Aeroservoelastic Modeling of Body Freedom Flutter for Control System Design

JEFFREY OUELLETTE

NASA ARMSTRONG FLIGHT RESEARCH CENTER

AEROSPACE CONTROL AND GUIDANCE SYSTEMS COMMITTEE MEETING #119

MARCH 29-31, 2017

Increasing Aspect Ratio

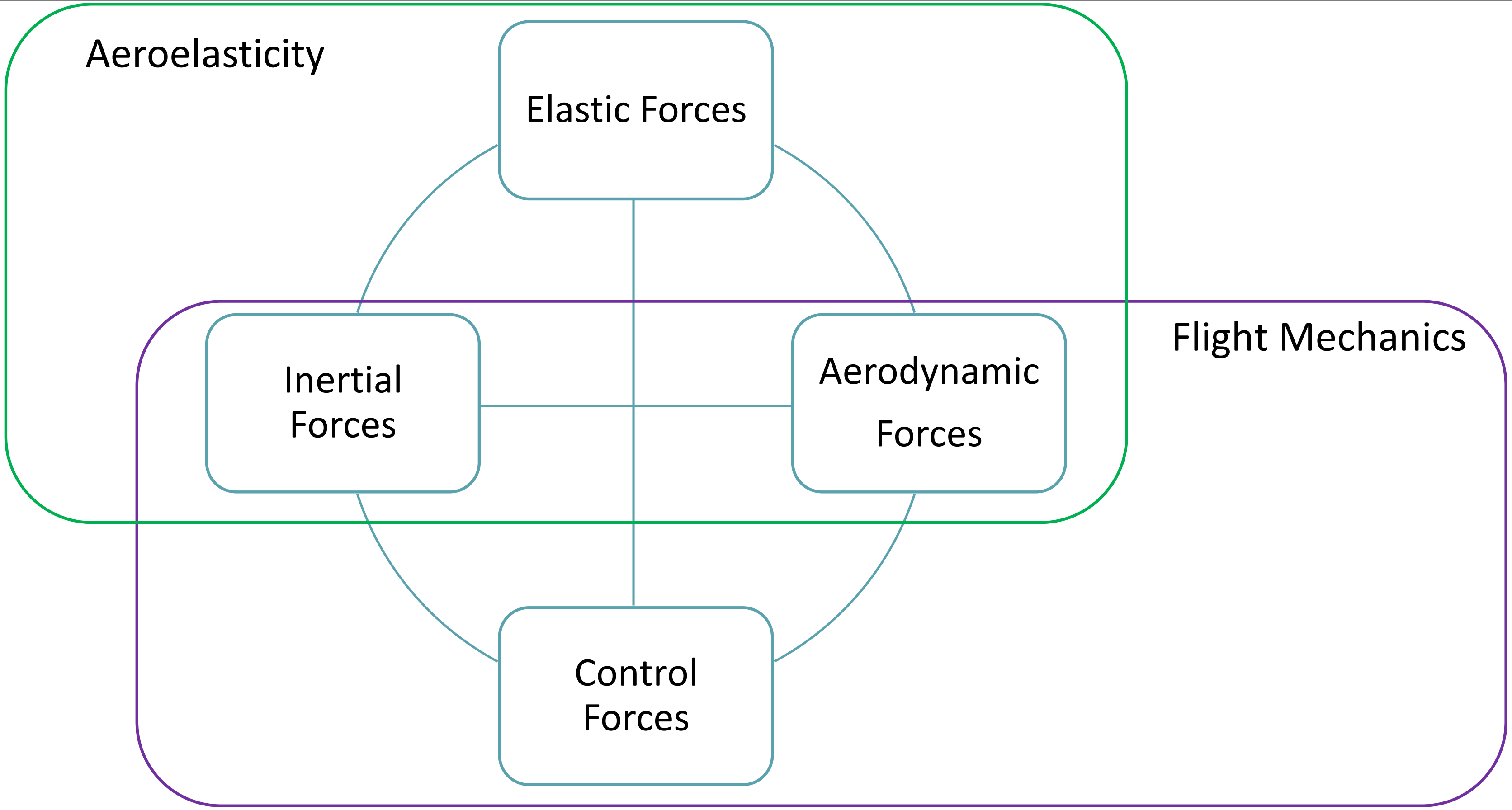
Improves aerodynamic performance

Increased flexibility

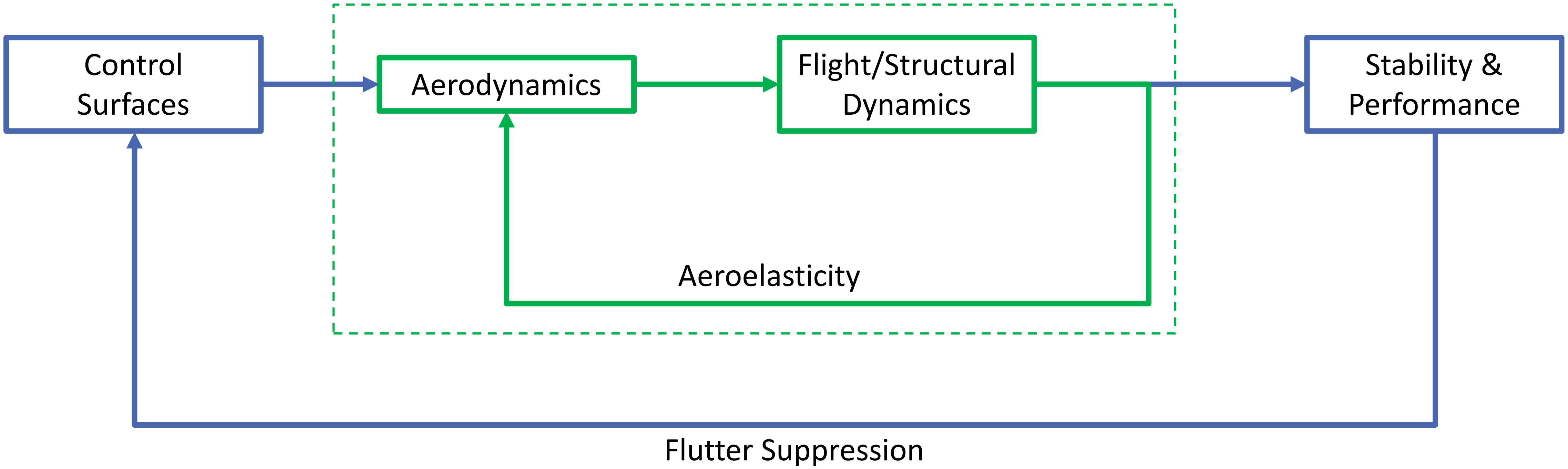
- Reduces aeroelastic margin
- Significant weight penalty to maintain margin

