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

Jeffrey Ouellette, Felipe Valdez

NASA Armstrong Flight Research Center

AIAA SciTech Conference

January 8, 2020

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

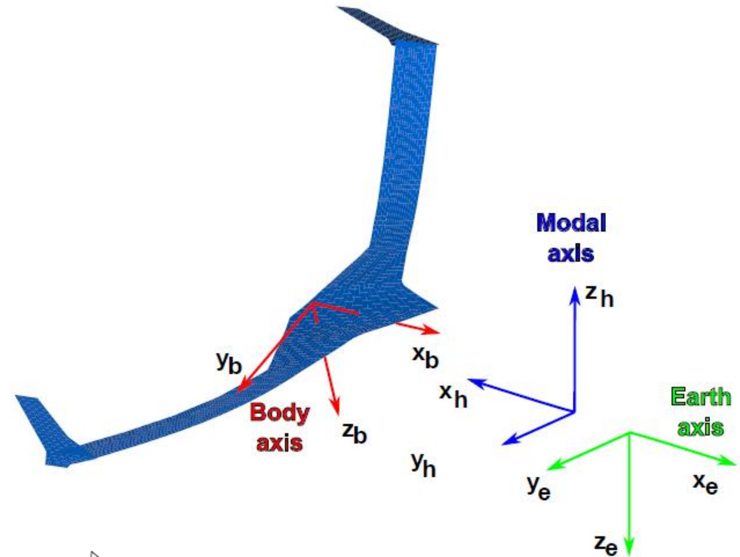
Coordinate Systems

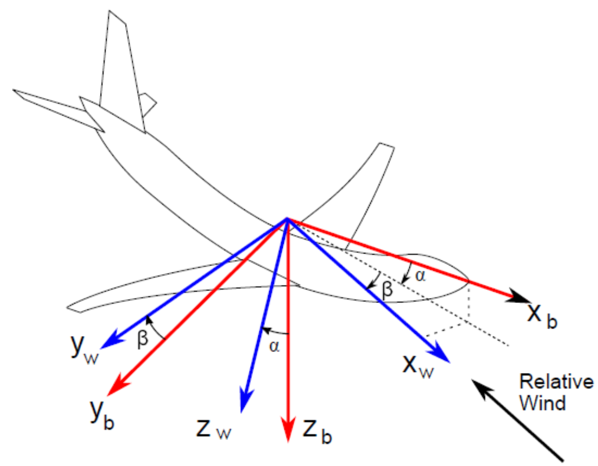
Earth Axis
- Flat earth and fixed (inertial) axis

