Aeroservoelastic Modeling of Body Freedom Flutter for Control System Design

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Increasing Aspect Ratio

- Improves aerodynamic performance
- Increased flexibility
  - Reduces aeroelastic margin
  - Significant weight penalty to maintain margin
- Greater interaction with the flight dynamics

Active Flutter Suppression

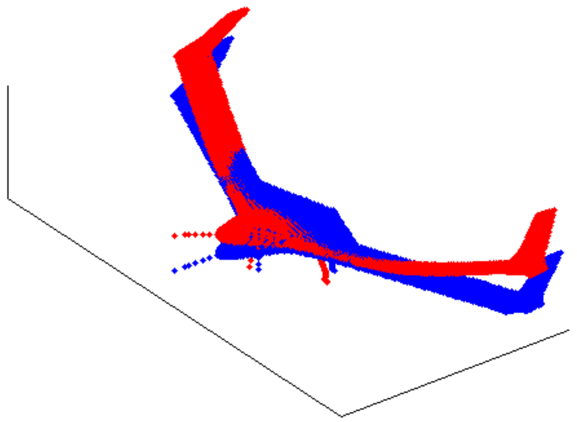
- Use flight controls to maintain stability
  - Does not have a weight penalty
- Past efforts have had mixed results
  - B-52 successfully suppress flutter 1973
  - DAST was unsuccessful
- Body freedom flutter
  - Structural dynamics destabilize flight dynamics

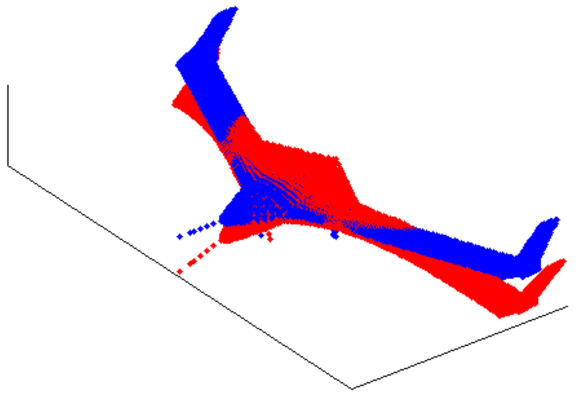
Then and Now

- Found several issues with existing modeling approaches
- Development to date
  - Keep trying to patch issues
  - Inconsistencies between disciplines
    - Coordinate systems
    - Definition of parameters
    - Etc.
- Building upon previous approaches
  - Intentionally similar to existing approaches
  - Addressing inconsistencies between disciplines

The Problem: State Consistency

- Models generally made for specific mass/flight condition
- Full envelope design
  - What happens between these conditions?
- No sign convention in mode shapes
  - The direction of the mode shapes can change
- New modes can appear with masses
- Ordering of the modes can change
  - Finite element models sort by frequency

