Flight-Dynamics, Flutter, and Active-Flutter-Suppression Analyses of a Flexible Flying-Wing Research Drone

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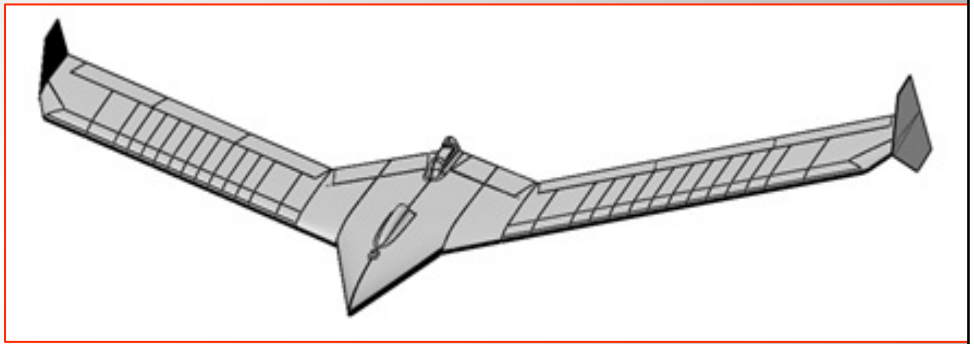

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Edwards AFB, CA

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The Overall Research Project

Lightweight Adaptive Aeroelastic Wing

Funded Under the
NASA AATT Program

The Team

University of Minnesota
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VPI&SU - Rakesh Kapania

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Jeremy Hollman

CM Soft Inc. – Charbel Farhat

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Project Overview

Goal: Actively Optimize Wing Shape - Transport Aircraft

Approach: Use Flexibility to an Advantage, MDAO, active control

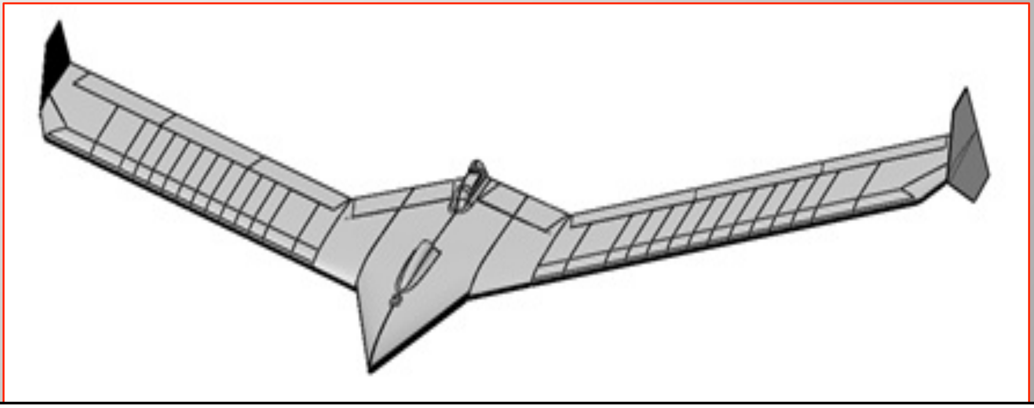
- Active flutter suppression is a key enabling technology
- Critical PAAW program components –

  Three different vehicles will be developed and flight tested

  The first will be very similar to Lockheed Martin's FFAD
  - which is the vehicle being discussed here

Weight	Wing Span
12 lb	10 ft

"Rigid" center body – flex wings



Outline

- Objectives and motivation
- The modeling methodology
- The vehicle's attitude dynamics
  Rigid and Elastic
- Flutter analysis
- Active flutter suppression
- Summary and conclusions

Objectives of this Investigation

- Assess the flutter and flight-dynamics characteristics of FFAD vehicle
- Synthesize integrated SAS/Active Flutter Suppression CLAWS
  (with no a priori knowledge of LM's CLAWS)
- Develop dynamic nDOF model early in design cycle
- Although several modeling approaches will be utilized in project, this task was is to-

  Explore the use of a "Flight-Dynamics" model, as opposed to a more traditional "Flutter" model

  Consider use of beam-element FEM and quasi-steady aero initially
- Feedback and suggestions sought
- NOTE: Longitudinal axis only, so far

"Flutter" vs. "Flight-Dynamics" nDOF Models

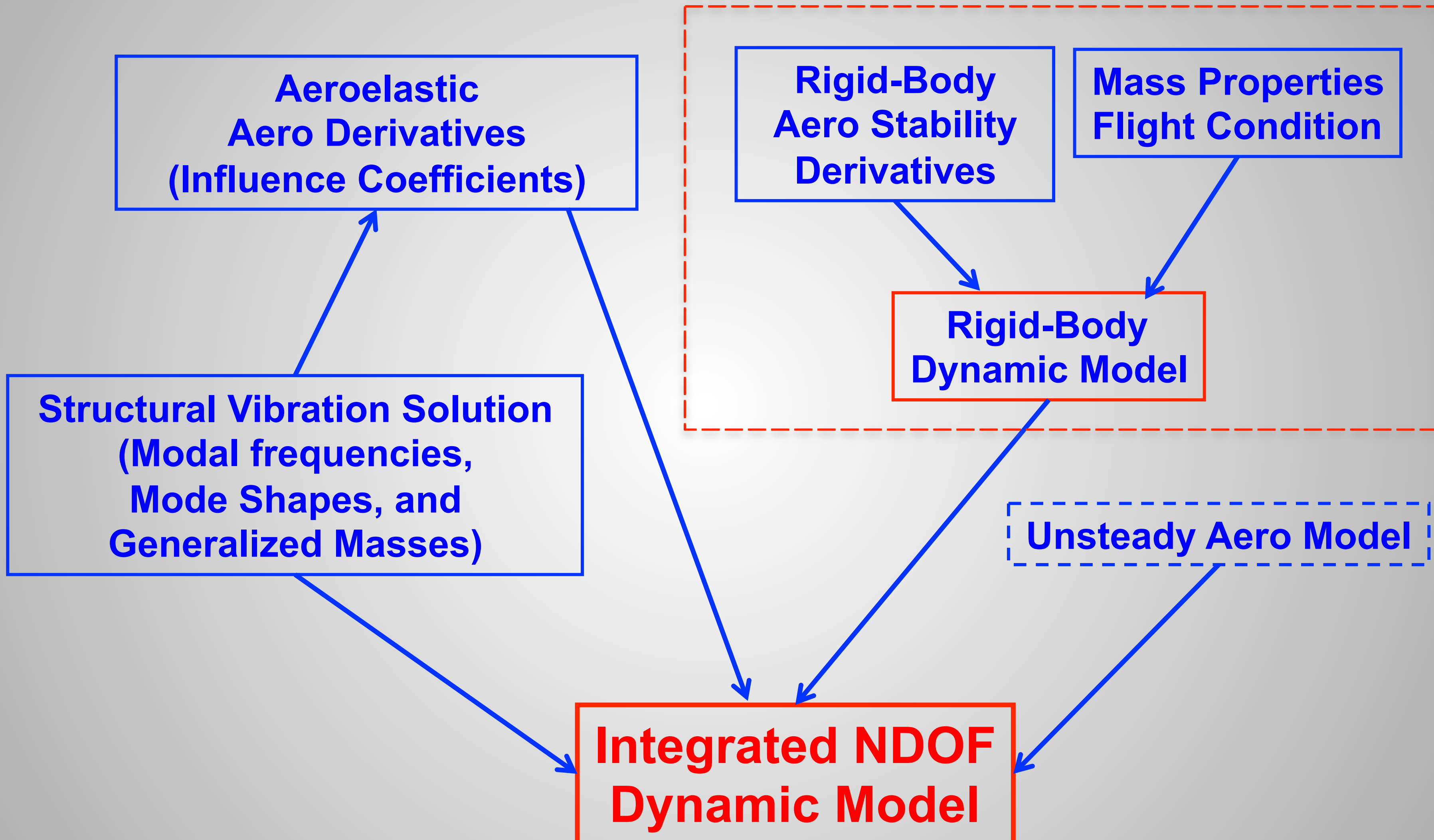
Flutter Based	Flight-Dynamics Based
Expand flutter model (elastic DOFs) to incorporate RB DOFs	Expand flight-dynamics model (RB DOFs) to incorporate elastic DOFs
EOMs in inertial frame	EOMs in vehicle-fixed frame
Linear	Linear (with potential for non-linear RB EOMs)
Familiar to aeroelasticians	Familiar to flight dynamicists

The "Flight-Dynamics" Modeling Formulation

- **Based on mean-axis formulation of Milne (1964)***
- **Mean axes replace the body-fixed axes used for rigid vehicles, as their motion describes the RB motion (DOFs), structure deforms relative to this mean axis**
- **EOMs expressed in "body-fixed" vs inertial axes and expressed in terms of aero coefficients - typical of flight-dynamics models of rigid vehicles.**
- **EOMs derived via Lagrange using method of assumed modes**
- **Uses free-free vibration mode shapes (NASTRAN) for the shape functions, thus satisfying Milne's mean-axis constraints**
- **Various aerodynamic modeling approaches – wind tunnel, slender-wing, VLM, DLM**

- Milne, "Dynamics of the Deformable Airplane," UK Ministry of Aviation, Aero Res Council Rept. 1964.
- Waszak and Schmidt, " Flight Dynamics of Aeroelastic Vehicles," *Journ. of AC*, 25 (6), June, 1988.
- Schmidt, *Modern Flight Dynamics*, McGraw Hill, 2012.