Greater interaction with the flight dynamics

Aeroservoelasticity



Aeroelasticity as a closed loop



Active Flutter Suppression

Use flight controls to maintain stability

- Does not have a weight penalty

Past efforts have had mixed results

- B-52 successfully suppressed flutter 1973
- DAST was unsuccessful, circa 1980
- See AIAA 2017-1119, by Eli Livne

Body freedom flutter

- Structural dynamics destabilize flight dynamics

Multi-Utility Technology Testbed X-56A MUTT

Designed for testing active flutter suppression

- Flexible wings have unstable flutter modes
- AFRL Funded
- Lockheed Martin Build

For developing technologies

Modeling Philosophy
How does MUTT translate to N+3?

Definition of model interfaces

- Discipline models will change
  - Origin of the parameters
  - Form of the equations
- The interfaces change less
  - Inputs and outputs are very common

Physics Based Modeling

- Predictive capability of the models
- How do the physics define the interface
- How do we model before flight test

Verifiable

- Keep complexity in check

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

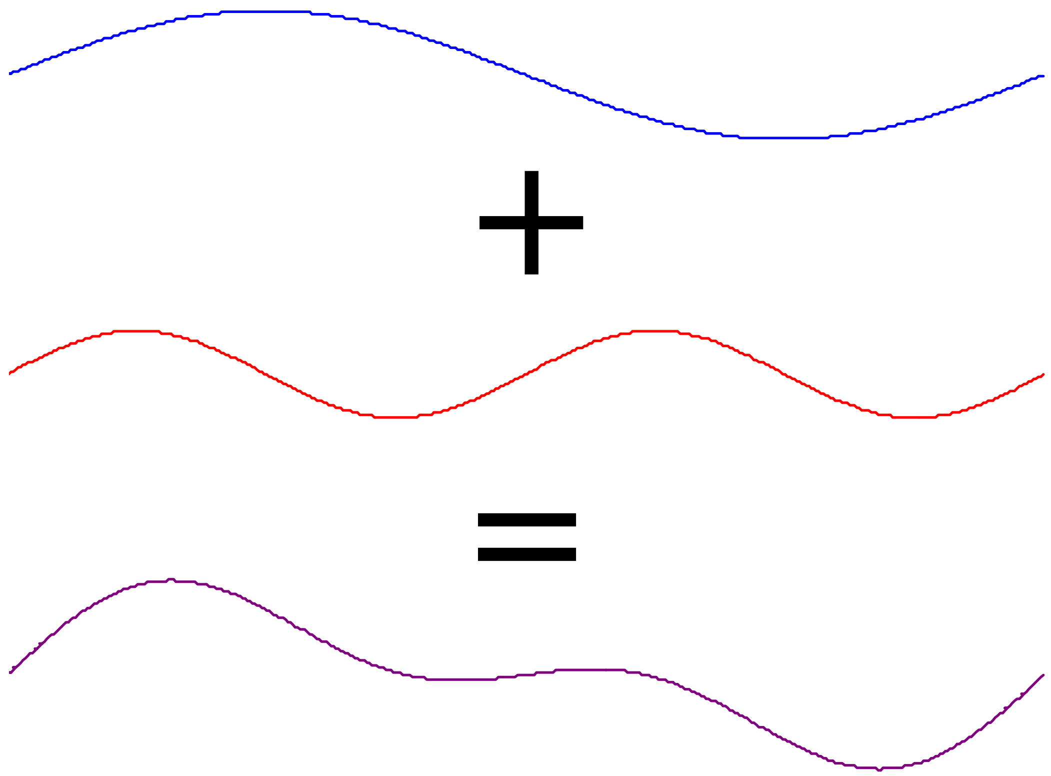
- Intentionally similar to existing approaches
- Addressing inconsistencies between disciplines

Structural (Modal) States

Deformed shape is combination of mode shapes
- What shapes do we use?

Orthonormal Modes
- Standard in structural analysis
- Modes do not exchange energy
  - No inertial coupling
  - No elastic coupling
- Aerodynamics add

Mean Axis
- Used for integration of nonlinear flight dynamics
- No inertial coupling between rigid body and flexible modes
  - Orthonormal modes are sufficient, but not necessary



The Problem: State Consistency

Models generally made for specific mass/flight condition

Full envelope design

- What happens between these conditions?