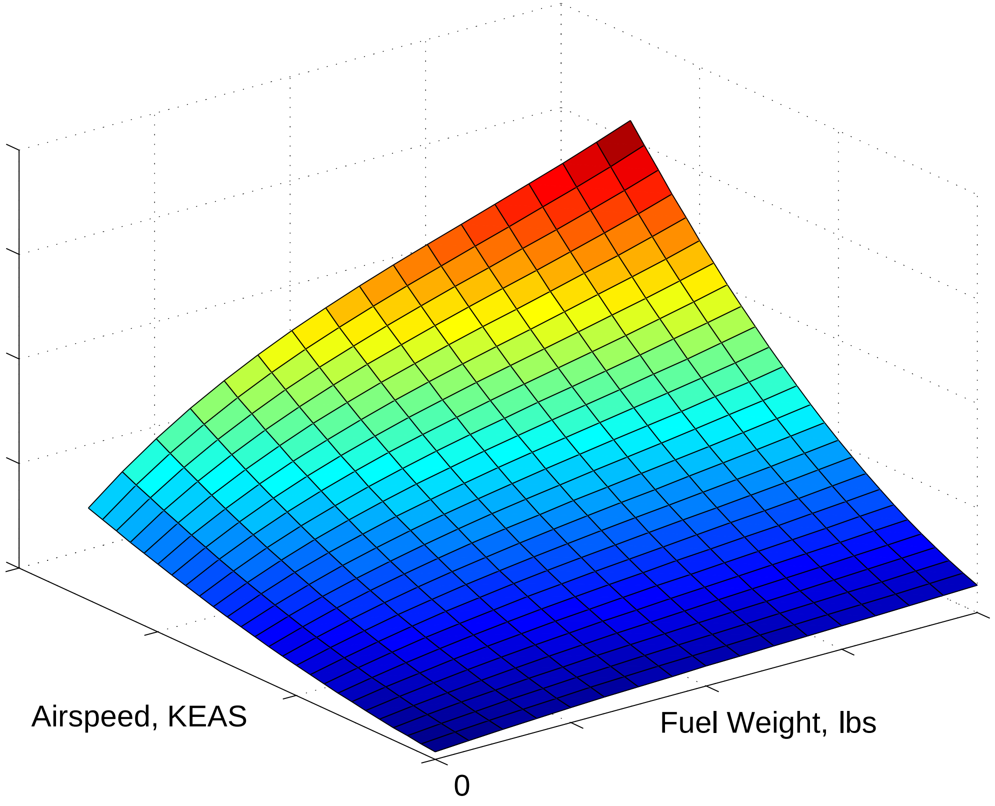




Previous methods: State Consistency

- Often simply ignored
  - Does not appear on simpler configurations
  - Can be bypassed by specific control architectures
- Corrective transformations
  - Applied to final models
  - Often not robust
  - Are there equivalent states?

Consistent Coefficient



The Solution: Assumed Modes

- Using an assumed mode method
  - The same mode shapes are used for all conditions
  - Changes are in modal mass and stiffness matrices
    - To match kinetic and potential (strain) energy
  - Aerodynamic coefficients are constant
- Assumed modes method is quite old
  - Using for state consistency is new
- Which mode shapes to use?
  - Are there sufficient mode shapes?
  - Are all of the modes represented?
- This is an issue with any method

The Problem:
Low frequency Dynamics

- Why do we care?
  - Static Instabilities
    - Short-period frequency is reduced
    - Very strong coupling with the phugoid
  - Often less control margin
    - MIL-STD-9490 below 0.06 Hz
    - Requires 4.5 dB gain margin
    - Requires 30 deg phase margin
- Do not want separate models for these dynamics

- What are the primary effects?
  - Phugoid mode
    - Dominates low frequency behavior
    - Transfer of energy
      - Kinetic energy
      - Potential energy (gravity)
  - Large velocity variations
    - Flutter methods assume constant velocity

Previous method: Apply rigid body model

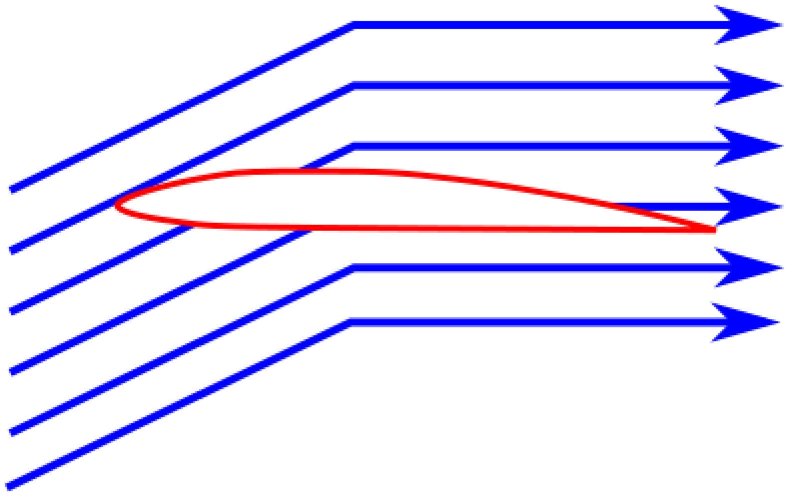
- Velocity Variations
  - Forces change due to changes in dynamic pressure
    - $\frac{\partial}{\partial V}\bar{q} = 2\frac{\bar{q}}{V}$
  - Applying 6DoF coefficients neglects change in force on the structure
  - $A_{1_{aug}} = S\begin{bmatrix} -2C_{D_0} & 0 & C_{L_0} & 0 & \cdots & 0 \\ -2C_{L_0} & 0 & -C_{D_0} & 0 & \cdots & 0 \\ 2\bar{c}C_{D_0} & 0 & 0 & 0 & \cdots & 0 \\ 2C_{\eta 1_0} & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 2C_{\eta 1_0} & 0 & 0 & 0 & \cdots & 0 \end{bmatrix}$
- Gravity
  - Can use 6 DoF results
    - If origin is at the center of gravity
  - Assumed modes complicates this
    - Mass matrix is not diagonal
    - Center of gravity moves with structural deformations