The Modeling Methodology



NDOF Model Structure
Longitudinal Dynamics

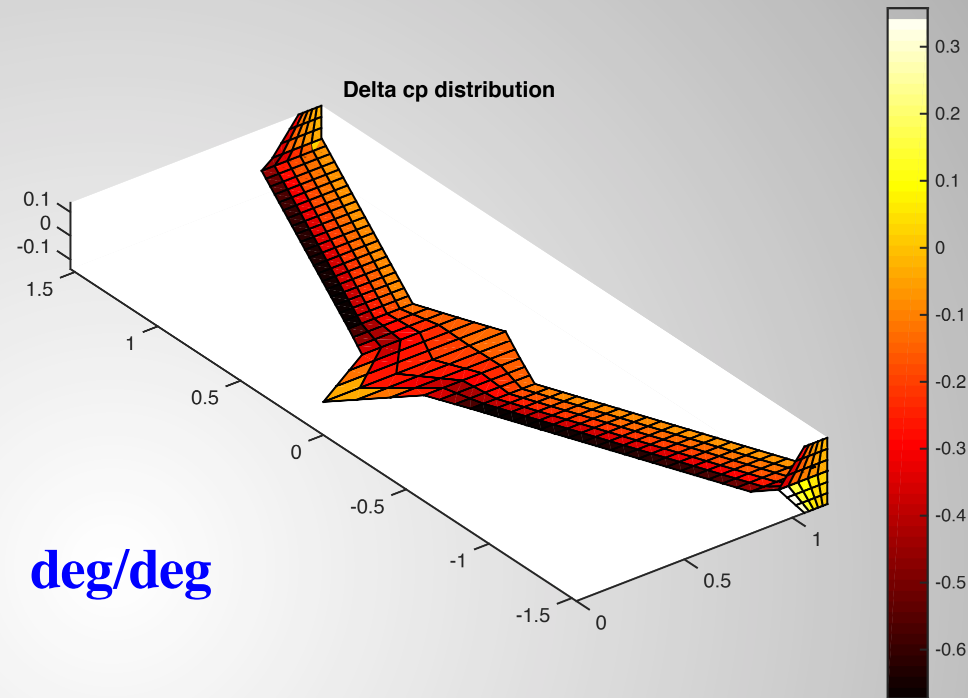
$$\mathbf{x}^T = \left[\begin{array}{cccc|cccccc} u_{rig} & \alpha_{rig} & \theta_{rig} & q_{rig} & \eta_1 & \dot{\eta}_1 & \eta_2 & \dot{\eta}_2 & \eta_3 & \dot{\eta}_3 \end{array}\right]$$

$$\mathbf{A} = \left[\begin{array}{cccc|ccccc}
X_u & X_\alpha & -g & X_q & 0 & 0 & \cdots & 0 & 0 \\
Z_u / \mathrm{U}_0 & Z_\alpha / \mathrm{U}_0 & 0 & 1 + Z_q / \mathrm{U}_0 & Z_{\eta_1} / \mathrm{U}_0 & Z_{\dot{\eta}_1} / \mathrm{U}_0 & \cdots & Z_{\eta_3} / \mathrm{U}_0 & Z_{\dot{\eta}_3} / \mathrm{U}_0 \\
0 & 0 & 0 & 1 & 0 & 0 & \cdots & 0 & 0 \\
M_u & M_\alpha & 0 & M_q & M_{\eta_1} & M_{\dot{\eta}_1} & \cdots & M_{\eta_3} & M_{\dot{\eta}_3} \\
\hline
0 & 0 & 0 & 0 & 0 & 1 & \cdots & 0 & 0 \\
0 & \Xi_{1_\alpha} & 0 & \Xi_{1_q} & \Xi_{1_{\eta_1}} - \omega_1^2 & \Xi_{1_{\dot{\eta}_1}} - 2\zeta_1\omega_1 & \cdots & \Xi_{1_{\eta_3}} & \Xi_{1_{\dot{\eta}_3}} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \cdots & \vdots & \vdots \\
0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 1 \\
0 & \Xi_{3_\alpha} & 0 & \Xi_{3_q} & \Xi_{0_{\eta_1}} & \Xi_{3_{\dot{\eta}_1}} & \cdots & \Xi_{3_{\eta_3}} - \omega_3^2 & \Xi_{3_{\dot{\eta}_3}} - 2\zeta_3\omega_3
\end{array}\right]$$

$$\mathbf{A} = \left[\begin{array}{c|c} \mathbf{A}_{RR} & \mathbf{A}_{RE} \\ \hline \mathbf{A}_{ER} & \mathbf{A}_{EE} \end{array}\right]$$

Rigid-Body Longitudinal Attitude Dynamics

35 kt

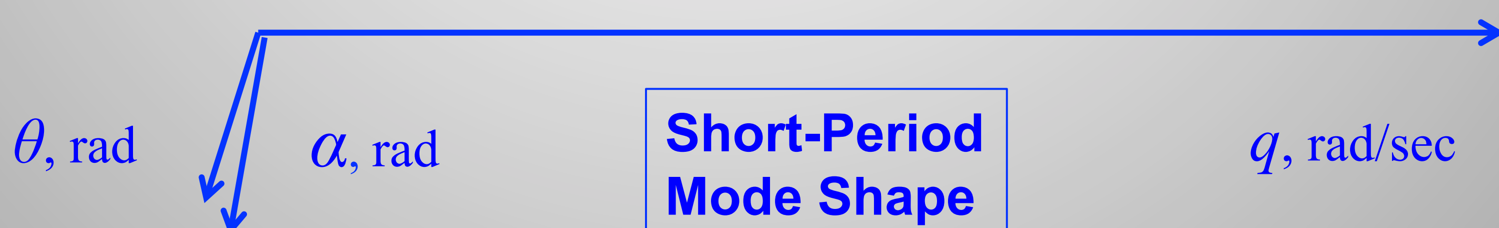


SM = 6%

Conventional modes

$$\frac{\theta(s)}{-\delta_E(s)} = \frac{105.0\ [0.049][6.66]}{[-0.01, 0.54][0.73, 12.4]} \quad \text{deg/deg}$$

$$\frac{n_{Zcg}(s)}{-\delta_E(s)} = \frac{3.38\ [0][-0.285][0.362][5.64]}{[-0.01, 0.54][0.73, 12.4]} \quad g/\text{deg}$$

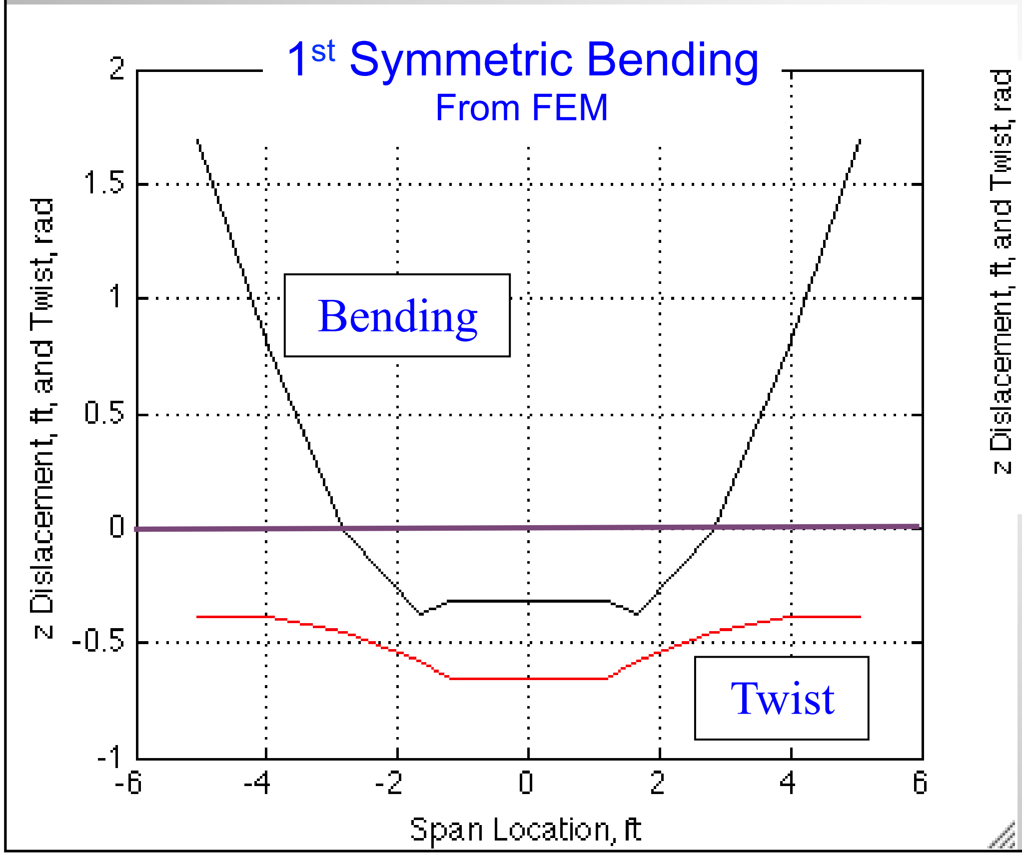


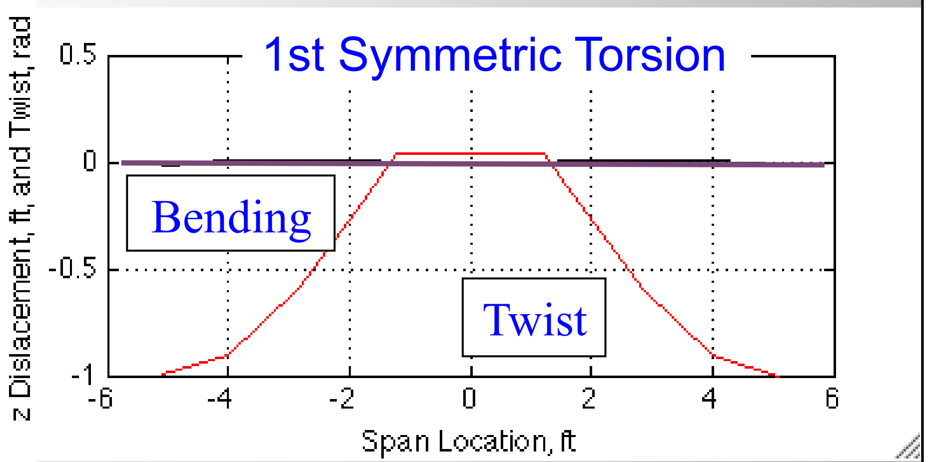
Short-Period Mode Shape

Structural Dynamics

Symmetric Free-Free Vibration Modes

Data and Source	Sym 1st Bending	Sym 1st Torsion	Sym 2nd Bending
Frequency, UMN (GVT)	34.6 r/s	117.8 r/s	145.6 r/s
Frequency, LM	35.4 r/s	123.4 r/s	147.3 r/s
Damping, UMN (GVT)	1.55%	2.06%	2.85%
Gen. Mass, UMN (FEM)	0.28950 sl-ft^2	0. 00772 sl-ft^2	0. 05239 sl-ft^2