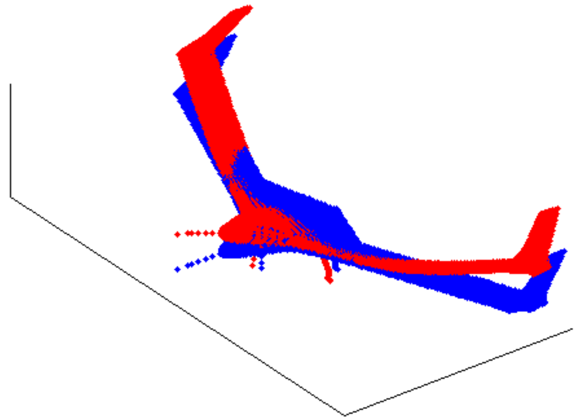
No sign convention in mode shapes

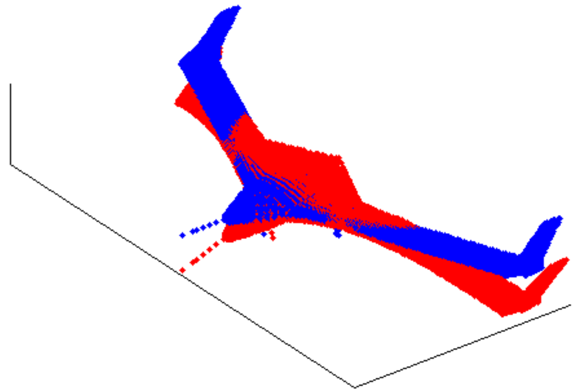
- The direction of the mode shapes can change

New modes can appear with masses

Ordering of the modes can change

- Finite element models sort by frequency





Previous methods: State Consistency

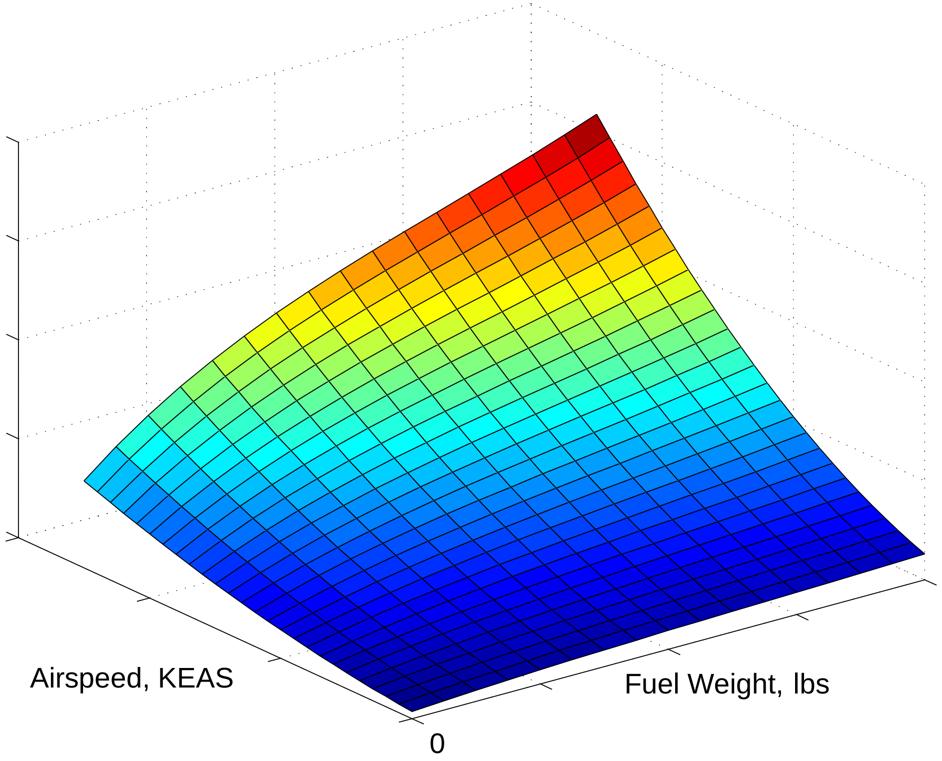
Often simply ignored

- 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

Assumed Modes: Other Benefits

Uncertainty

- There is no uncertainty in the mode shape
- Uncertainty is captured in other physical parameters

Structural Nonlinearities

- Can generate parameter varying model
- Only mass and stiffness matrices change

Constant Aerodynamic Coefficients

- Structural properties don't effect the behavior of the airflow
- Aerodynamic coefficients do not change with structural properties