The Solution: Gravitational Forces

- Using the complete mass matrix from the finite element model
  - Modal mass is not diagonal
    - Due to assumed modes method
- For each element
  - $\boldsymbol{F}_{gravity} = m_{element}\, g(\hat{\boldsymbol{z}} + \boldsymbol{T}(\alpha_0)\boldsymbol{\theta}_{element})$
    - $\hat{\boldsymbol{z}}$: Vertical vector
    - $\boldsymbol{T}(\alpha_0)$: Rotation matrix from trim angle
    - $\boldsymbol{\theta}_{element}$: Rotation of element from mode shape

The Problem: Unsteady Aerodynamics

- The structural motions are high frequency
  - On the order of the dynamics of the flow
  - Significant delays in the response
  - Need to model the flow dynamics
- Frequency domain aeroelasticity tools
  - Considering harmonic motions simplifies the dynamics
  - Time histories are required for evaluating closed loop performance
  - No closed form solution from frequency response to time history



Previous method: Rational Function Approximation

- Rogers Rational Function Approximation
  - $\{\boldsymbol{q}\} \approx (\boldsymbol{A}_0 + \boldsymbol{A}_1 ik + \boldsymbol{A}_2 k^2 + \boldsymbol{D}(ik\boldsymbol{I} - \boldsymbol{R})^{-1}\boldsymbol{E}ik)\boldsymbol{\eta}$
  - Has been used many times (40+ years old)
  - Developed with weak interactions between flight dynamics and aeroelasticity
  - Uses a modal coordinate system
    - Inertial coordinate system (origin is fixed in space)
    - Does not work for flight mechanics
      - Origin must move with the aircraft

Previous method: Time domain transformation

- Transformation
  - Applied to final model
  - Equivalent to
    - $\boldsymbol{A}_0^* = \boldsymbol{A}_0 \boldsymbol{T}_{\eta 2x} + \boldsymbol{A}_1 \boldsymbol{T}_{\dot{\eta} 2x}$
    - $\boldsymbol{A}_1^* = \boldsymbol{A}_1 \boldsymbol{T}_{\dot{\eta} 2u} + \boldsymbol{A}_2 \boldsymbol{T}_{\dot{\eta} 2x} \boldsymbol{T}_{\eta 2x}^{-1} \boldsymbol{T}_{\dot{\eta} 2u}$
    - $\boldsymbol{A}_2^* = \boldsymbol{A}_2 \boldsymbol{T}_{\dot{\eta} 2u}$
  - Results in erroneous coefficients
    - Vehicle heading does not effect aerodynamic forces
    - Issues are emphasized in model reduction
    - Removing increases the error in the RFA