Knowing The Mode Shapes Is Critical

Elastic Vehicle Attitude Dynamics

35 kt < V_{F1}

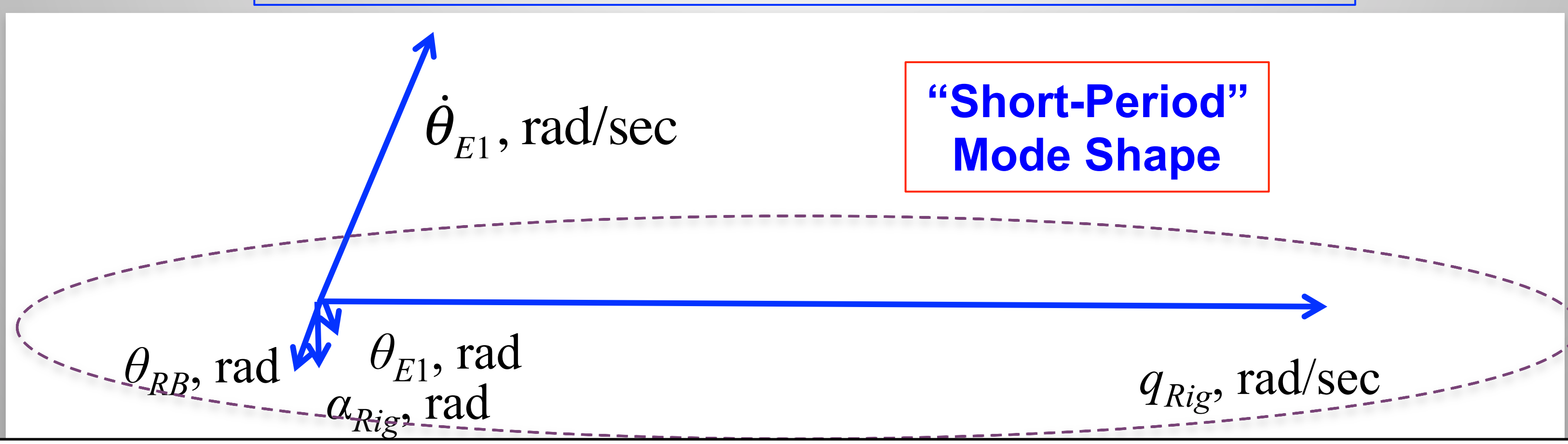
$$\frac{\theta_{cg}(s)}{-\delta_E(s)} = \frac{65.2\,[0.0536][7.044]\,[0.22,41.2][0.05,101.7][0.05,165.3]}{[-0.01,0.61][0.59,18.1][0.15,30.9][0.07,103.7][0.08,146.0]}\ \text{deg/deg}$$

$$\frac{n_{Zcg}(s)}{-\delta_E(s)} = \frac{-0.228\,[0][-0.0279][29.58][-25.58][0.24,42.3][0.07,104.1][-282.6][246]}{[-0.01,0.61][0.59,18.1]\,[0.15,30.9][0.07,103.7][0.08,146.0]}\ \text{g/deg}$$

Rigid

$$\frac{\theta(s)}{-\delta_E(s)} = \frac{105.0\,[0.049][6.66]}{[-0.01,0.54][0.73,12.4]}\ \text{deg/deg}$$

$$\frac{n_{Zcg}(s)}{-\delta_E(s)} = \frac{3.38\,[0][-0.285][0.362][5.64]}{[-0.01,0.54][0.73,12.4]}\ g/\text{deg}$$



Elastic Vehicle Attitude Dynamics

35 kt < V_{F1}

No classical short-period mode
"Elastic-short-period mode"

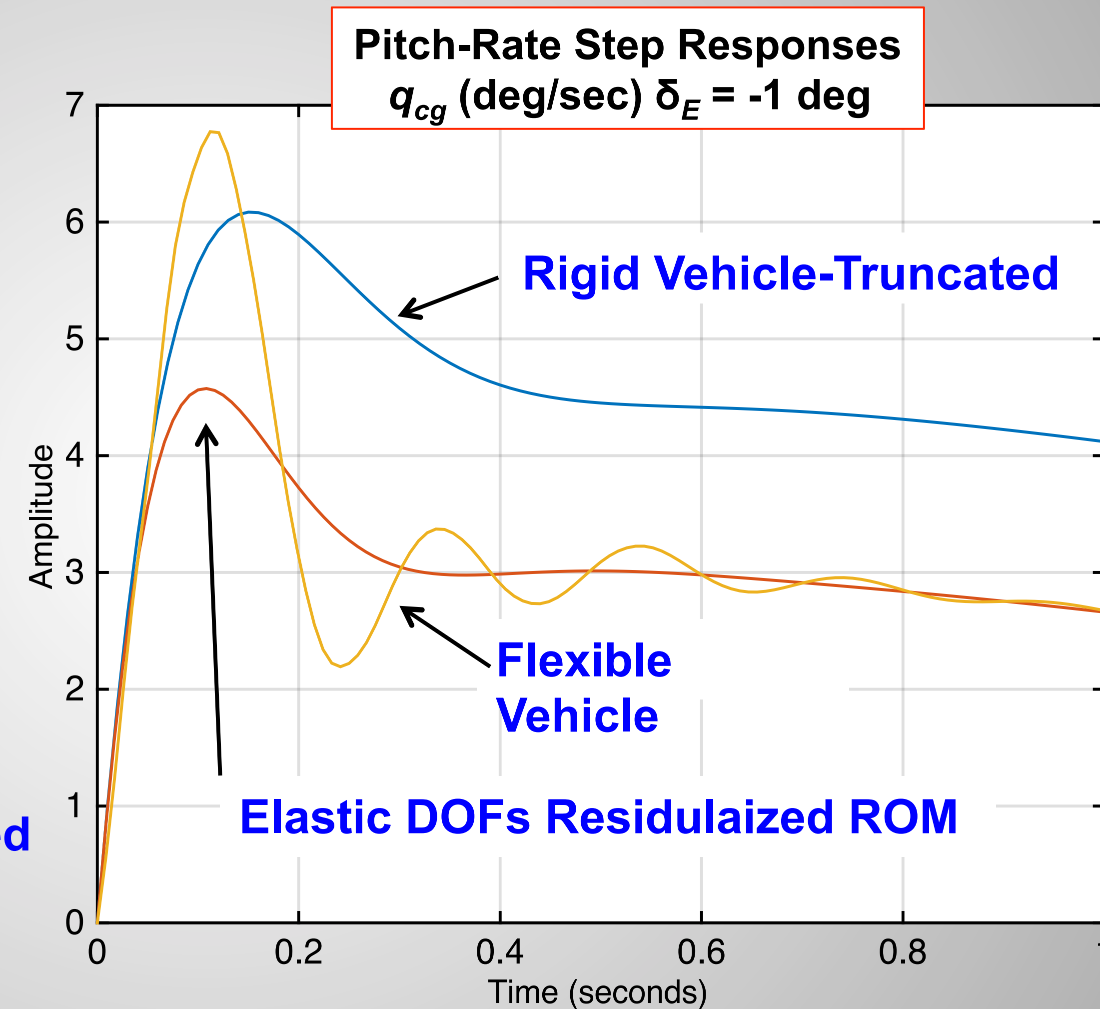
Pitch attitude highly coupled with aeroelastic response (1^{st} bending/tors. vibr. mode)

