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

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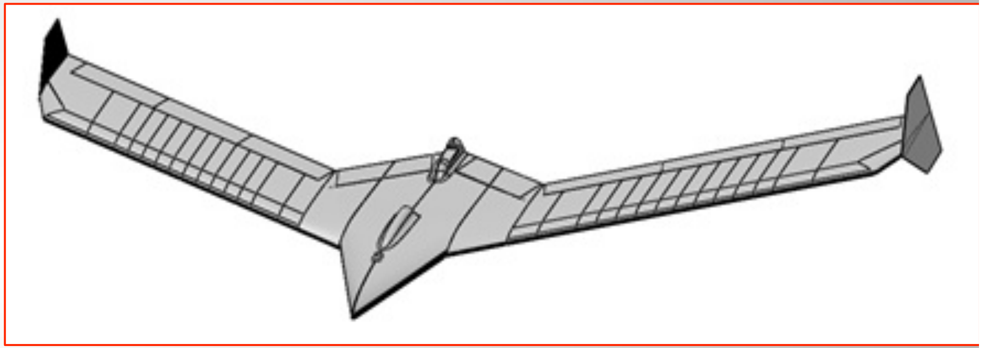

As presented at the

Aerospace Flutter and Dynamics Council (AFDC) Meeting
NASA Ames Research Center
Moffett Field, CA

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The Overall Research Project

Lightweight Adaptive Aeroelastic Wing

Funded Under the
NASA AATT Program

The Team

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Project Overview

Goal: Actively Optimize Wing Shape - Transport Aircraft

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

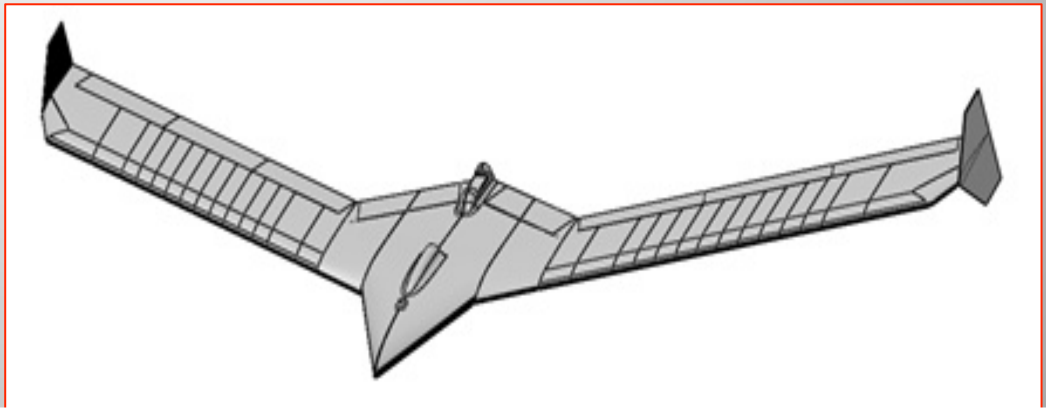
- Active flutter suppression is a key enabling technology
- Critical PAAW program components –

  Three different vehicles will be developed and flight tested

  The first will be very similar to Lockheed Martin's FFAD (X-56)
  - 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

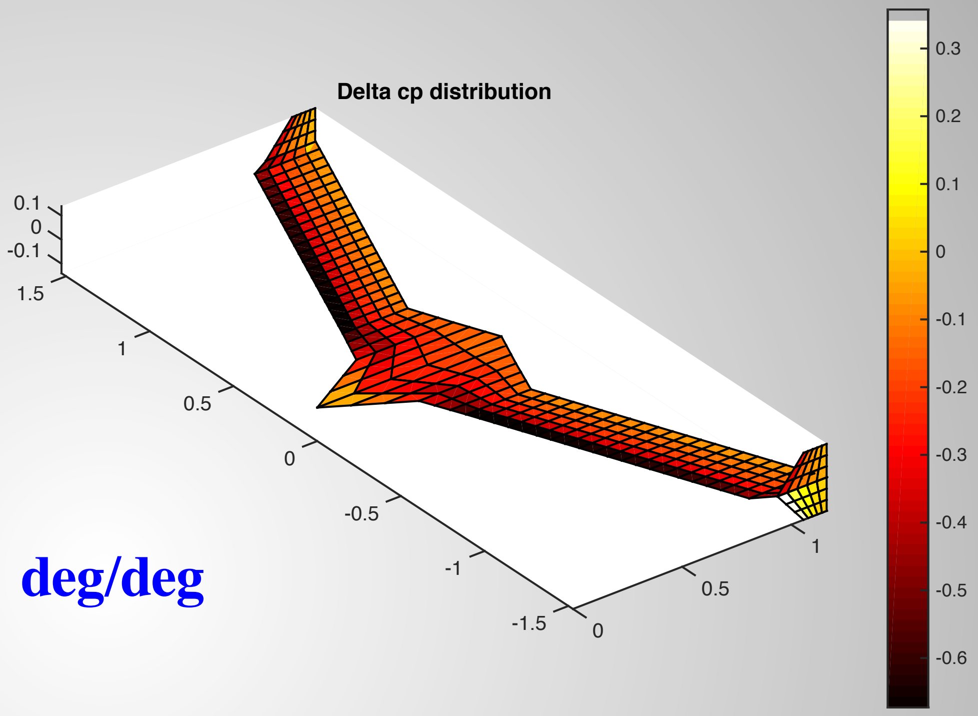
  Consider use of beam-element FEM and quasi-steady aero initially
- **Feedback and suggestions sought from this group**
- **NOTE: Longitudinal axis only, so far**

“Flight-Dynamics” vs. “Flutter” 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