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

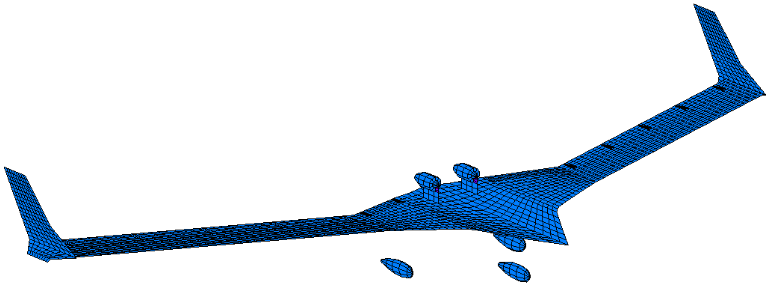




Model Elements

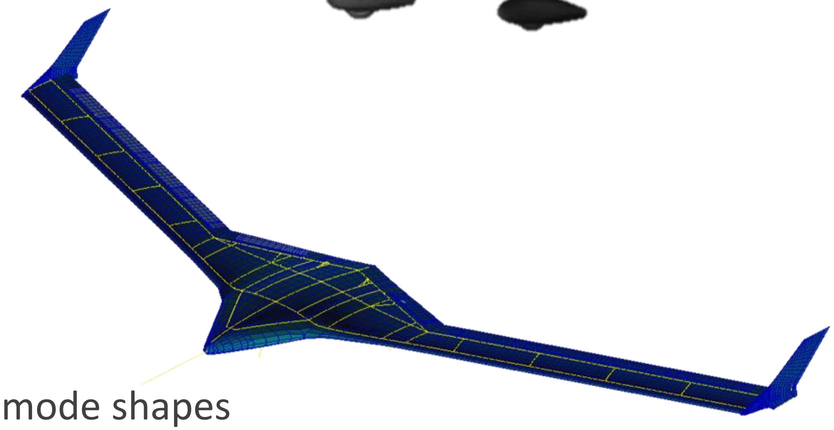
Aerodynamics

- 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

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

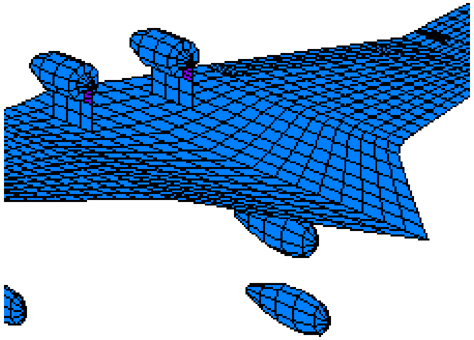
Flight Dynamics

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

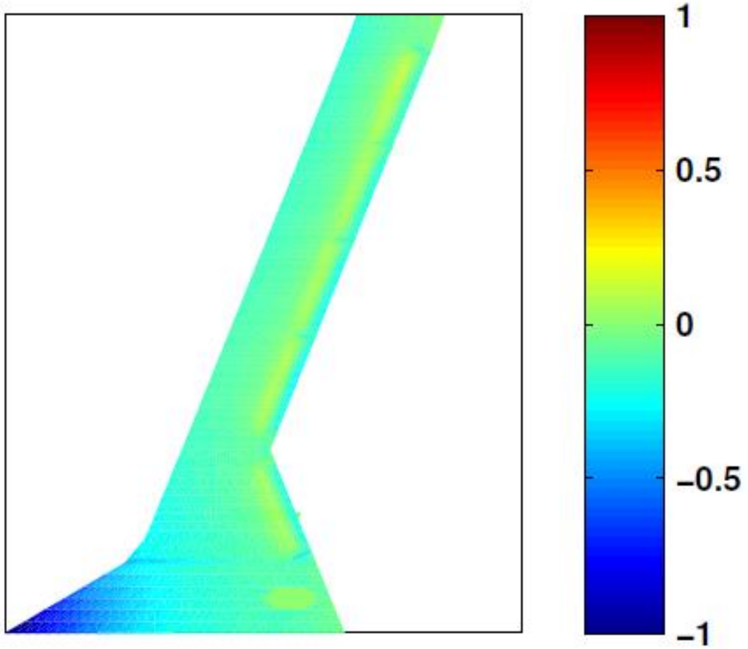
- They are very problematic
- Primary issue is selection of parameters

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

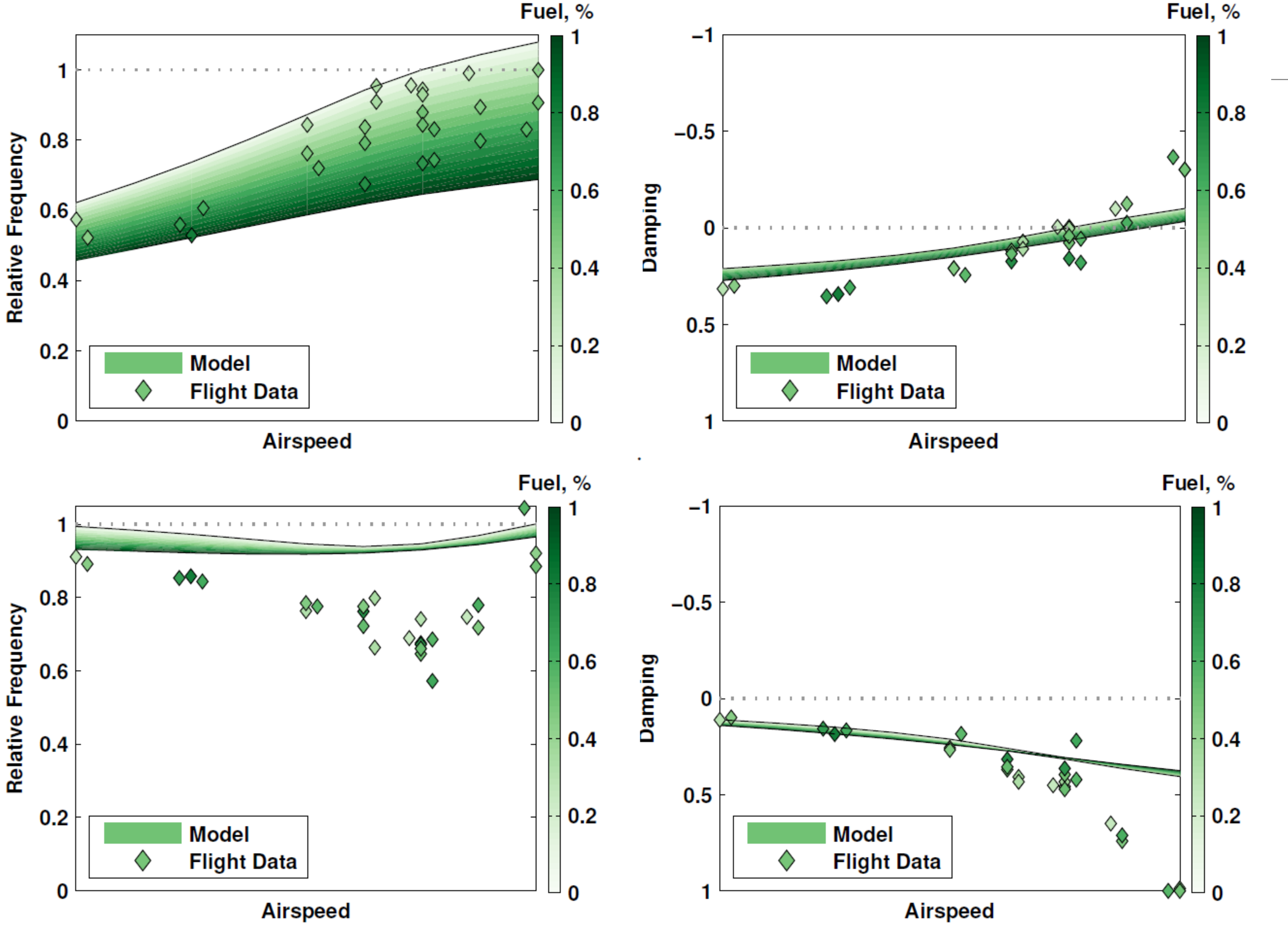
Nonparametric Frequency Responses

- 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