"Short Period" –
Higher frequency,
lower damping

$1/T_{\theta 2}$ Increased

n_Z Numerator dynamics affected

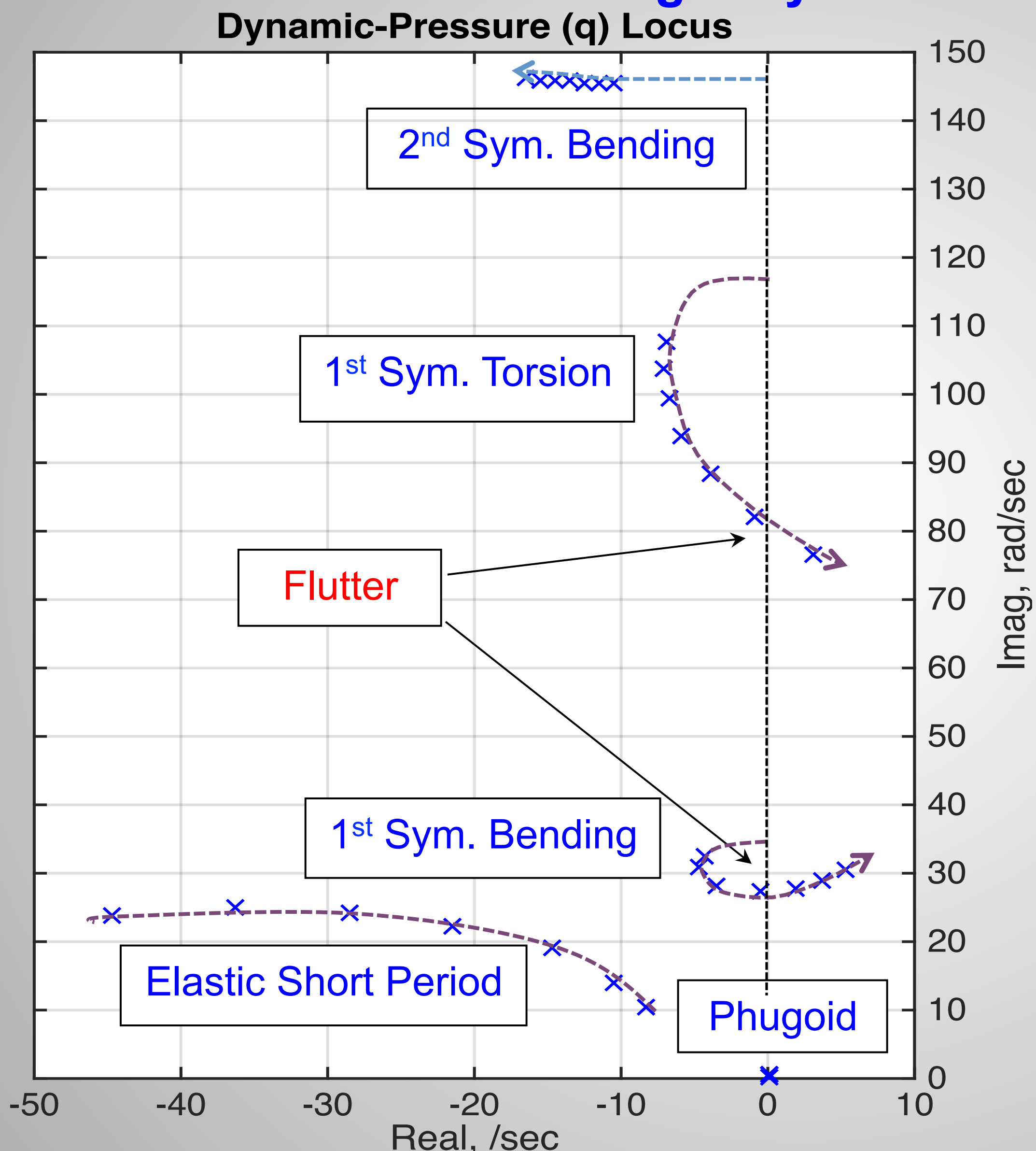
Higher-order elastic dipoles



Flutter Analysis

Flutter Analysis - q Locus

From "Flight Dynamics" Model



BFF Vehicle
Longitudinal Dynamics
Sea Level

Two flutter conditions

BFF and BT flutter

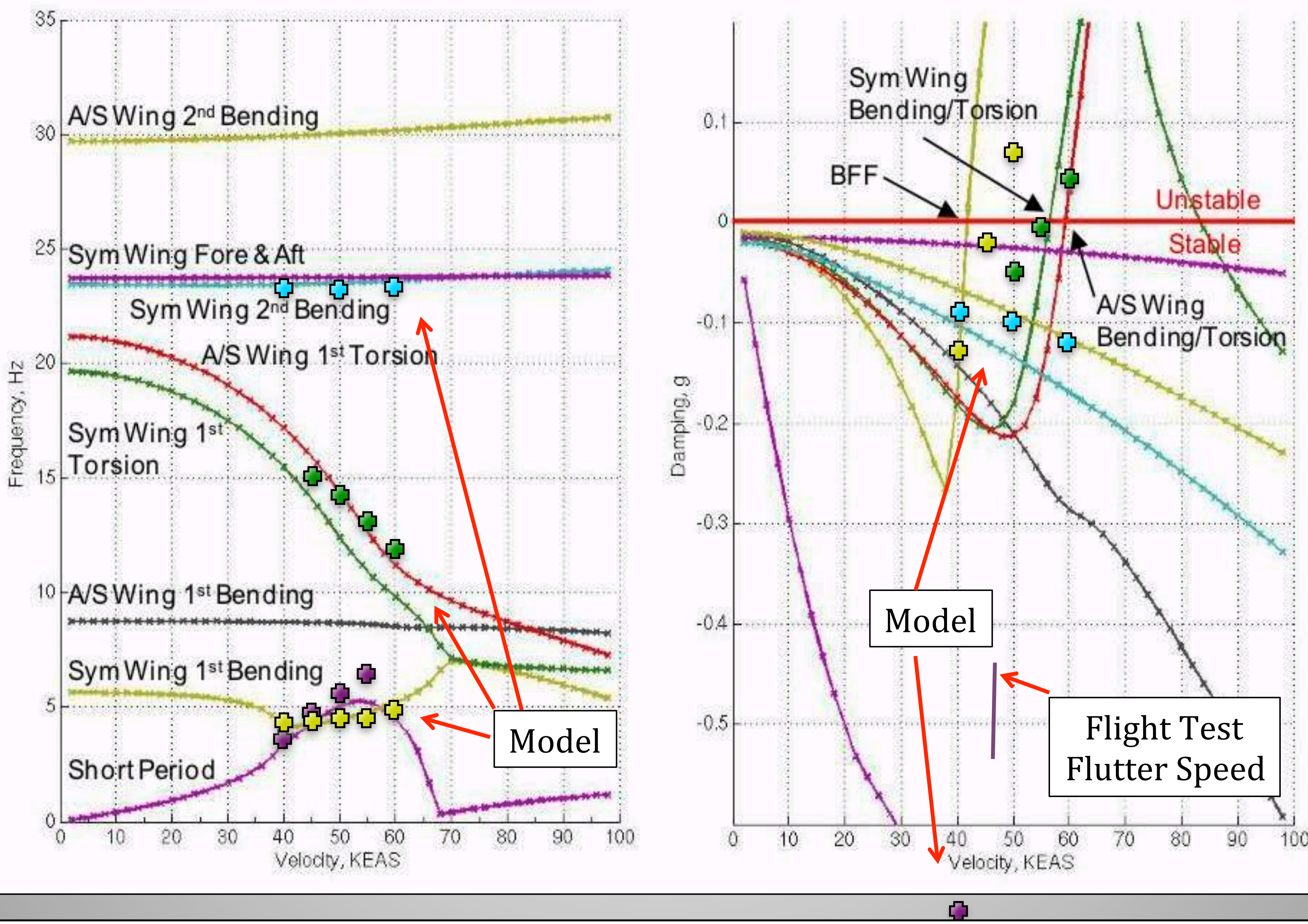
BFF $V_{flutter}$ = 47 kt.

BT $V_{flutter}$ = 57 kt.

BFF genesis mode – 1st symmetric bending

BT genesis mode – 1st symmetric torsion

VFG Comparison



Comparison With LM Results*

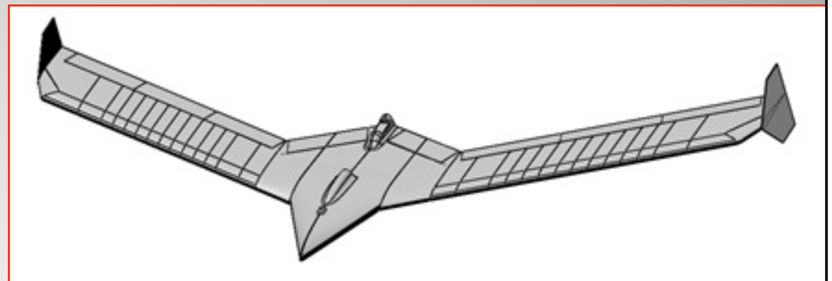
Model/Test	BFF Flutter Speed	BFF Flutter Frequency	BT Flutter Speed	BT Flutter Frequency
LM Analytical	43 kt	4.2 Hz	57 kt	10.5 Hz
LM Flight Test	46 kt	4.5 Hz	NA	NA
FD Model	47 kt	4.4 Hz	57 kt#	12.7 Hz
Residualized FD Model	47 kt	4.4 HZ	NA	NA
Truncated FD Model	No Flutter	No Flutter	NA	NA

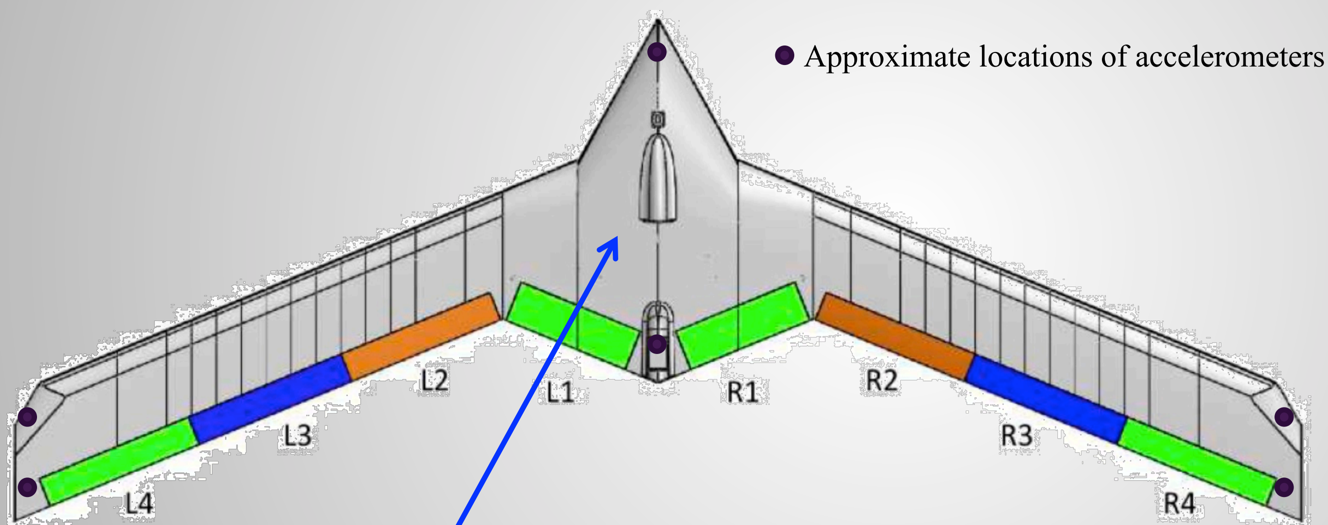
- **Correctly captured both flutter modes**
- **Matched both genesis flutter modes**
- **Matched BFF flutter speed - # BT Adjusted**
- **Matched BFF Flutter frequency**
- **Torsion mode SE aero effects critical to BFF condition**

- Burnett, Edward L., et al, “ NDOF Simulation Model for Flight Control Development with Flight Test Correlation,” Lockheed Martin Aeronautics Co., AIAA Modeling and Simulation Tech. Conf., 2010-7780, 2010.

Active Flutter Suppression
and
Stability Augmentation

Vehicle Sensors and Control Surfaces





FCS
Gyros. Accels, GPS

Body Flaps	L1 – R1
Aileron	L2 – R2
Elevator	L3 – R3
OB Flaps	L4 – R4

Control-Law Synthesis - ILAF

- Require integrated approach to SAS and active flutter suppression
- Seek robustness against vibration mode-shape uncertainty
- One approach - concept of ILAF (Wykes*)
  "Identically Located Acceleration and Force"
- ILAF – "A point force applied to a structure proportional to the velocity of the structure measured at the point of application of the force will increase the damping of all structural modes."
- Requires no knowledge of the vibration mode shapes – robust
  If can implement true ILAF – point force.
- Used to design active-structural-mode-control system on B-1 & XB-70

- Wykes, et al, "Design and Development of a Structural Mode Control System," NASA CR-143846, Rockwell Int.., 1977.