Rigid-Body Longitudinal Attitude Dynamics

35 kt

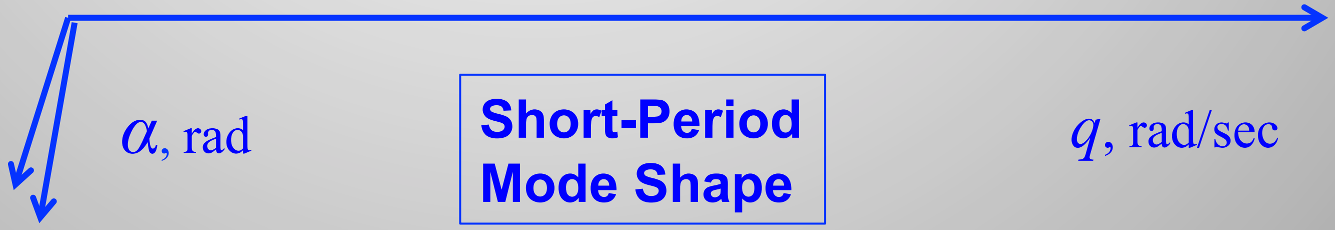


SM = 6%

Conventional modes

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

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



θ, rad

α, rad

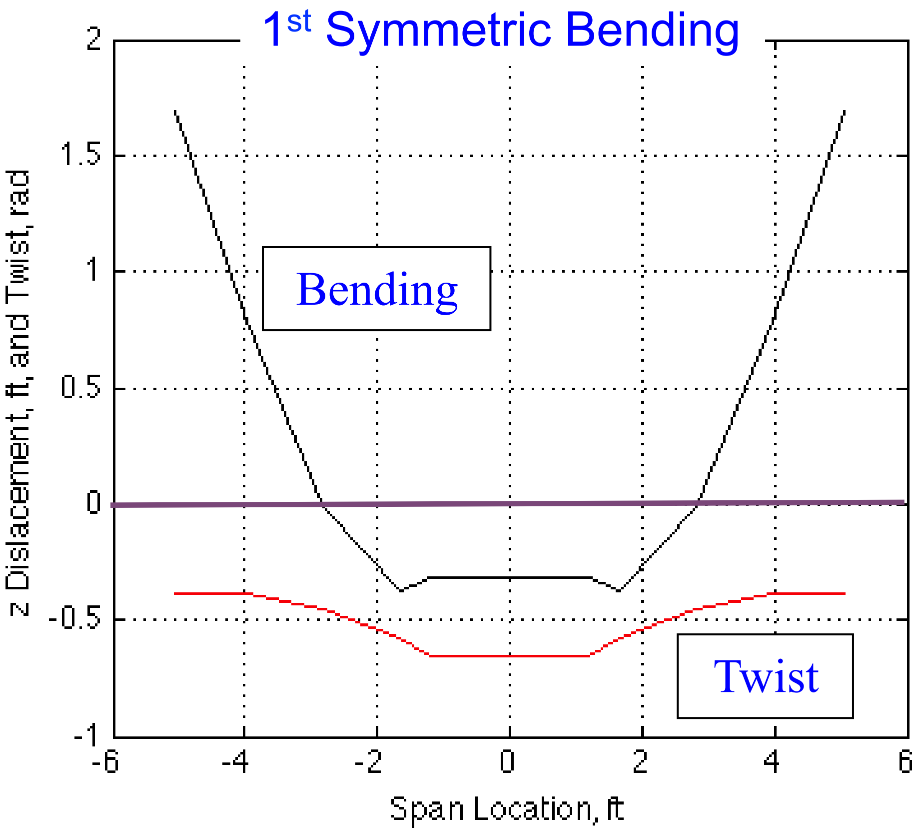
Short-Period Mode Shape

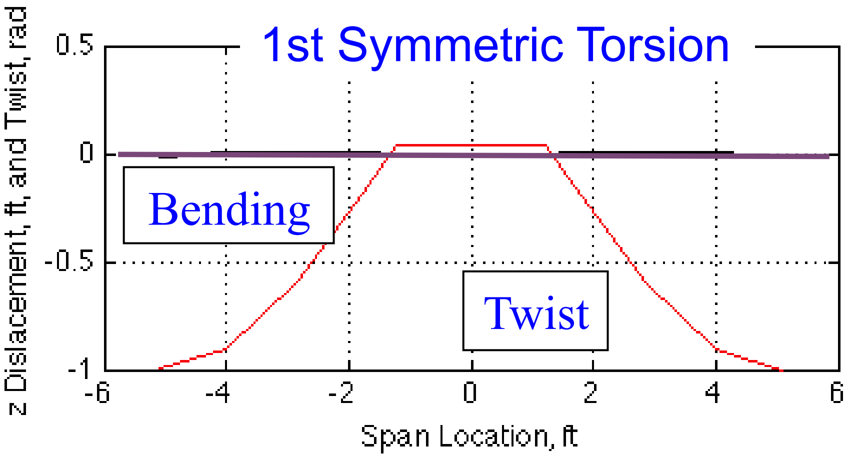
q, rad/sec

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





Elastic Vehicle Attitude Dynamics

35 kt < V_{F1}

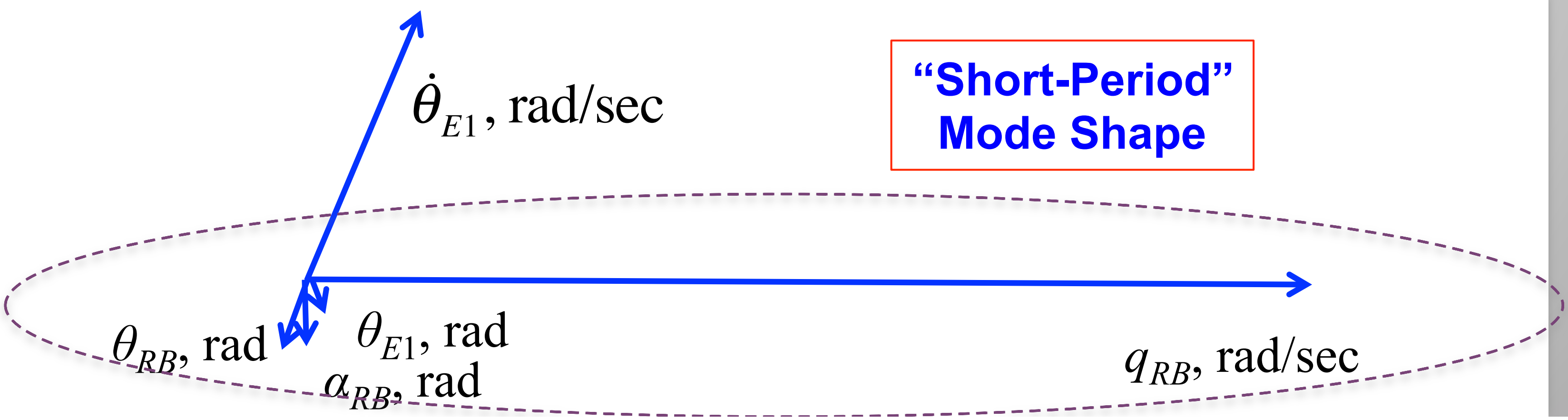
$$\frac{\theta_{cg}(s)}{-\delta_E(s)} = \frac{65.2\ [0.0536][7.044]\ \ [0.22,41.2][0.05,101.7][0.05,165.3]}{[-0.01,0.61][0.59,18.1][0.15,30.9][0.07,103.7][0.08,146.0]}\ \text{deg/deg}$$

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

Rigid

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

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



"Short-Period" Mode Shape

Elastic Vehicle Attitude Dynamics

35 kt < V_{F1}

No classical short-period mode
“Elastic-short-period mode”