The Solution: Frequency domain Transformation

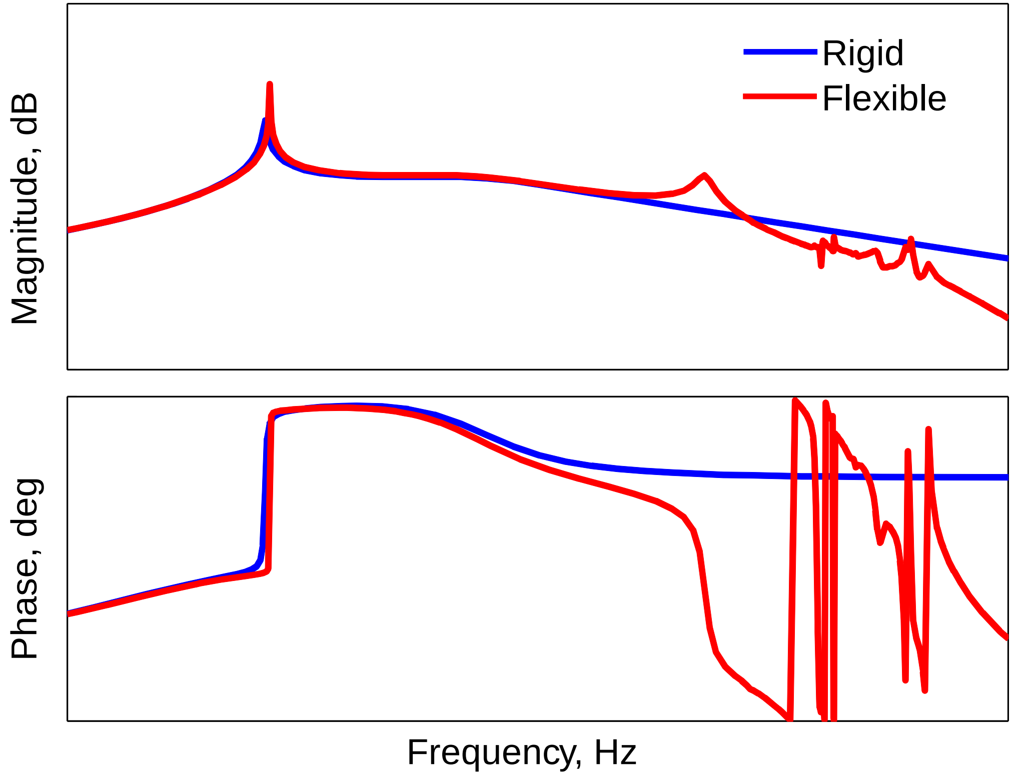
- Apply transformation directly to frequency domain aerodynamics
  - $\begin{Bmatrix} ik\boldsymbol{\eta} \\ \boldsymbol{\eta} \end{Bmatrix} = \begin{bmatrix} \boldsymbol{T}_{\dot{\eta}2u} & \boldsymbol{T}_{\dot{\eta}2x} \\ 0 & \boldsymbol{T}_{\eta 2x} \end{bmatrix} \begin{Bmatrix} \boldsymbol{u} \\ \boldsymbol{x} \end{Bmatrix}$
- Stability Axis RFA
  - $\{\boldsymbol{q}\} \approx \boldsymbol{A}_0\boldsymbol{x} + (\boldsymbol{A}_1 + \boldsymbol{A}_2 ik + \boldsymbol{D}(ik\boldsymbol{I} - \boldsymbol{R})^{-1}\boldsymbol{E})\boldsymbol{u}$
  - Separate positions ($\boldsymbol{x}$) and velocities ($\boldsymbol{u}$)
  - Euler angles appear only in $\boldsymbol{A}_0$
    - Only need to constrain single matrix
    - Curve fit remains minimum error solution

Applying the method: X-56A MUTT

- Designed for testing active flutter suppression
  - Flexible wings have unstable flutter modes
- Currently have stiff wing data
  - No unstable flutter modes
- Using frequency domain potential flow aerodynamics