Conceptual Idea Behind ILAF

The EOM for the *i*'th elastic modal coordinate is

$$\ddot{\eta}_i + 2\zeta_i\omega_i\dot{\eta}_i + \omega_i^2\eta_i = Q_i / \mathcal{M}_i$$

The generalized force from a force F applied at point P is

$$Q_i = \phi_i\left(x_P, y_P, z_P\right) \cdot \mathbf{F}$$

If the force is proportional to the negative local velocity then

$$\mathbf{F} = -K \left.\frac{d\mathbf{d}_E}{dt}\right|_{Body} \left(x_P, y_P, z_P\right) = -K \sum_{i=1}^{n} \phi_i\left(x_P, y_P, z_P\right)\dot{\eta}_i$$

Hence the generalized force becomes

$$Q_i = -K\phi_i\left(x_P, y_P, z_P\right) \cdot \sum_{j=1}^{n} \phi_j\left(x_P, y_P, z_P\right)\dot{\eta}_j = \boxed{-K'\dot{\eta}_i} + \sum_{\substack{j=1 \\ j \neq i}}^{n} K_j\dot{\eta}_j$$

Where $K' > 0$

Substitution in to EOM yields increased damping

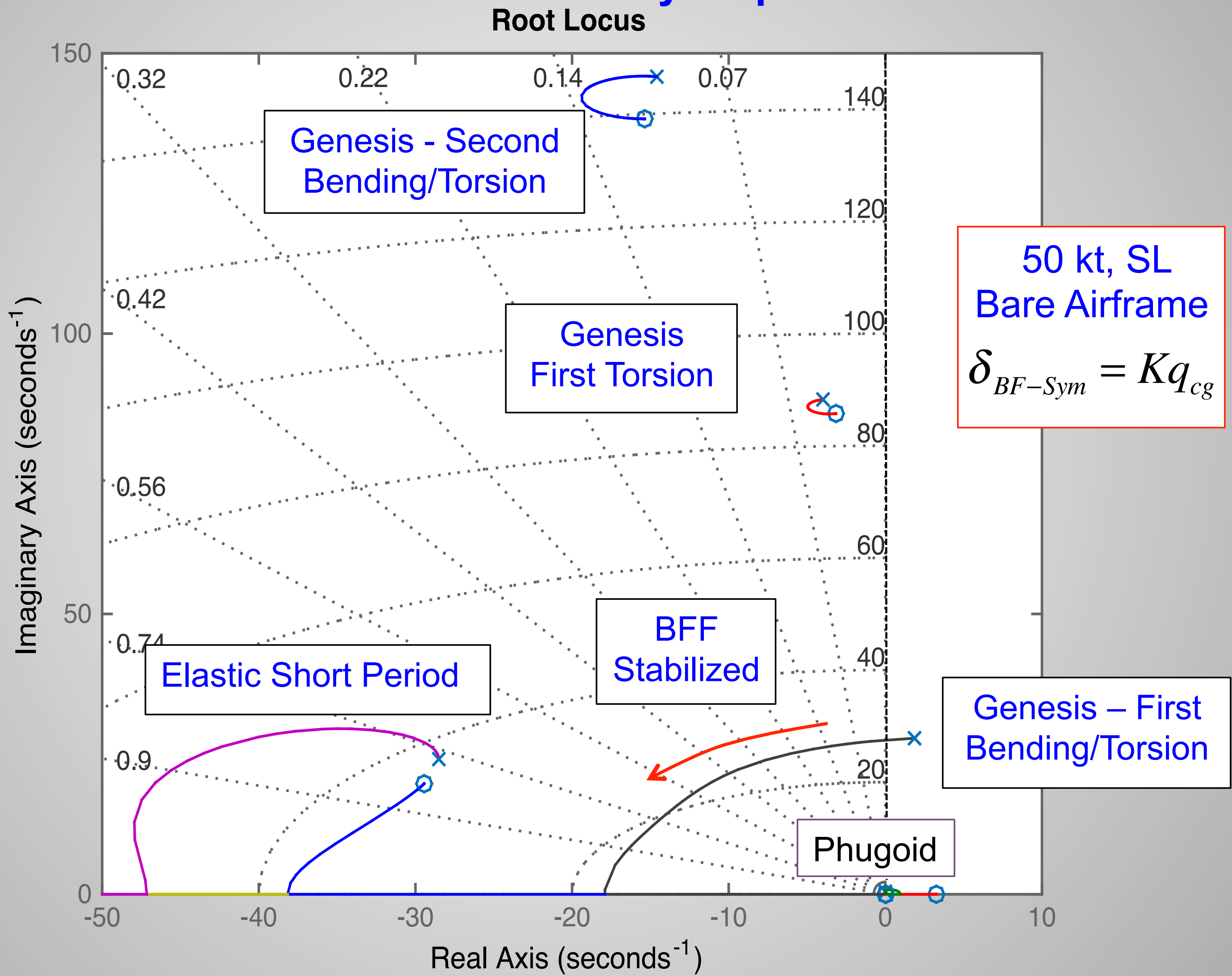
ILAF Applied to BFF Vehicle

Sensor-Actuator Selection

- BFF condition - interactions between the vehicle pitch-dominant mode (elastic-short-period) and the first aeroelastic mode
- First aeroelastic mode involves bending, center-body pitching, and wing twist.
- "Rigid-body" pitching replaces wing twist in the conventional bending-torsion flutter mechanism.
- Second flutter mode is more classical bending-torsion – max deflection at wing tips
- Corollaries to ILAF –
  1. Apply pitching moment to location on the structure proportional to pitch rate measured at the same location.
  2. Apply wing torque at tips proportional to wing-tip twist.
- Approximate ILAF – feedback center-body pitch rate to body flaps and feedback wing-tip twist to outboard flaps