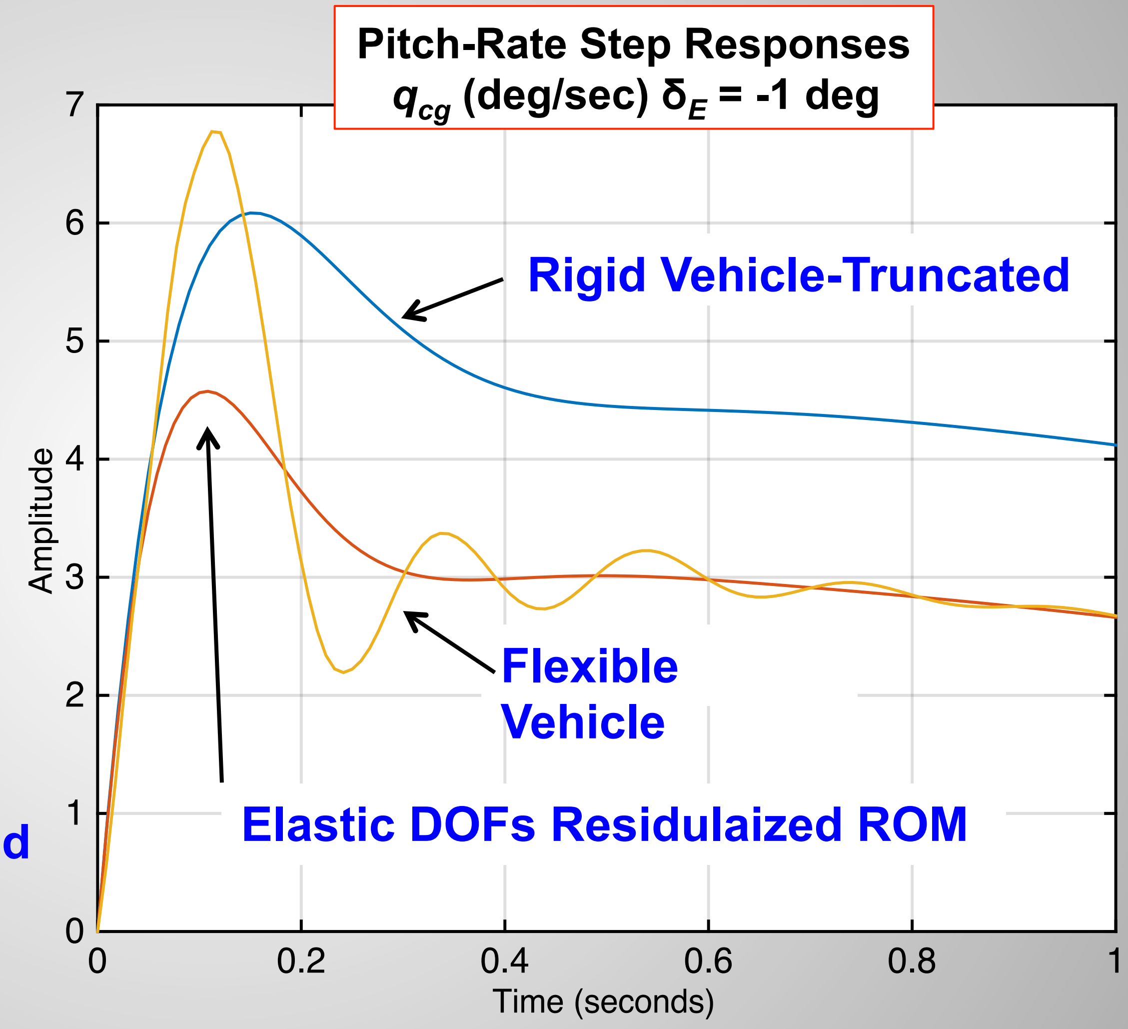
Pitch attitude highly coupled with aeroelastic response (1st bending/tors. vibr. mode)

“Short Period” –
Higher frequency,
lower damping

$1/T_{\theta 2}$ Increased

n_Z Numerator dynamics affected

Higher-order elastic dipoles



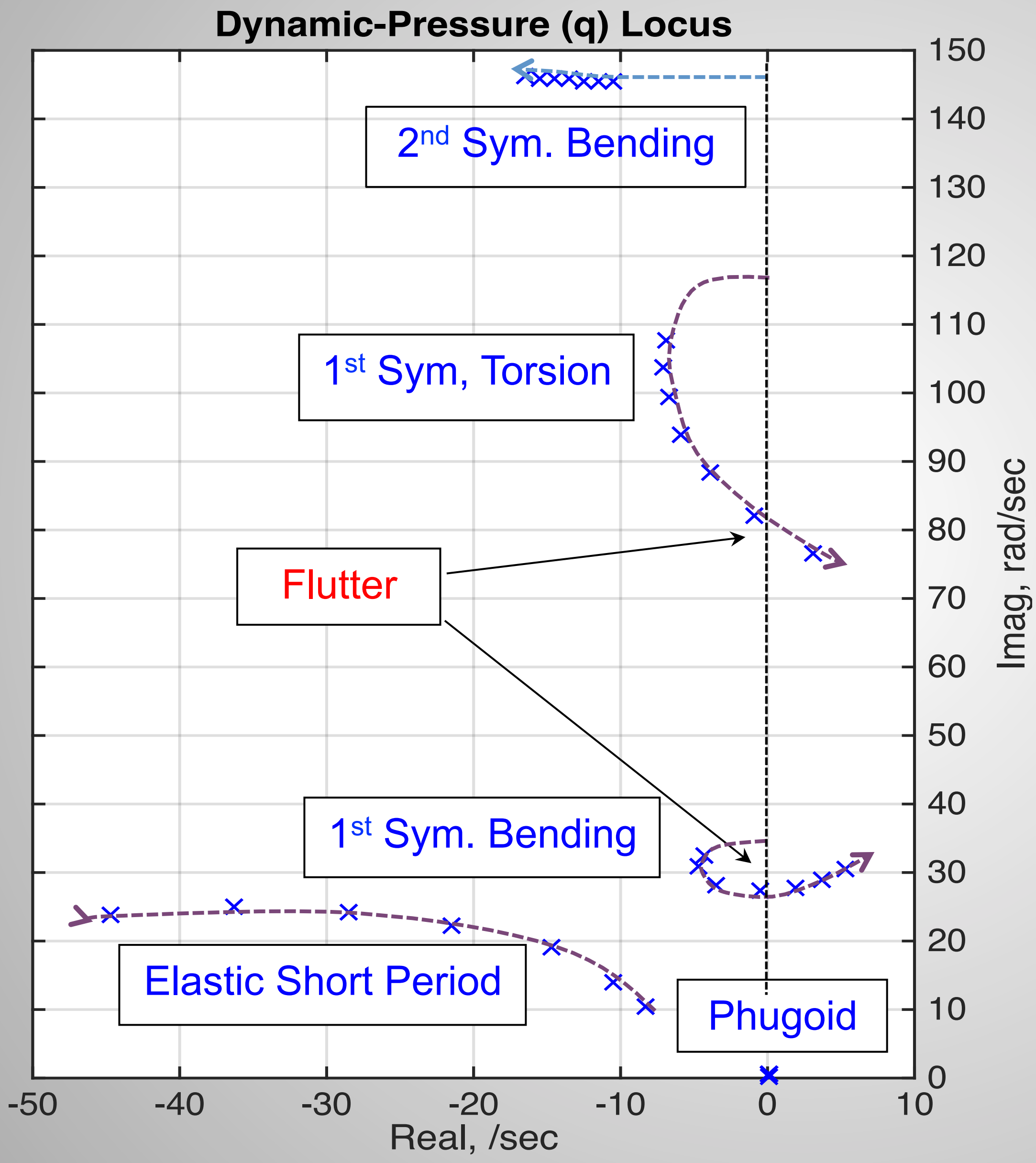
Pitch-Rate Step Responses
q_{cg} (deg/sec) δ_E = -1 deg