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

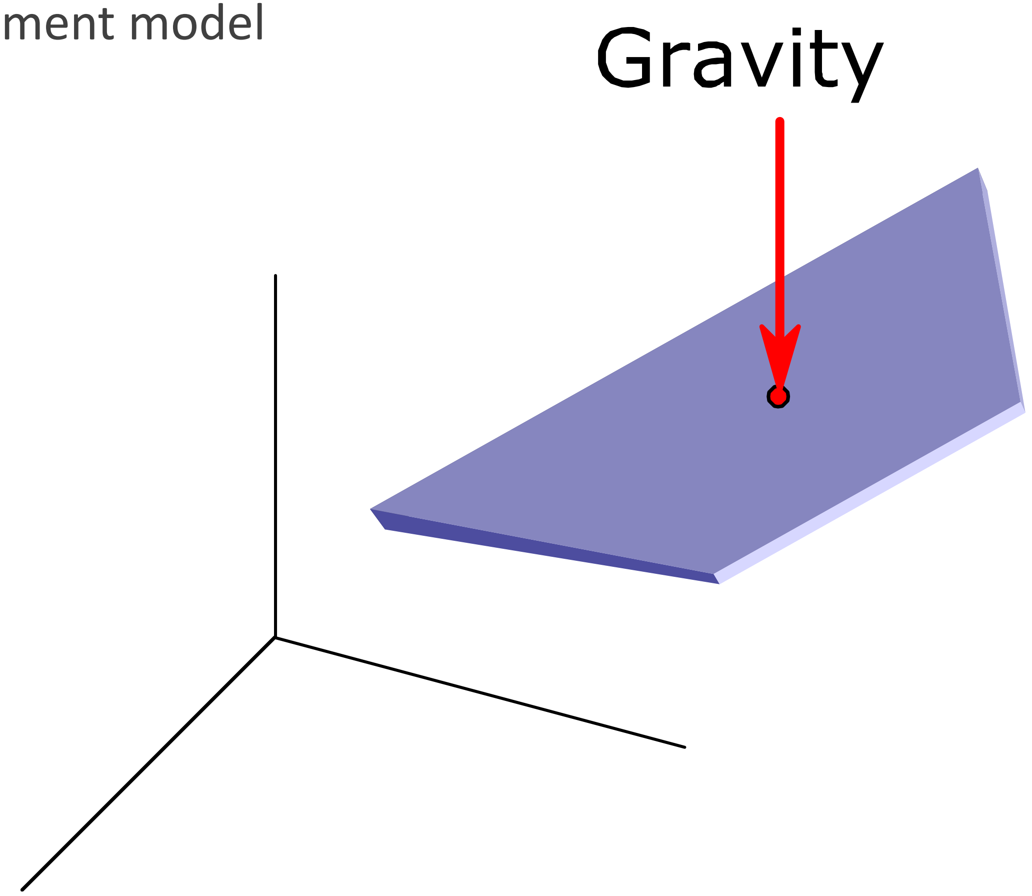
The Solution: Gravitational Forces

Using the complete mass matrix from the finite element model

- Modal mass is not diagonal
  - Due to assumed modes method

For each element

- $\boldsymbol{F}_{gravity} = m_{element}\, g(\hat{\mathbf{z}} + \boldsymbol{T}(\alpha_0)\boldsymbol{\theta}_{element})$
  - $\hat{\mathbf{z}}$: Vertical vector
  - $\boldsymbol{T}(\alpha_0)$: Rotation matrix from trim angle
  - $\boldsymbol{\theta}_{element}$: Rotation of element from mode shape



The Problem: Unsteady Aerodynamics

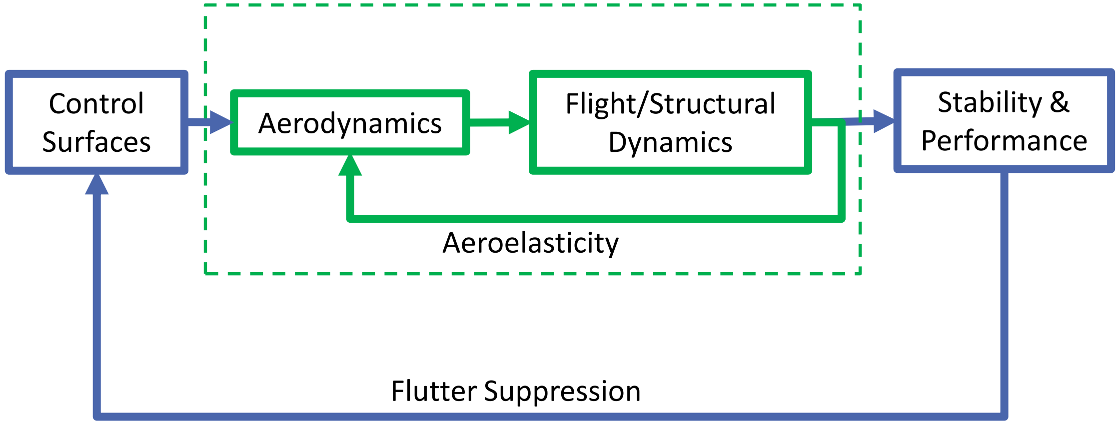
Flight dynamics

- Low frequency
- Aerodynamics are algebraic
  - Depend only on the current state

Structural Dynamics

- High frequency
  - On the order of the dynamics of the flow
- Significant delays in the response

Need to model the flow dynamics



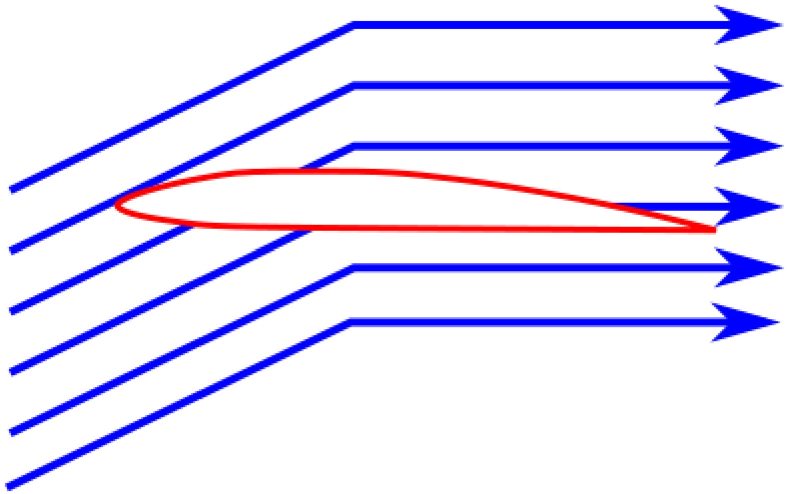
The Problem: Unsteady Aerodynamics

Time scales

- Wide range required
  - Very long for phugoid
  - Very short for structural dynamics
- Increases computational cost

Frequency domain aeroelasticity tools

- Considering harmonic motions simplifies the dynamics
- No closed form solution from frequency response to time history
- Time histories are required for evaluating closed loop performance



Previous method: Rational Function Approximation

Rogers Rational Function Approximation

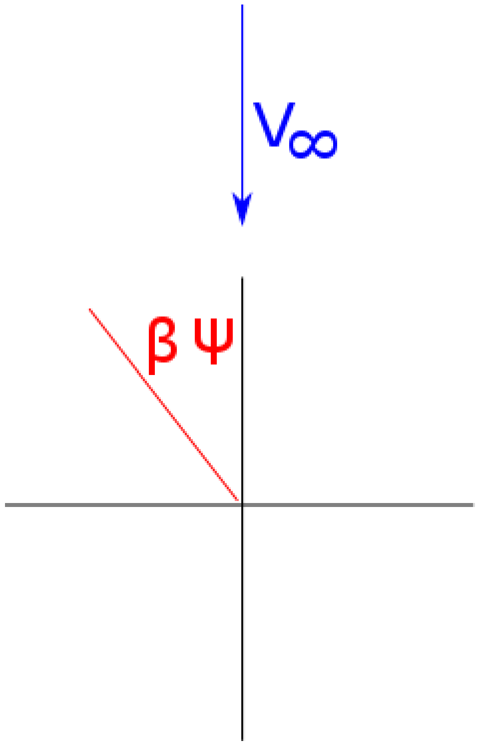
- $\{\boldsymbol{q}\} \approx (\boldsymbol{A}_0 + \boldsymbol{A}_1 ik + \boldsymbol{A}_2 k^2 + \boldsymbol{D}(ik\boldsymbol{I} - \boldsymbol{R})^{-1}\boldsymbol{E}ik)\boldsymbol{\eta}$
- Has been used many times (40+ years old)
- Developed with weak interactions between flight dynamics and aeroelasticity
- 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