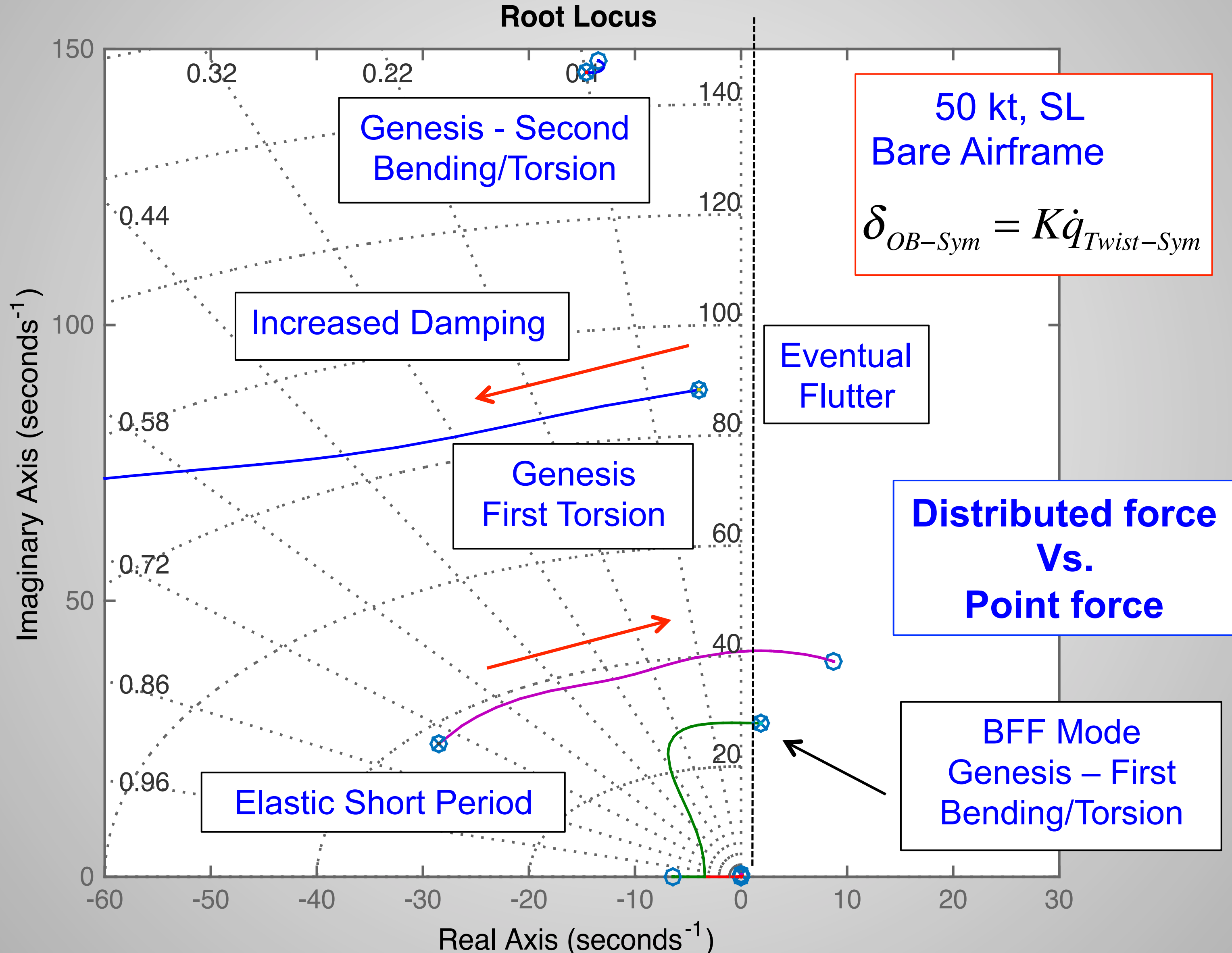
Gain Root Locus - BFF Stabilized

Pitch Rate to Body Flap



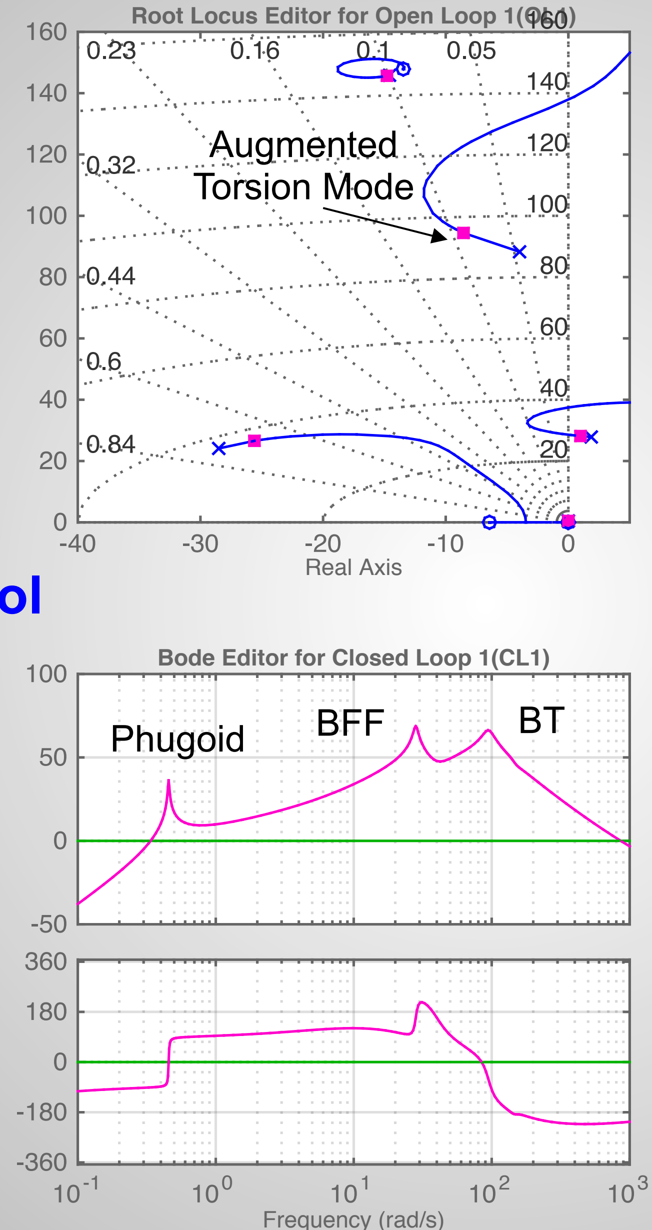
Second Flutter-Mode Suppression

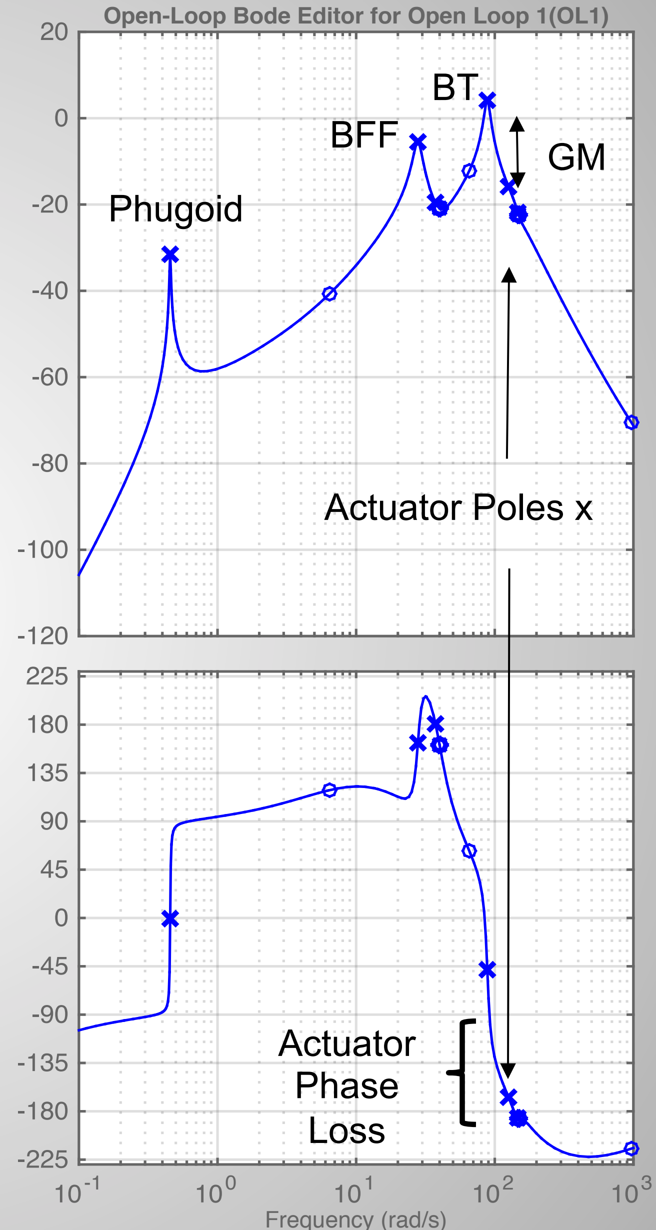
Wing-Tip Twist Accel. to Outboard Flaps



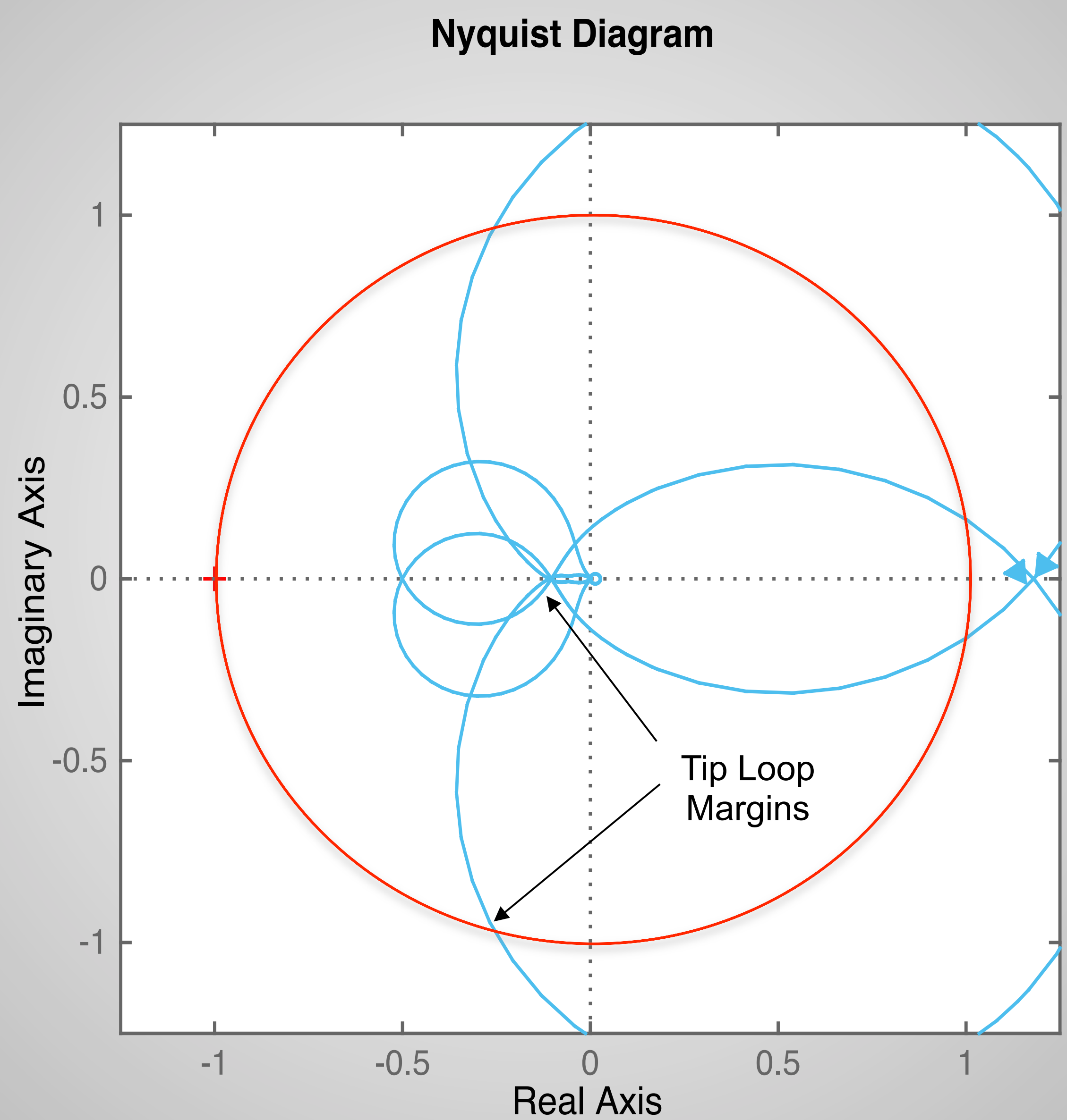
With Actuators – 50 kts

MATLAB's Control Design Tool



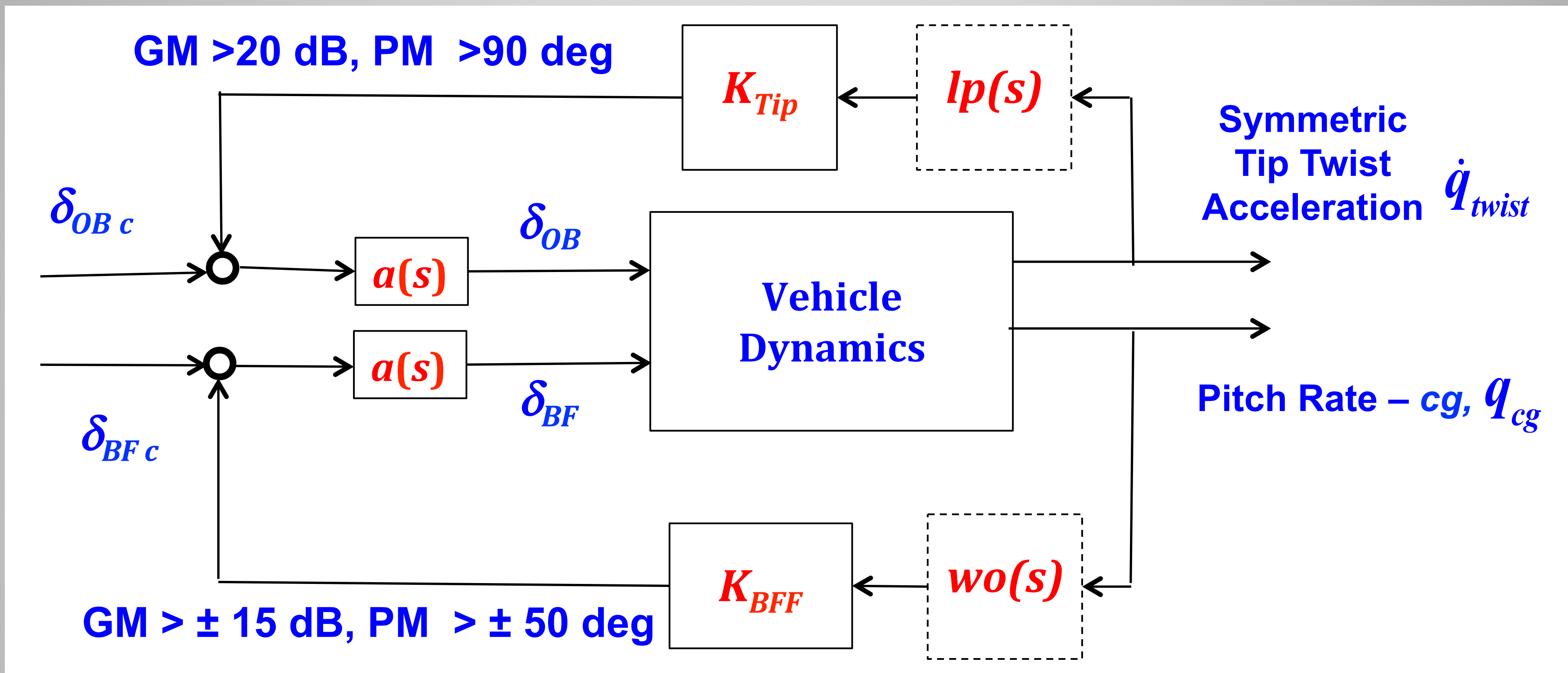


Tip-Twist Loop Nyquist



Control-Law Architecture – ILAF

V = 50 and 60 kts



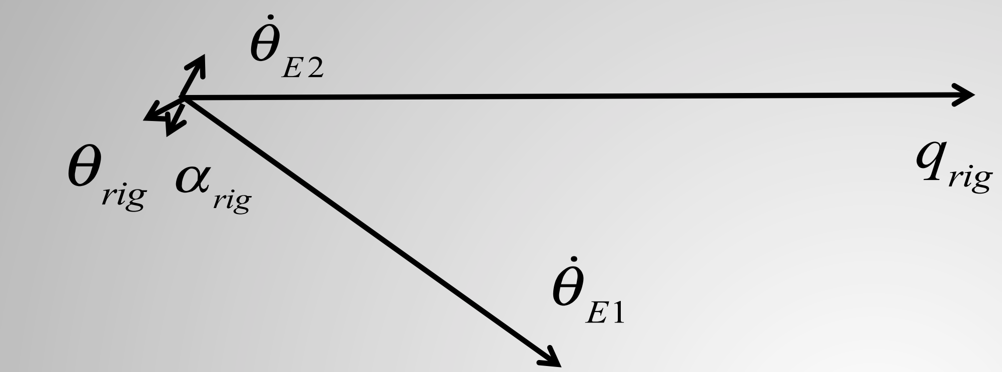
Center-body pitch rate to symmetric body flap – K_{BFF} ~ 0.2 deg/deg/sec

Symmetric blended accelerometer to symmetric outboard flap
- K_{Tip} ~ 0.0005 deg/deg/sec^2

Notes: Second flutter mode (torsion) suppression is actuator limited at 60 kt
Washout and low-pass filters also being considered

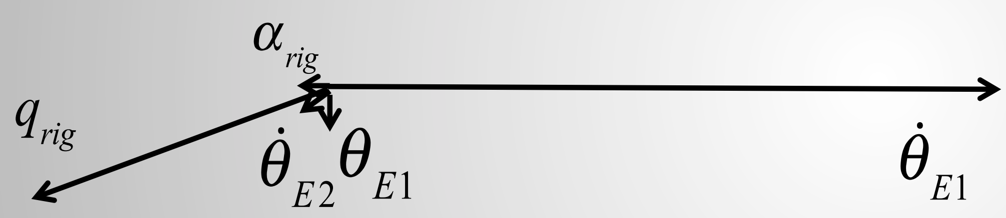
The Mode Shapes – 50 kts