Rigid Vehicle-Truncated

Flexible Vehicle

Elastic DOFs Residulaized ROM

Flutter Analysis - q Locus



BFF Vehicle
Longitudinal Dynamics
Sea Level

Two flutter conditions

BFF and BT flutter

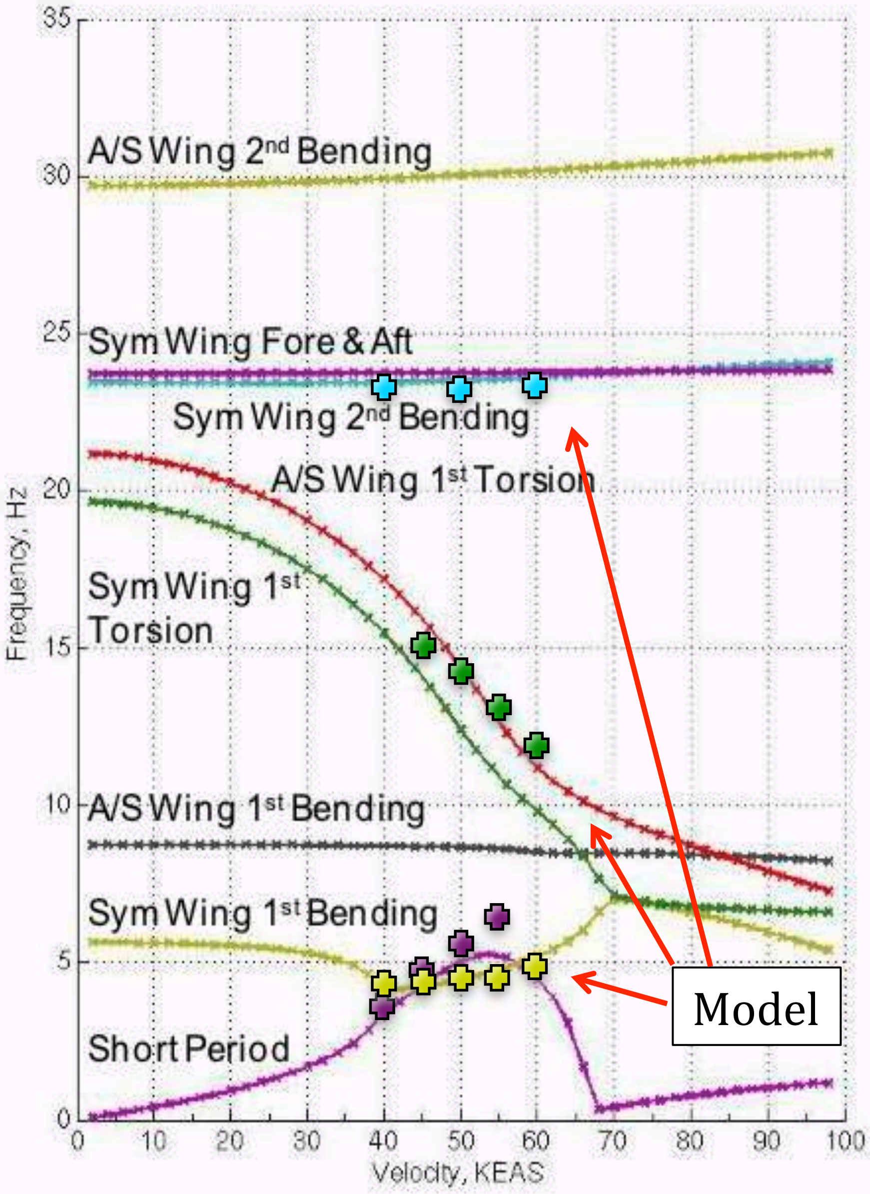
BFF $V_{flutter}$ = 47 kt.

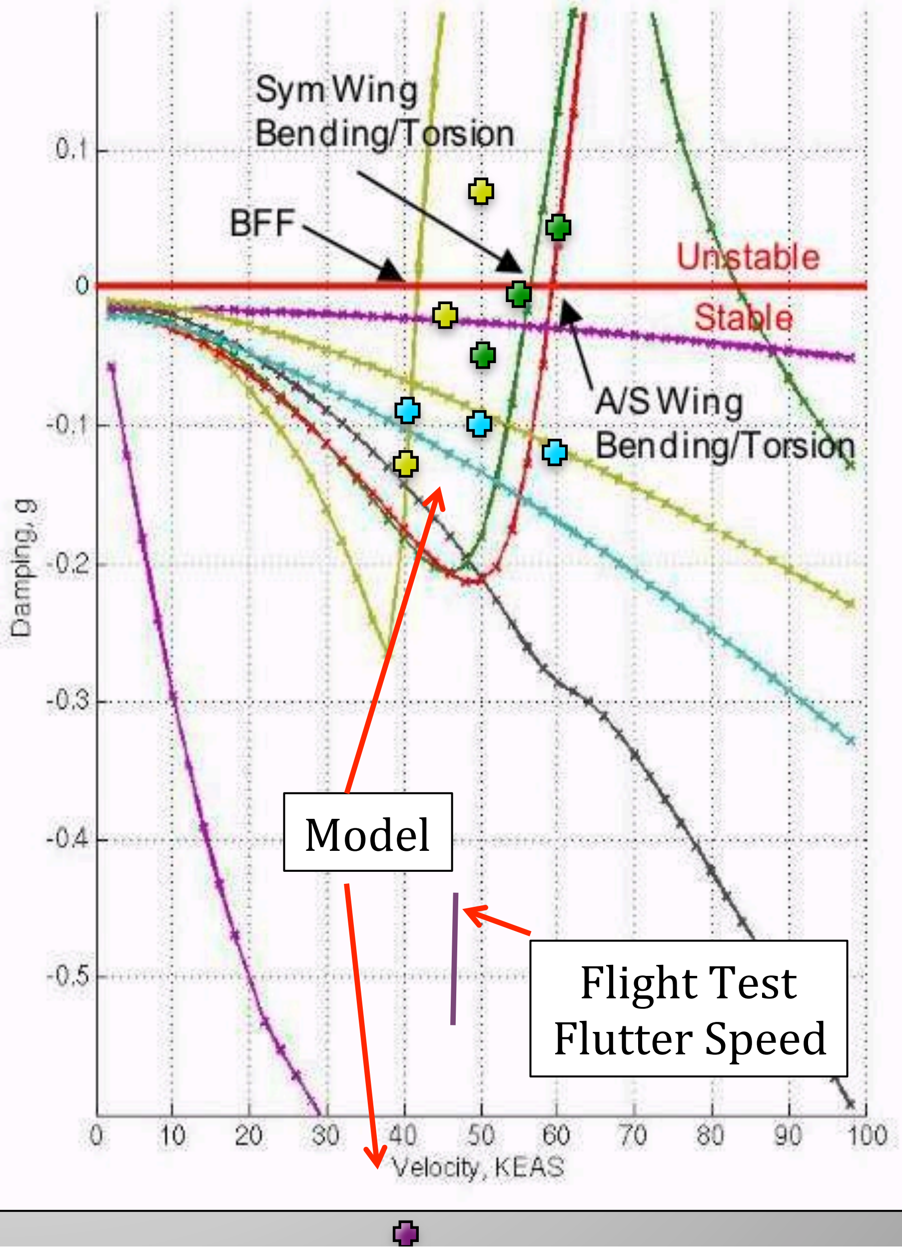
BT $V_{flutter}$ = 57 kt.