Results

Comparing to rigid models

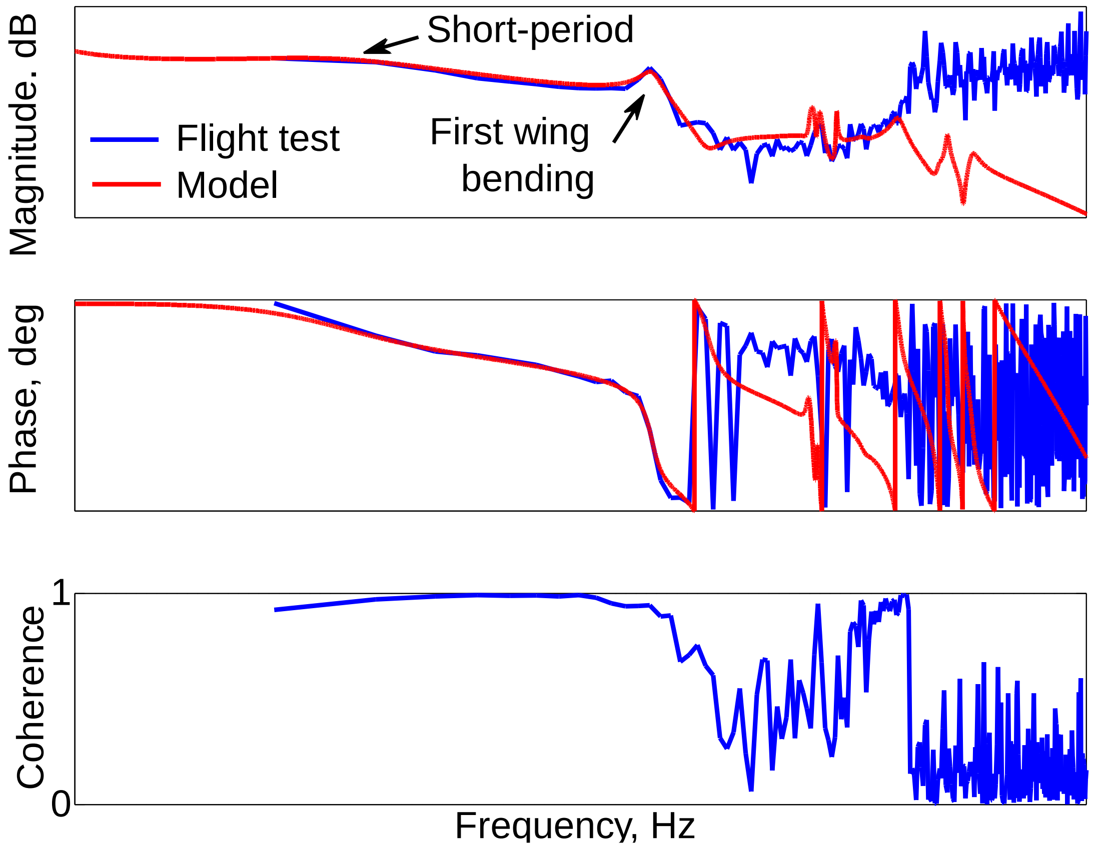


Comparing to flight data

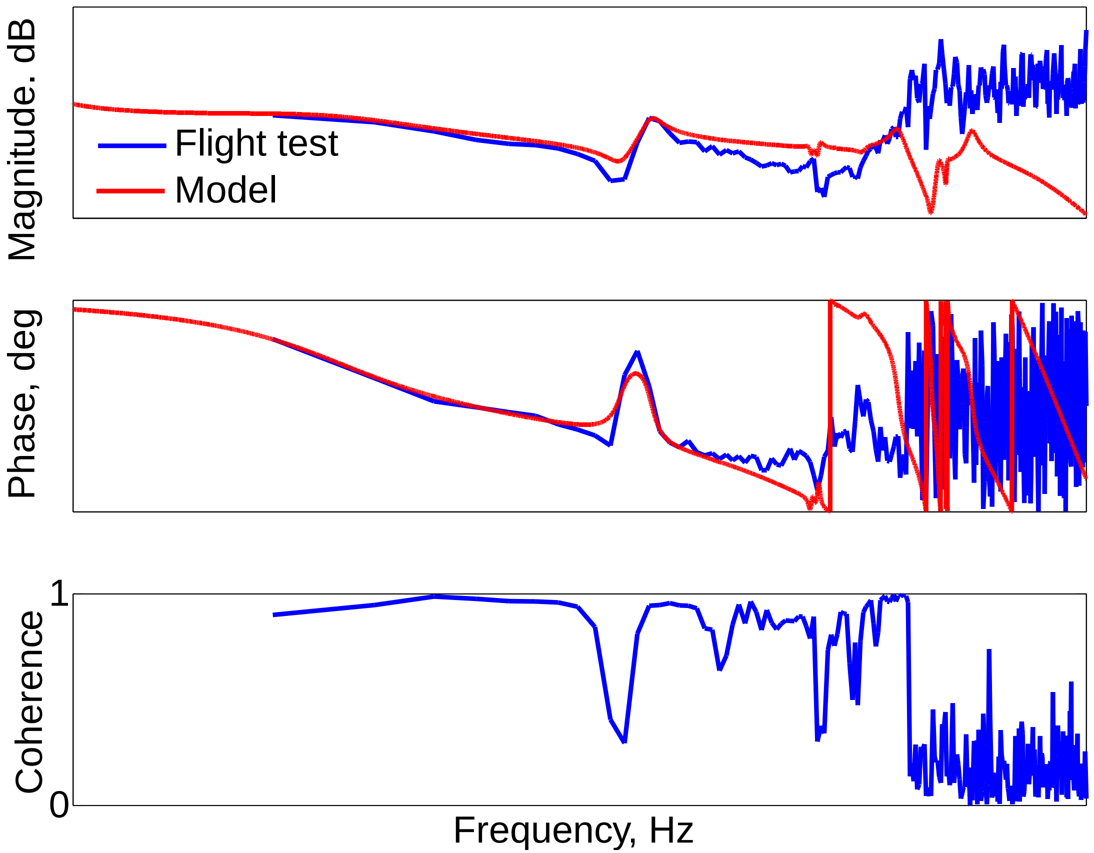
Test Case	Fuel Mass	Airspeed	Input
1	Low	Low	Pitch
2	High	Low	Pitch
3	**Low**	**High**	**Pitch**
4	**Low**	**High**	**Roll**