Unstable



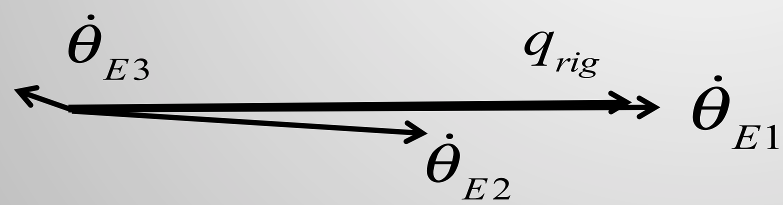
Elastic Short Period

$\lambda = -28.5 \pm 24.1j$



1st Aeroelastic - BFF

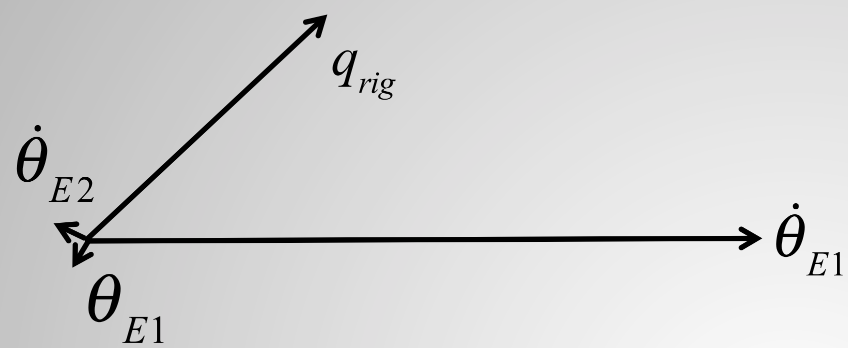
$\lambda = 1.9 \pm 27.8j$



2nd Aeroelastic – Torsion

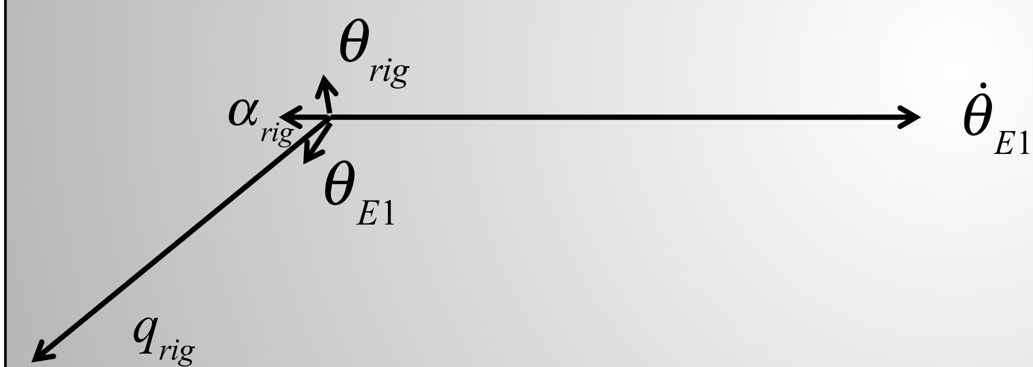
$\lambda = -4.0 \pm 88.3j$

Mode Shapes – 50 kts
Augmented



Former Elastic Short Period

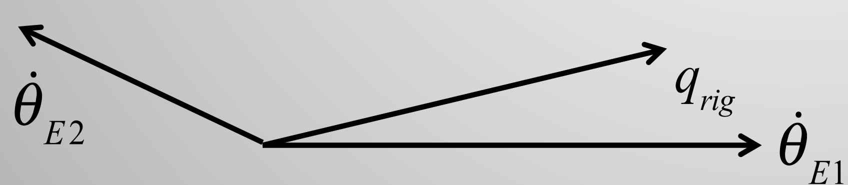
$\lambda = -33.6 \pm 35.7$



Stabilized BFF

New Elastic Short Period

$\lambda = -12.1 \pm 16.1j$



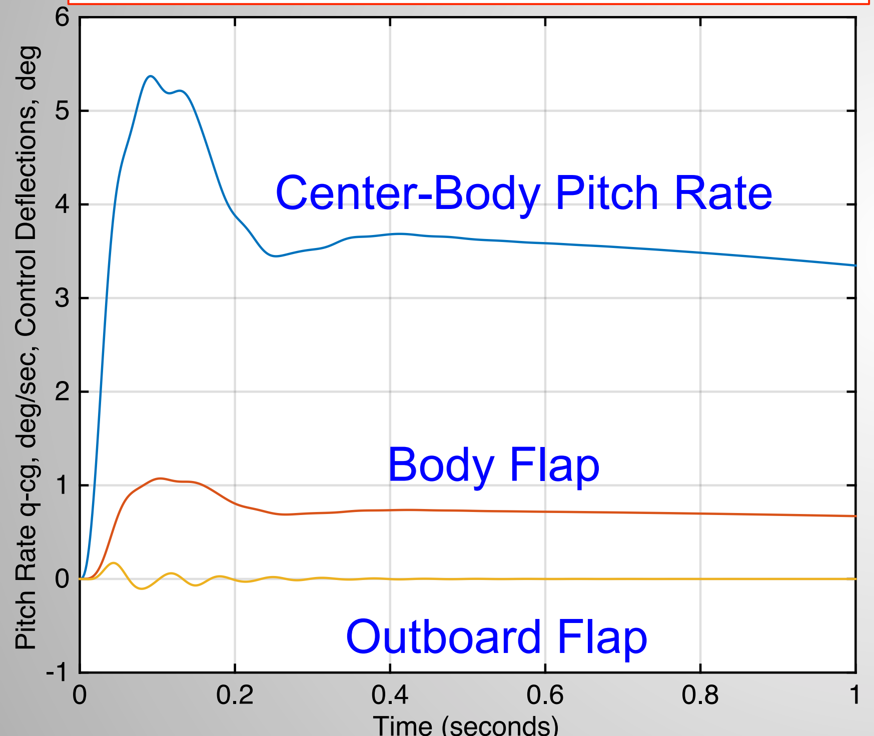
2nd Aeroelastic (Torsion)

$\lambda = -17.3 \pm 83.1j$

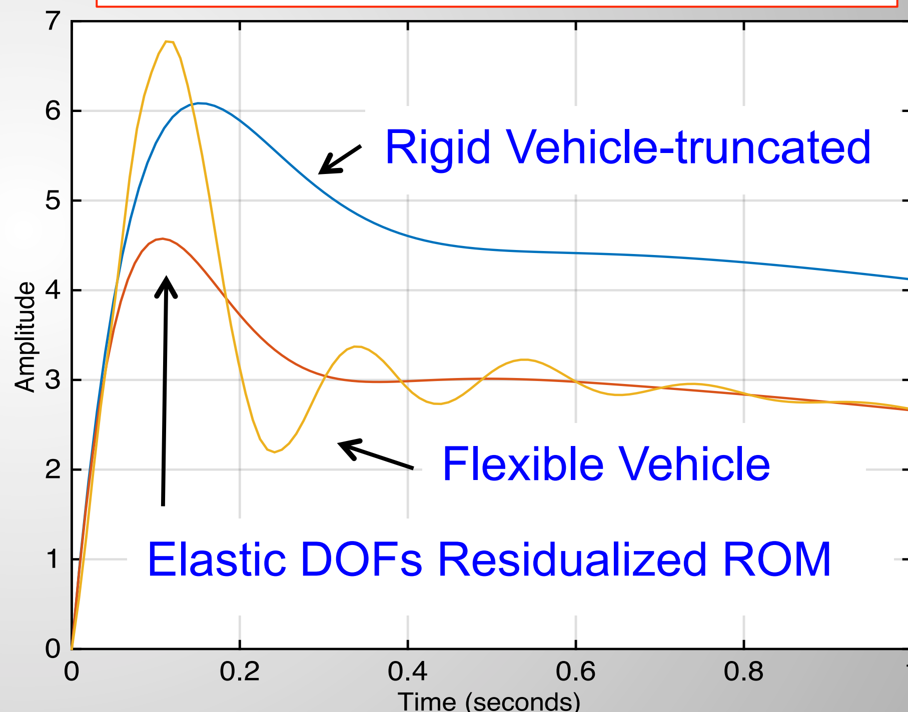
Closed-Loop Pitch-Rate Step Responses

$$\delta_E = -1 \text{ deg}$$

Center-Body Pitch-Rate (deg/sec)
50 kt > V_{BFF}



Center-Body Pitch-Rate (deg/sec)
35 kt < V_{BFF}



Based on These Results,
Addition Pitch Stability Augmentation
May Not Be Required