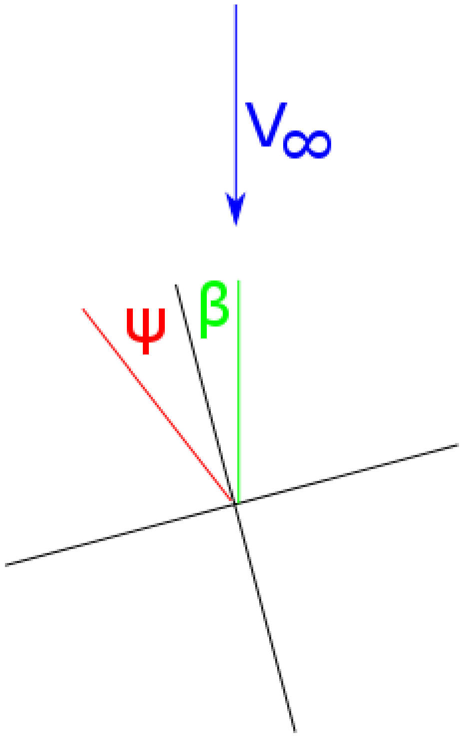
Transformation

- Applied to final model
- Equivalent to
  - $A_0^* = A_0 T_{\eta 2x} + A_1 T_{\dot{\eta} 2x}$
  - $A_1^* = A_1 T_{\dot{\eta} 2u} + A_2 T_{\dot{\eta} 2x} T_{\eta 2x}^{-1} T_{\dot{\eta} 2u}$
  - $A_2^* = A_2 T_{\dot{\eta} 2u}$
- Results in erroneous coefficients
  - Vehicle heading does not effect aerodynamic forces
  - Issues are emphasized in model reduction
  - Removing increases the error in the RFA

Steady Modal Axis



Steady Stability Axis



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

Stability Axis RFA: Other Benefits

Model Calibration/Tuning

- Quasi-Steady Model
  - $\boldsymbol{A}_0\boldsymbol{x} + (\boldsymbol{A}_1 - \boldsymbol{D}\boldsymbol{R}^{-1}\boldsymbol{E})\boldsymbol{u}$
- Form identical to classical flight mechanics

Integration with lookup tables

- Set quasi-steady to zero
  - $\boldsymbol{A}_1 = \boldsymbol{D}\boldsymbol{R}^{-1}\boldsymbol{E}$
- Allows non-linear aero tables
  - Unsteady model is increment to tables
  - Does not double count loads
  - Captures unsteadiness
  - Captures rigid-flexible coupling