Flight Data Comparison:
Pitch response, low fuel, low speed

Pitch Rate

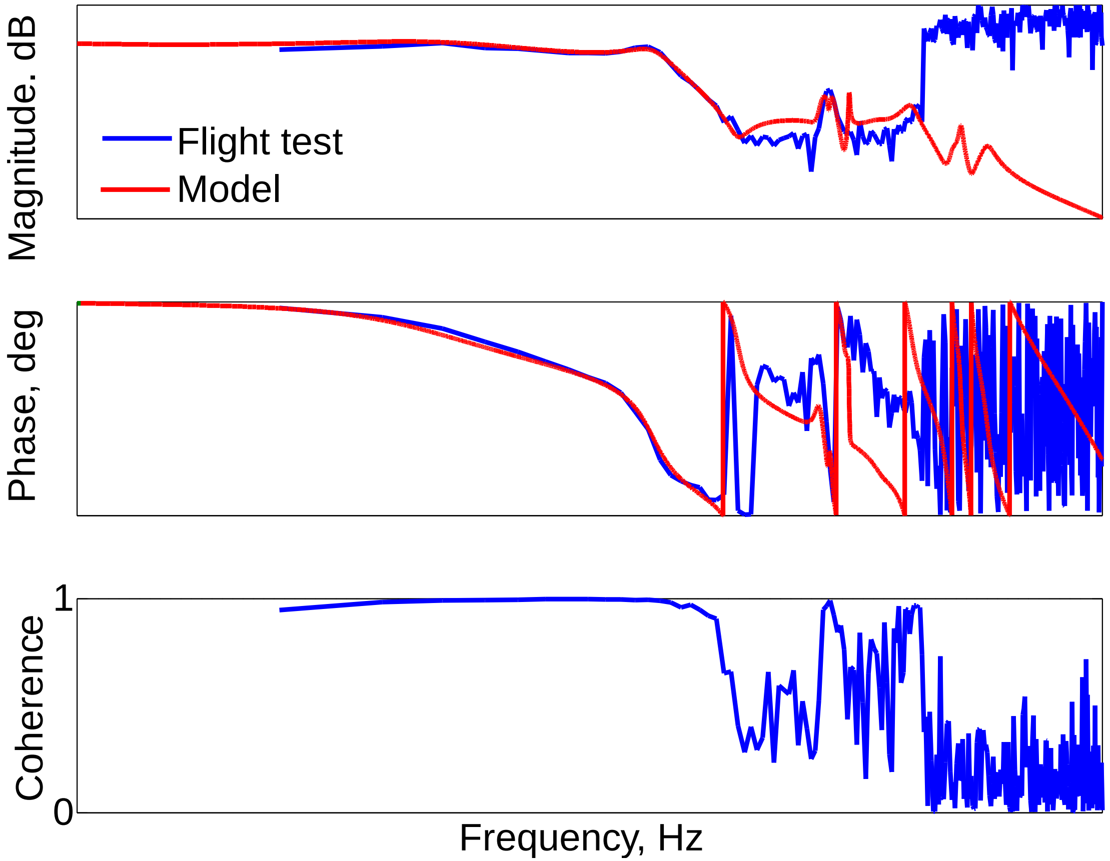


Wing Tip Accelerometer

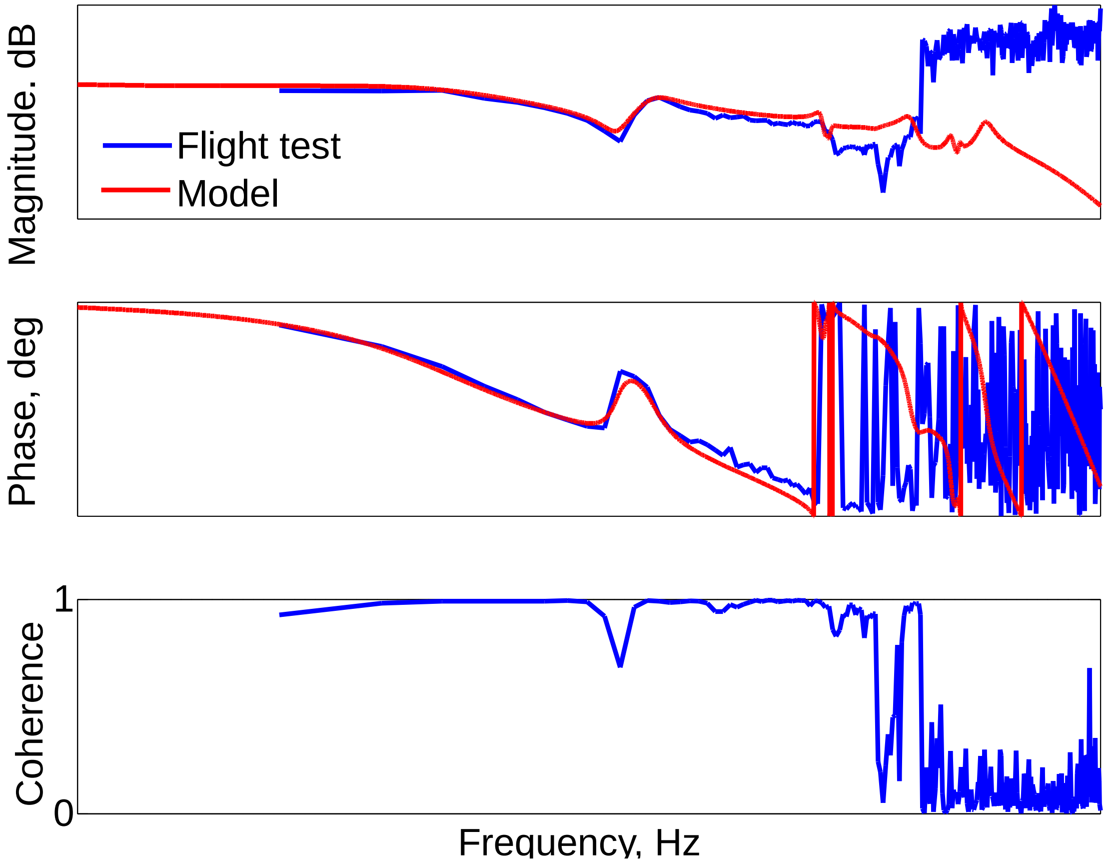


Flight Data Comparison: Pitch response, low fuel, high speed