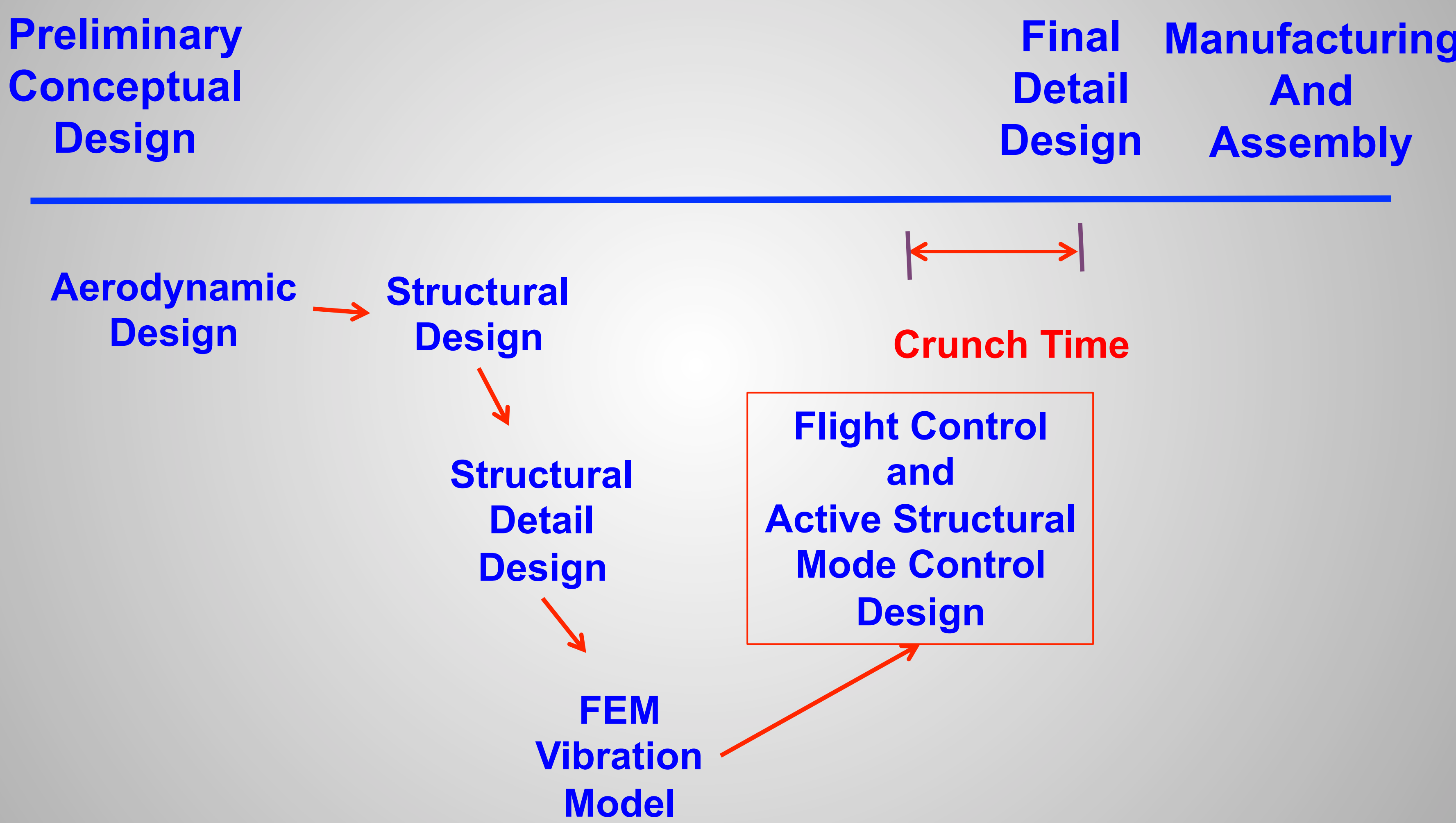
Summary and Conclusions

- **Longitudinal nDOF "Flight-Dynamics" model developed**
- **Good agreement with LM flutter predictions and flight test results**
- **Vehicle exhibits highly coupled "RB" pitch and 1st aeroelastic modes**
- **AFS stabilized both BFF and BT flutter modes, at both 50 and 60 kt.**
- **Reasonable margins achieved in all cases (> ± 12 dB, > ± 40 deg) Including effects of actuator bandwidth (125 rad/sec).**
- **Simple, two-loop, constant-gain architecture with sensor blending.**
- **Reasonable pitch responses – similar to that for stable vehicle < V_{BFF}**
- **Modest control-surface demands**

1. Schmidt, MATLAB-Based Flight-Dynamics and Flutter Modeling of a Flexible Flying-Wing Research Drone," DKS PAAW Working Paper, January, 2015. Submitted to *Journal of Aircraft*.
2. Schmidt, "Integrated Stability Augmentation and Active Body-Freedom-Flutter Suppression For a Flexible Flying-Wing Research Drone," DKS PAAW Working Paper, January, 2015. Submitted to *JGCD*.

Backups

Design-Cycle Time Line (Notional)



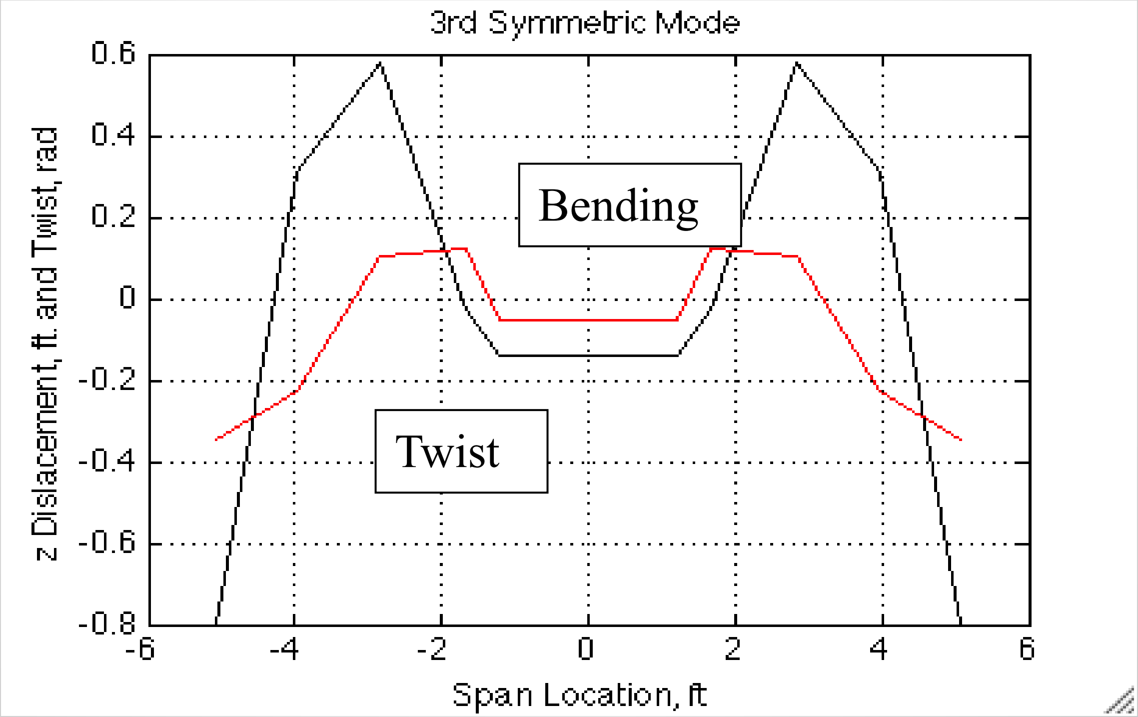
Simplifications Employed to Obtain "Early" Model

- Use rigid-body aero data and model the rigid vehicle first
- Start with quasi-steady aero in aeroelastic analysis
- Use simple beam-element FEM for vibration analysis

Data Sources for This Task

- FEM - UMN
- Mass properties - UMN
- Aerodynamics
  - Digital DATCOM (slender-wing, empirical)
  - Strip theory
  - VLM
  - DLM later

Third Symmetric Mode



Aero Stability Derivatives

Table 3, Rigid-Body Longitudinal Stability Derivatives

C_{L_α} /rad	C_{M_α} /rad	C_{L_q} /rad	C_{M_q} /rad	C_{D_α} /rad	$C_{L_{\delta_1}}$ /rad	$C_{M_{\delta_1}}$ /rad
4.074	-0.310	2.657	-3.830	0.129	0.774	-0.014*
$C_{L_{\delta_2}}$ /rad	$C_{M_{\delta_2}}$ /rad	$C_{L_{\delta_3}}$ /rad	$C_{M_{\delta_3}}$ /rad	$C_{L_{\delta_4}}$ /rad	$C_{M_{\delta_4}}$ /rad	
0.630	-0.246	0.530	-0.410	0.301	-0.353	
$C_{D_{\delta_1}}$ /rad	$C_{D_{\delta_2}}$ /rad	$C_{D_{\delta_3}}$ /rad	$C_{D_{\delta_4}}$ /rad			
0.0012	0.0015	0.0018	0.0012			

* From UMN UAV Lab

$$SM = \frac{-C_{M_\alpha}}{C_{L_\alpha}} = \frac{0.310}{4.074} = 7.6\%$$

$$\frac{\theta(s)}{-\delta_E(s)} = \frac{105.04\ (s+0.049)(s+6.66)}{(s^2-0.0125s+0.2964)(s^2+18.05s+154.4)} \quad \text{rad/rad}$$

$$\frac{n_{Zcg}(s)}{-\delta_E(s)} = \frac{6245\ s(s-0.285)(s+0.3617)(s+5.64)}{(s^2-0.0125s+0.2964)(s^2+18.05s+154.4)} \quad \text{ft/sec}^2\text{/rad}$$