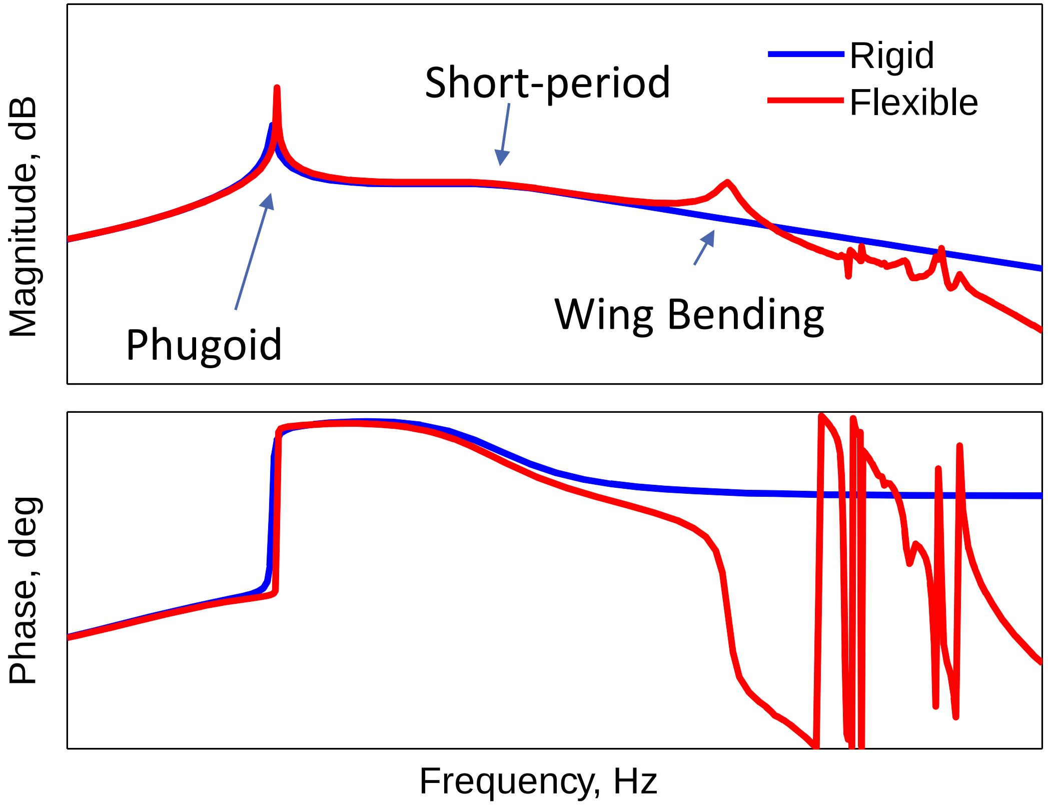
Applying the method: X-56A MUTT

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
- Basic 6-DoF model

Matching the flight dynamics
- Short-period
- Phugoid

Does not capture structural modes

Higher roll-off and phase loss
- Sensors
- Unsteady aero

Structural control
- Requires higher bandwidth controller

Flight Data

INPUTS

Orthogonal Multisines

High Bandwidth

Reduced Surface Rates

Short Maneuvers

Statistical Reputability

TEST POINTS

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

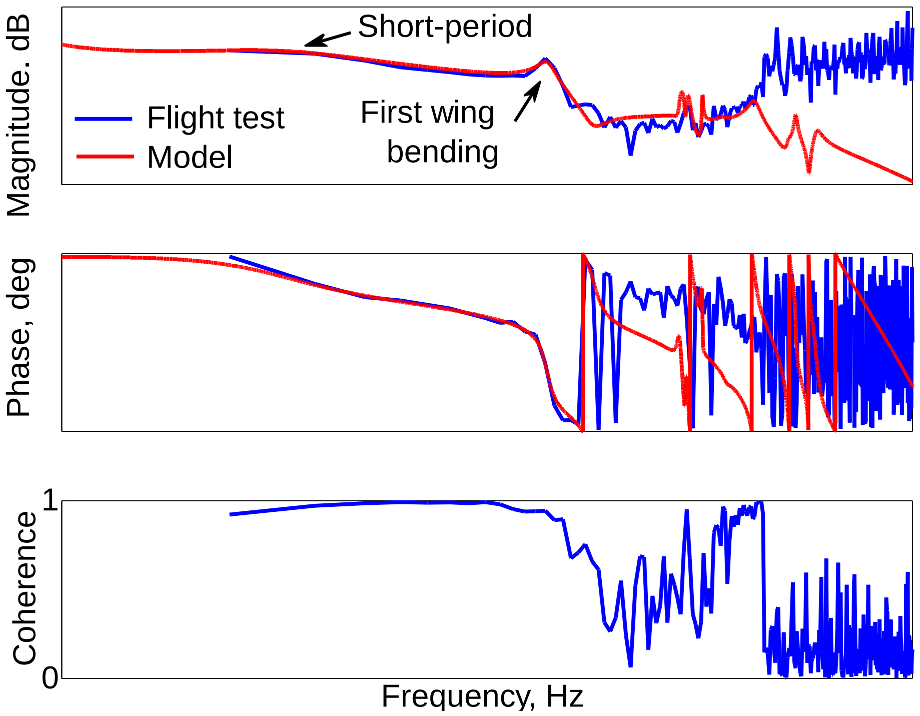
Low fuel emphasize assumed modes

Low speed emphasizes aerodynamic lags

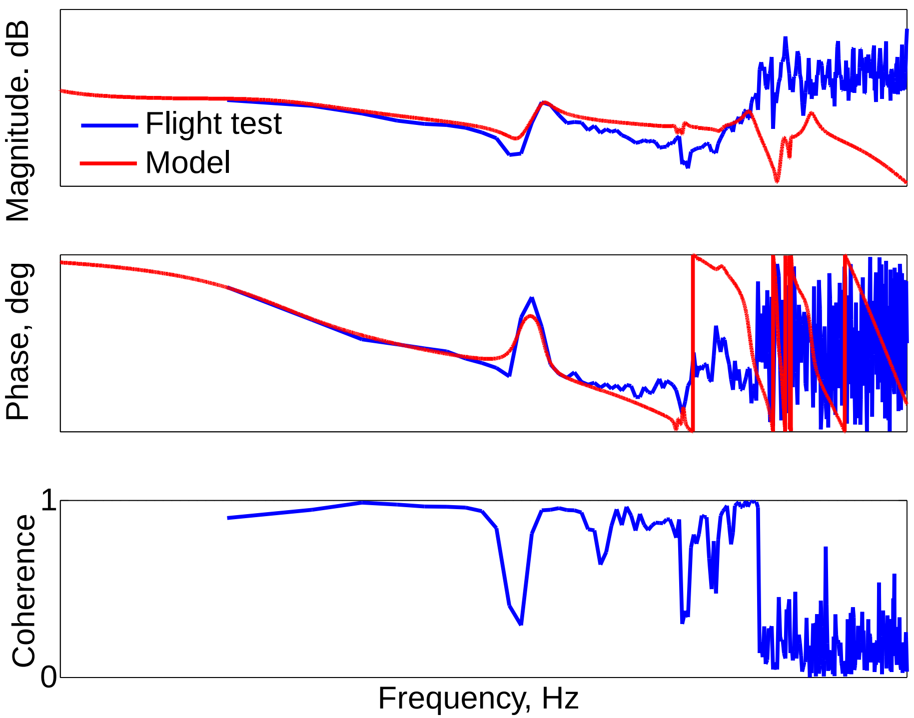
High speed emphasize aerodynamic coupling