Pitch Rate

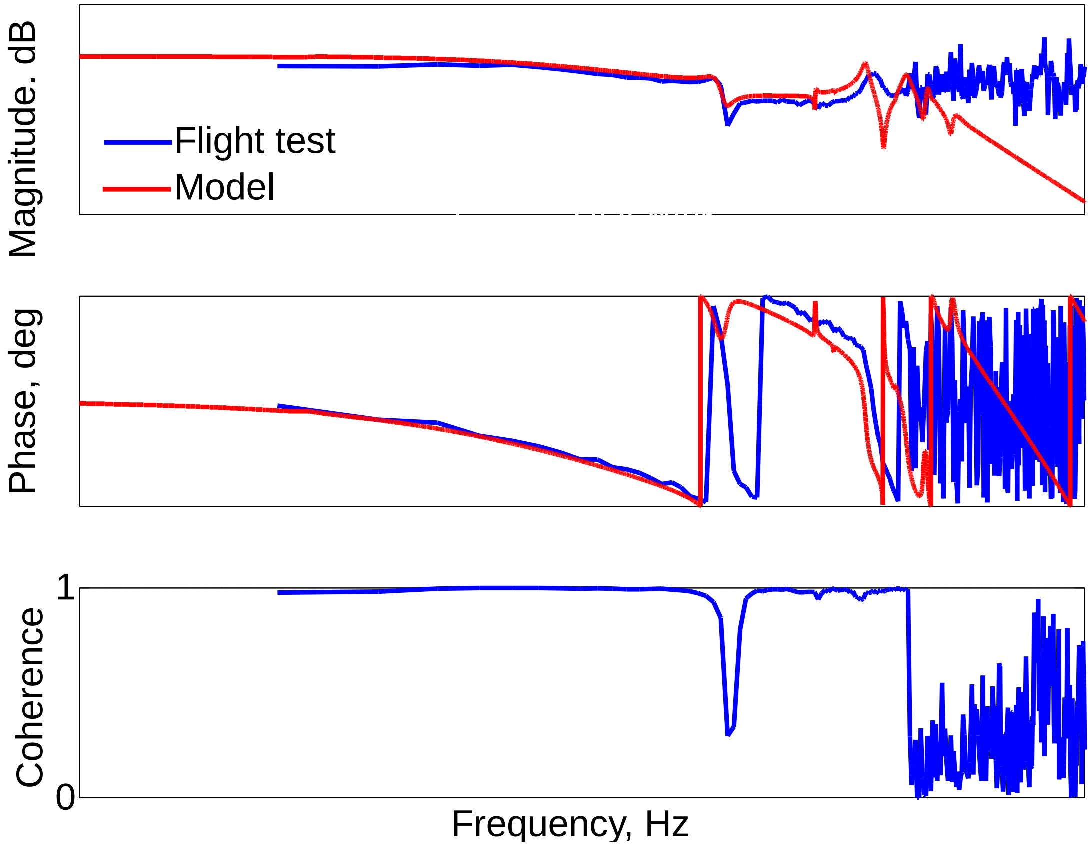


Wing Tip Accelerometer

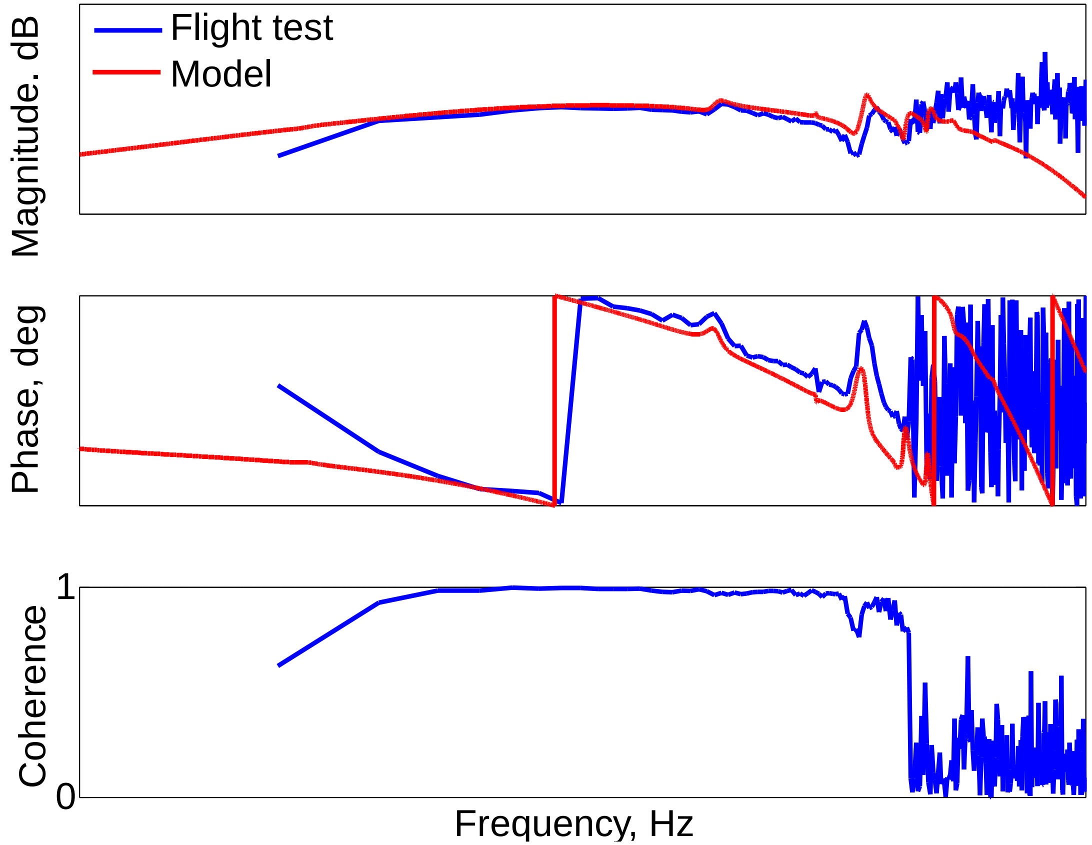


Flight Data Comparison:
Roll Response, low fuel, high speed

Roll Rate



Wing Tip Accelerometer



Conclusions

- Model generation for body freedom flutter
- Addressing issues in:
  - State Consistency
  - Low frequency dynamics
  - Unsteady aerodynamics
- Applied approach to X-56A MUTT
  - Comparing to flight test data