BFF genesis mode –
1st symmetric bending

BT genesis mode –
1st symmetric torsion

VFG Comparison





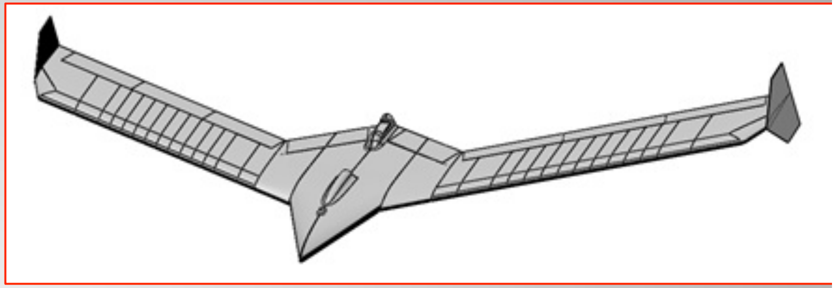
Comparison With LM Results*

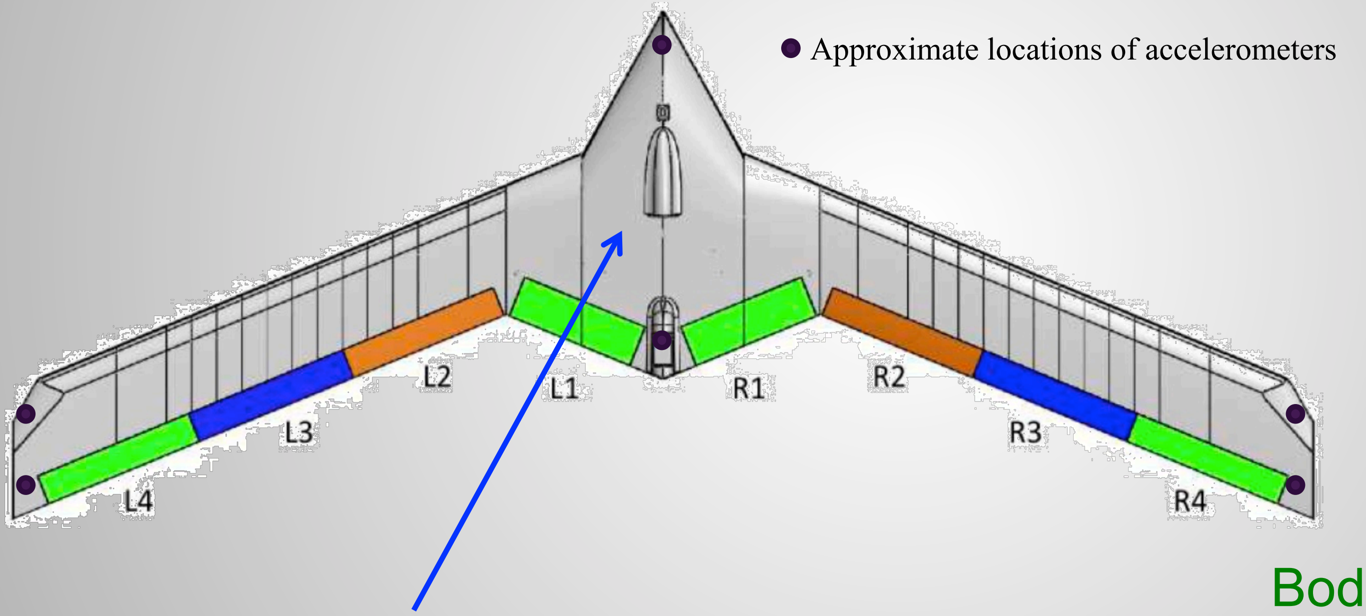
Model/Test	BFF Flutter Speed	BFF Flutter Frequency	BT Flutter Speed	BT Flutter Frequency
LM Analytical	43 kt	4.2 Hz	57 kt	10.5 Hz
LM Flight Test	46 kt	4.5 Hz	NA	NA
FD Model	47 kt	4.4 Hz	57 kt#	12.7 Hz
Residualized FD Model	47 kt	4.4 HZ	NA	NA
Truncated FD Model	No Flutter	No Flutter	NA	NA

- **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.

Vehicle Sensors and Control Surfaces





● Approximate locations of accelerometers

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

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

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.

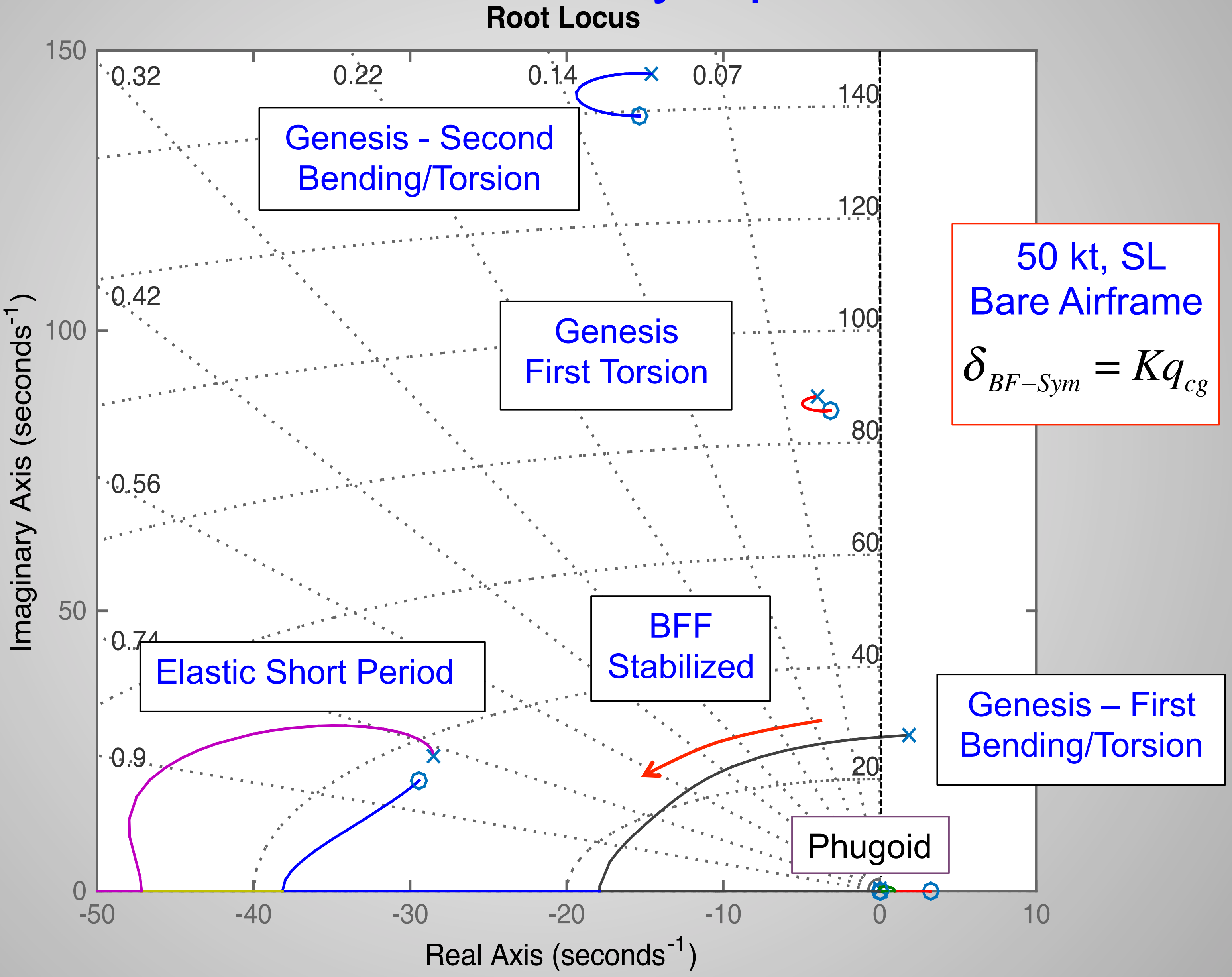
- Second flutter mode is more classical bending-torsion – max deflection at wing tips