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

PITCH RATE

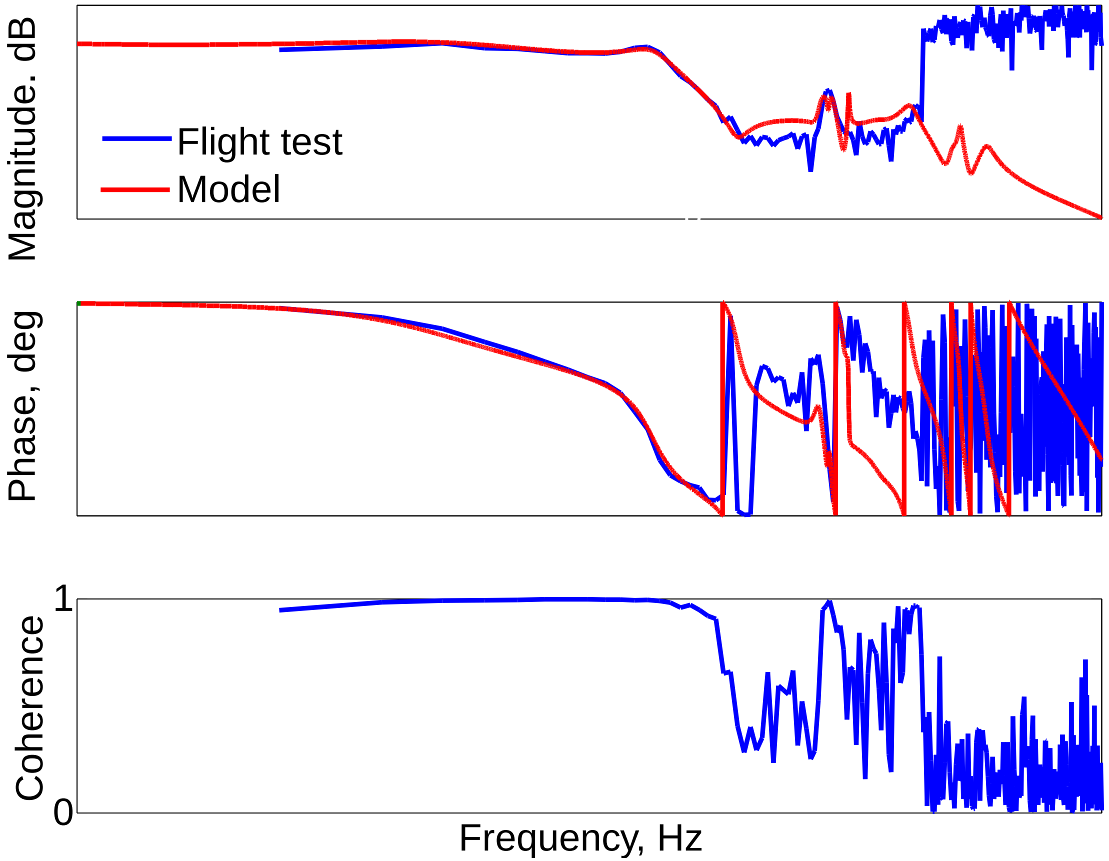


WING TIP ACCELEROMETER

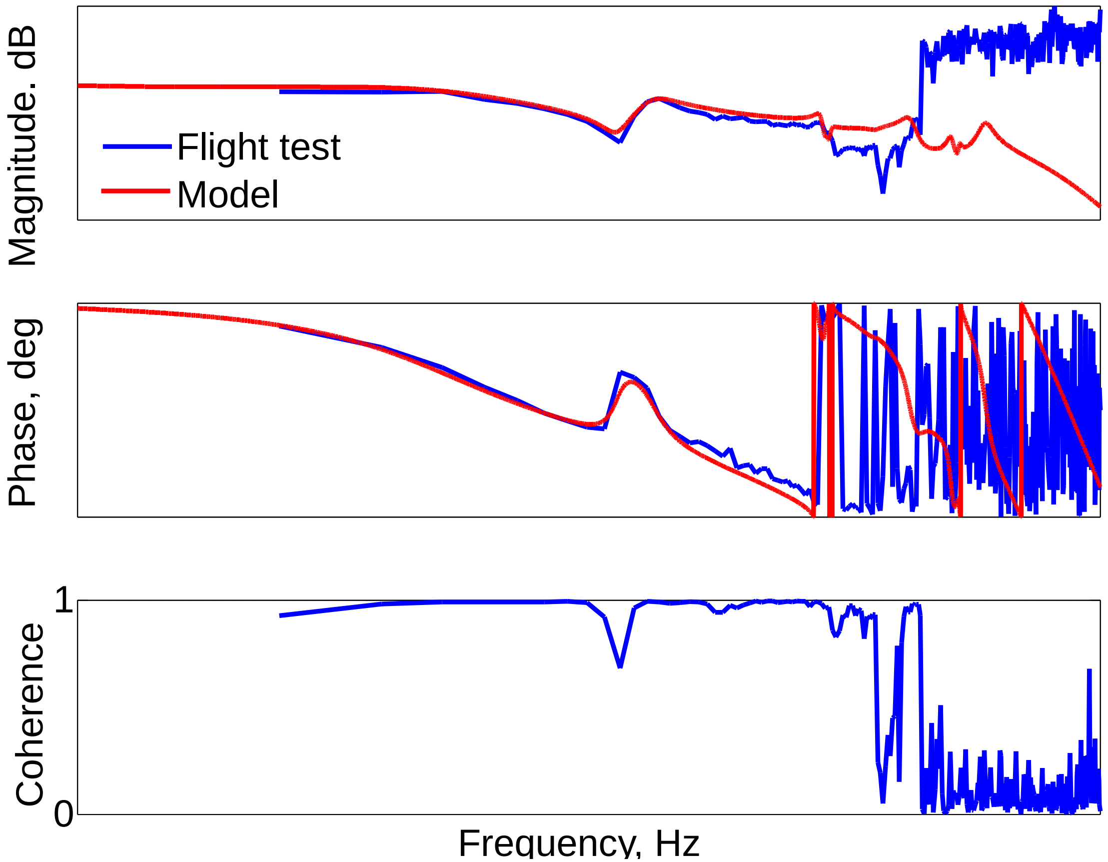


Flight Data Comparison:
Pitch response, low fuel, high speed

PITCH RATE

