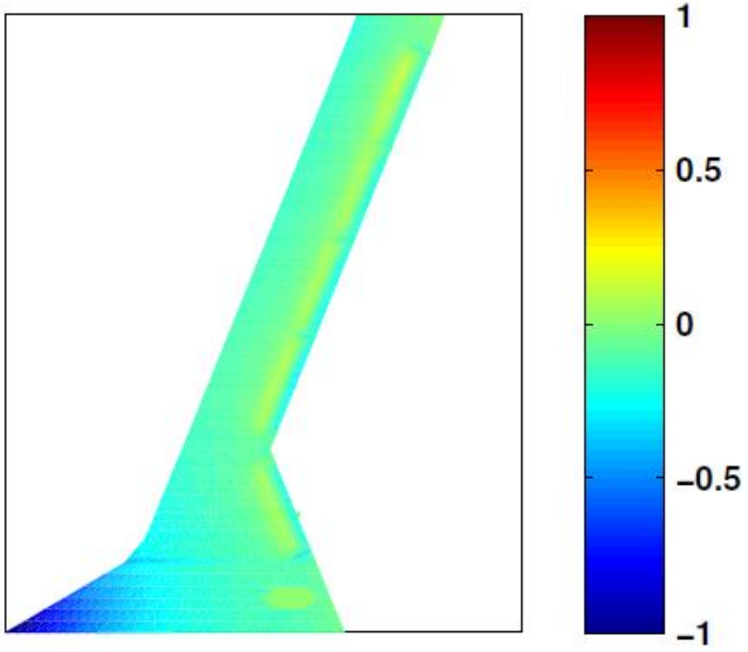
- They are very problematic
- Primary issue is selection of parameters

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^{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

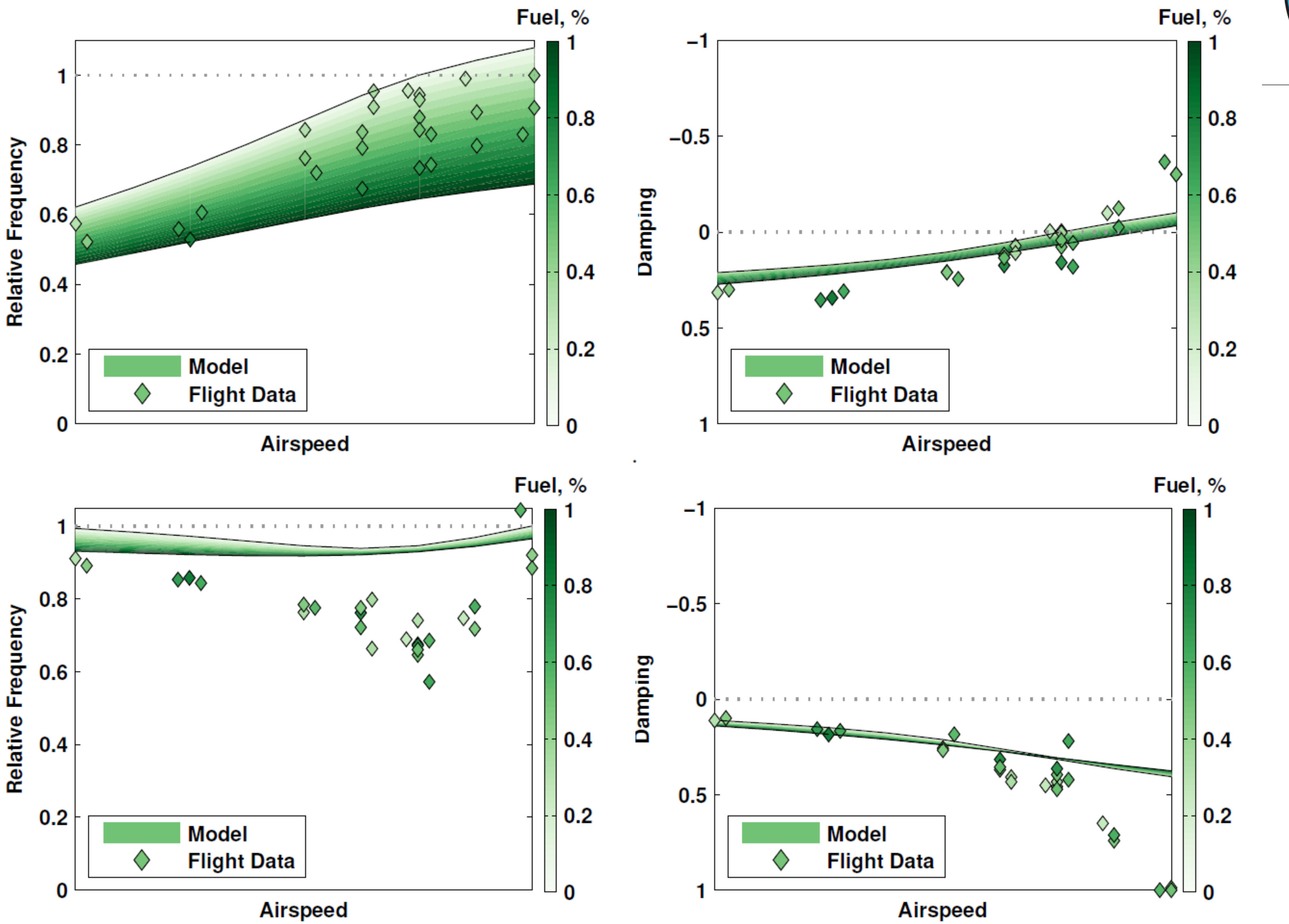
Nonparametric Frequency Responses

- 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



Accuracy of Frequency Responses