- 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



Genesis - Second Bending/Torsion

Genesis First Torsion

BFF Stabilized

Elastic Short Period

Phugoid

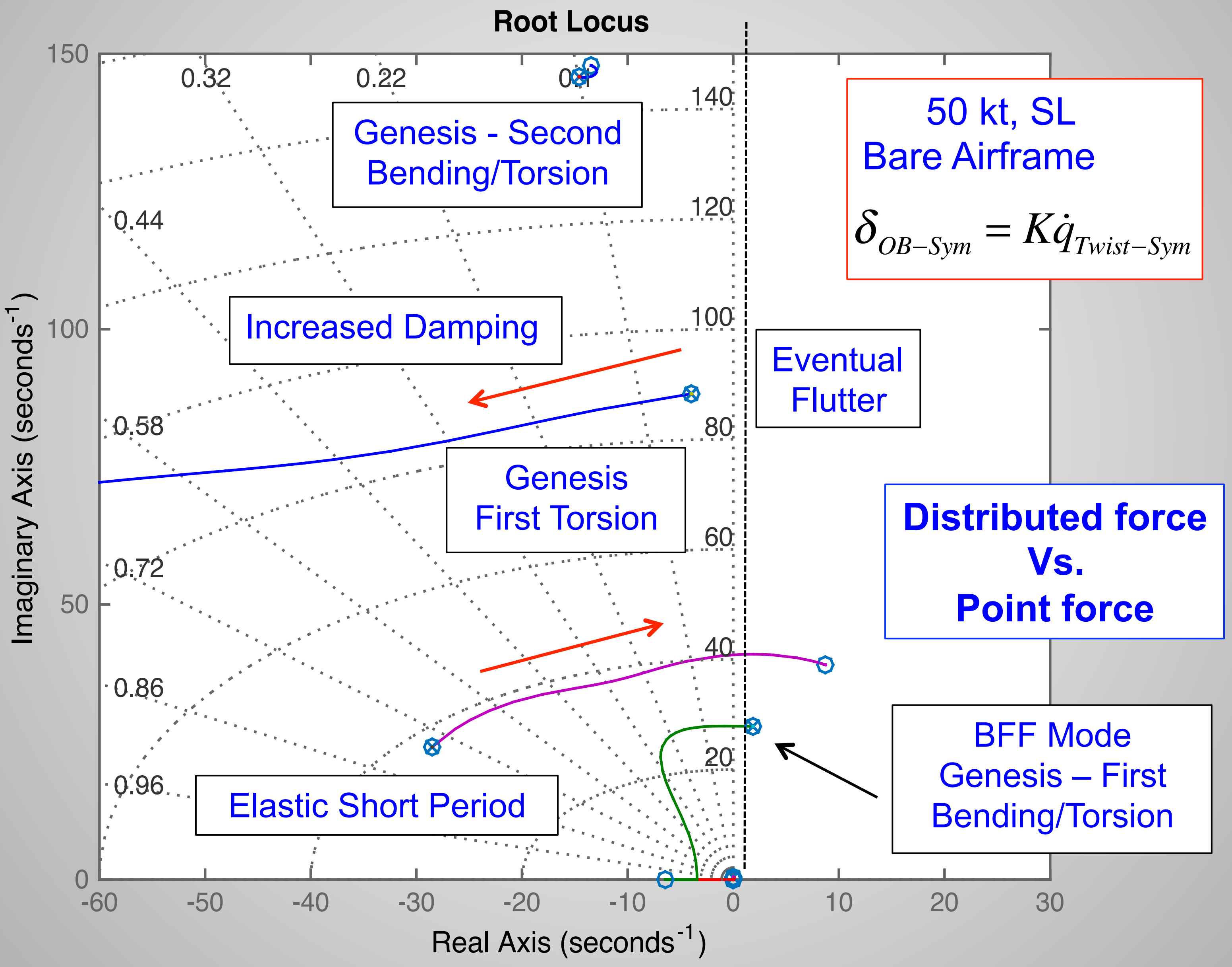
Genesis – First Bending/Torsion

50 kt, SL
Bare Airframe

$$\delta_{BF-Sym} = Kq_{cg}$$

Second Flutter-Mode Suppression

Wing-Tip Twist Accel. to Outboard Flaps



Genesis - Second Bending/Torsion

Increased Damping

Genesis First Torsion

Elastic Short Period

Eventual Flutter

50 kt, SL
Bare Airframe

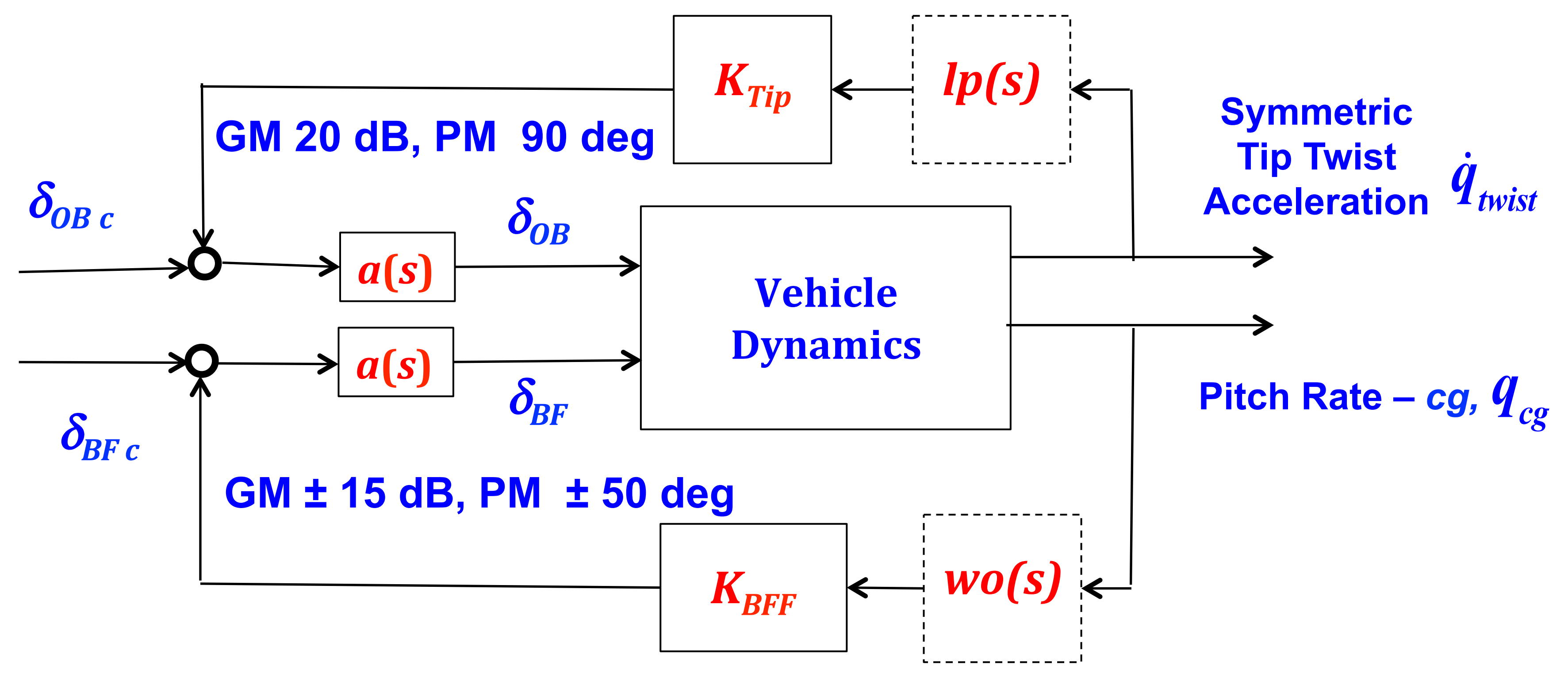
$$\delta_{OB-Sym} = K\dot{q}_{Twist-Sym}$$