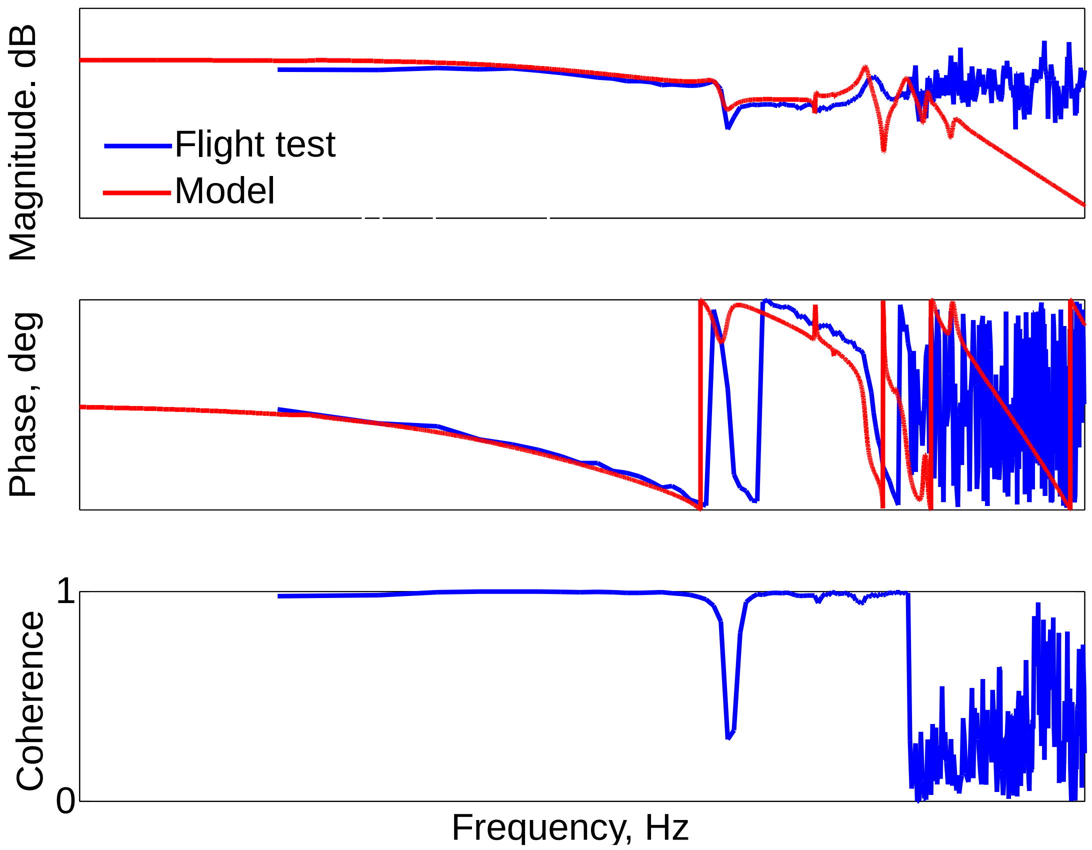


WING TIP ACCELEROMETER

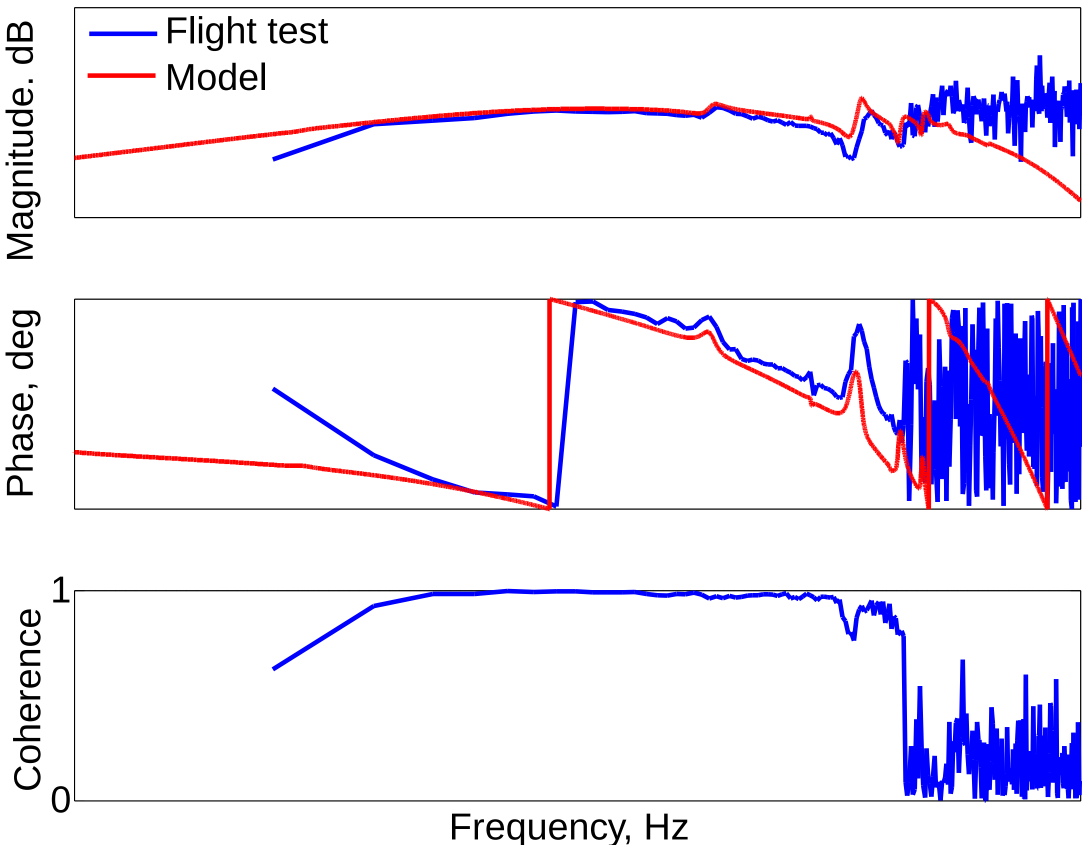


Flight Data Comparison: Roll Response, low fuel, high speed

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

Details in paper AIAA 2017-0019