Distributed force Vs. Point force

BFF Mode Genesis – First Bending/Torsion

Control-Law Architecture – ILAF

V = 50 kts



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

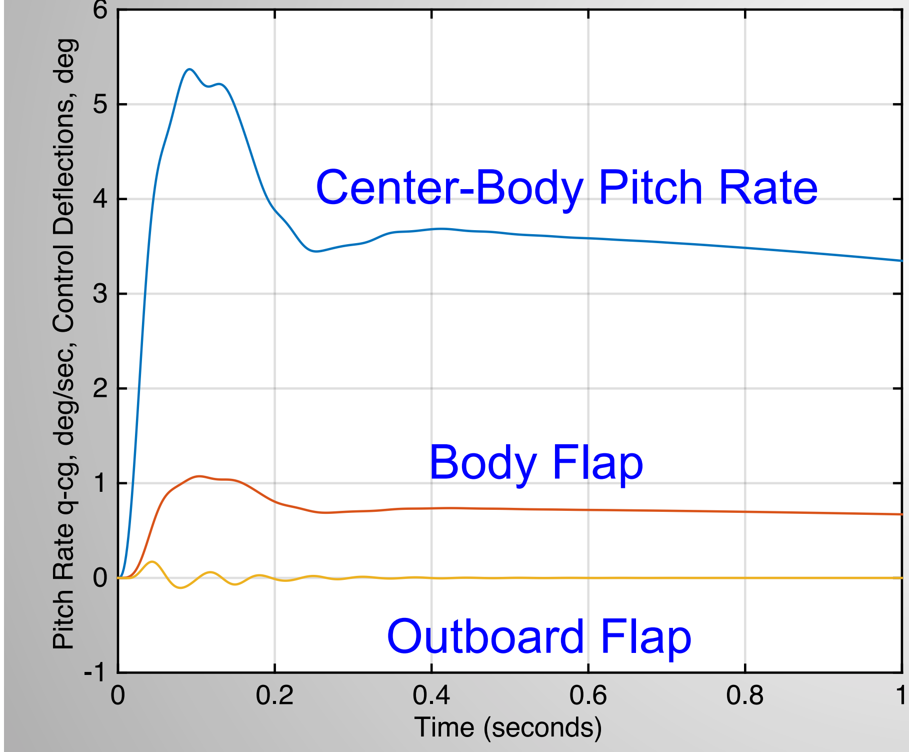
Symmetric blended accelerometer to symmetric outboard flap
- K_{Tip} ~ 0.0005 deg/deg/sec^2

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

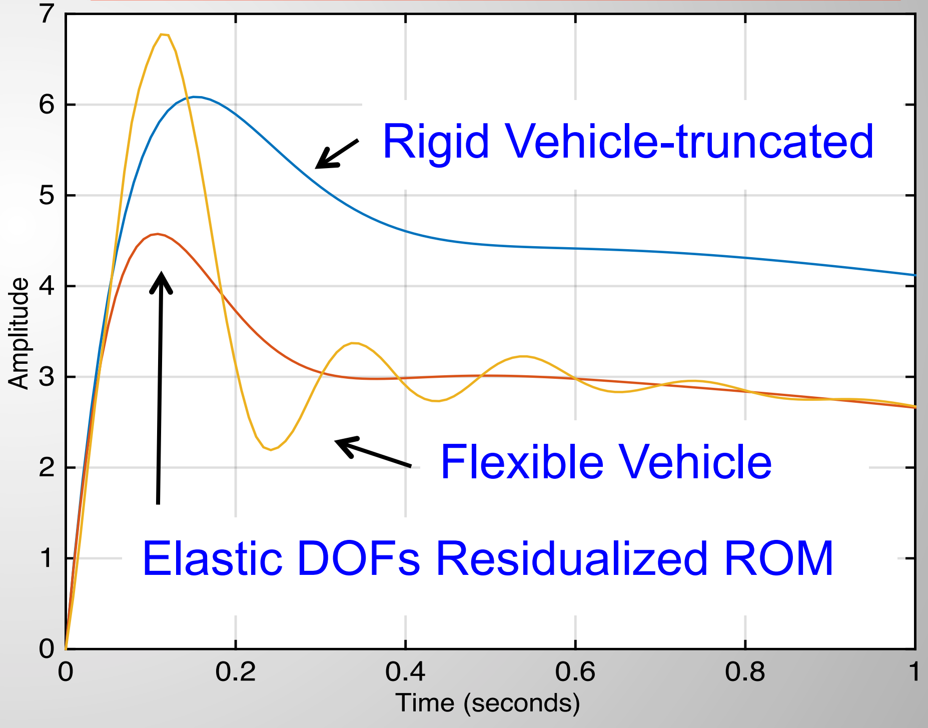
Closed-Loop Pitch-Rate Step Responses

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

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



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



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. To be submitted for publication.
2. Schmidt, “Integrated Stability Augmentation and Active Body-Freedom-Flutter Suppression For a Flexible Flying-Wing Research Drone,” DKS PAAW Working Paper, January, 2015. To be submitted for publication.

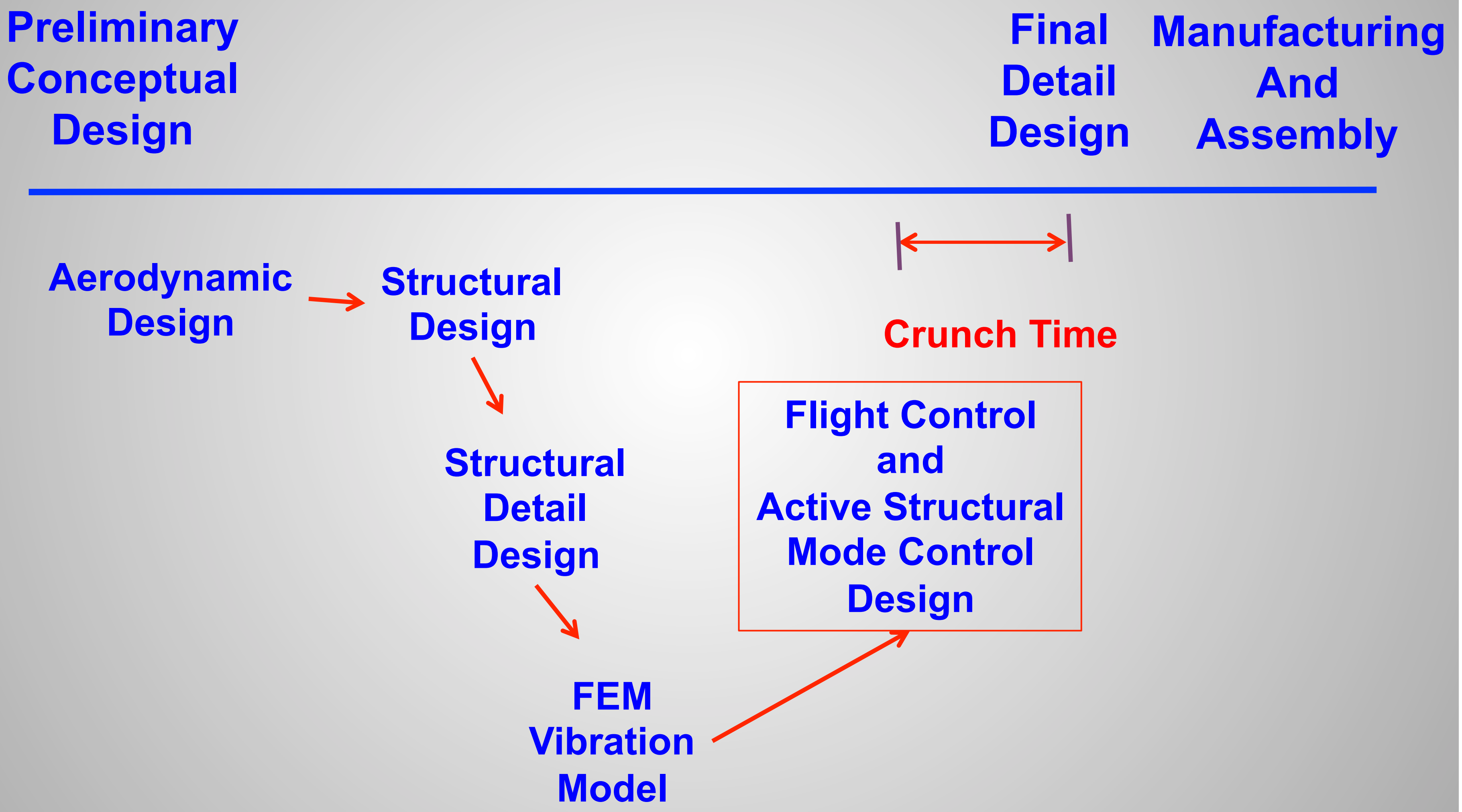
Backups

The “Flight-Dynamics” Modeling Formulation

- Based on mean-axis formulation of Milne (1964)*
- Mean axes replace the body-fixed axes used for rigid vehicles, their motion corresponds to RB 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.

Design-Cycle Time Line (Notional)



Preliminary Conceptual Design

Final Detail Design

Manufacturing And Assembly

Aerodynamic Design

Structural Design

Structural Detail Design

FEM Vibration Model

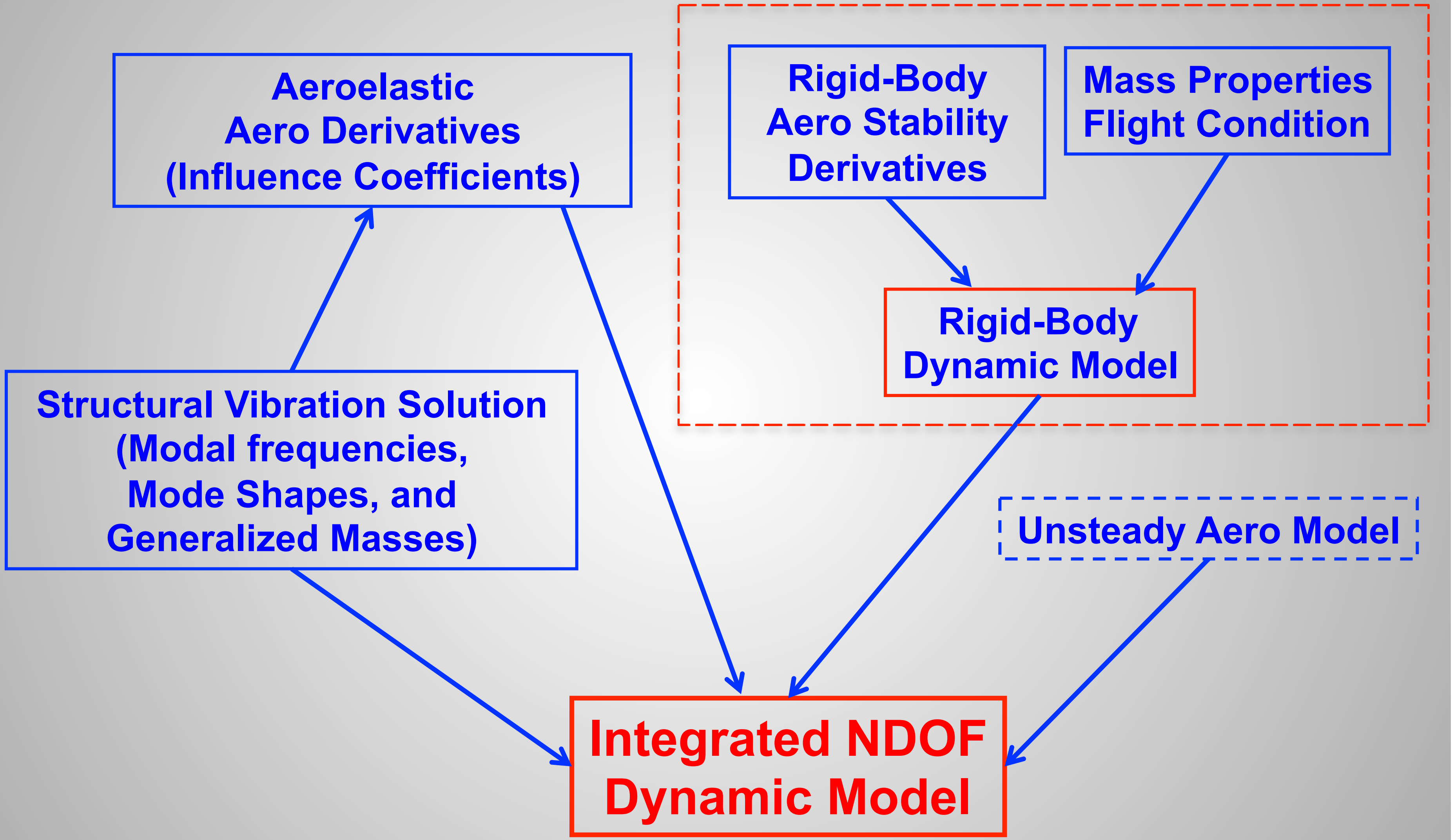
Crunch Time

Flight Control and Active Structural Mode Control Design

Potential Acceleration Enablers

- **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**

The Modeling Methodology



Aeroelastic
Aero Derivatives
(Influence Coefficients)

Rigid-Body
Aero Stability
Derivatives

Mass Properties
Flight Condition

Rigid-Body
Dynamic Model

Structural Vibration Solution
(Modal frequencies,
Mode Shapes, and
Generalized Masses)

Unsteady Aero Model

Integrated NDOF
Dynamic Model

NDOF Model Structure

Longitudinal Dynamics

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

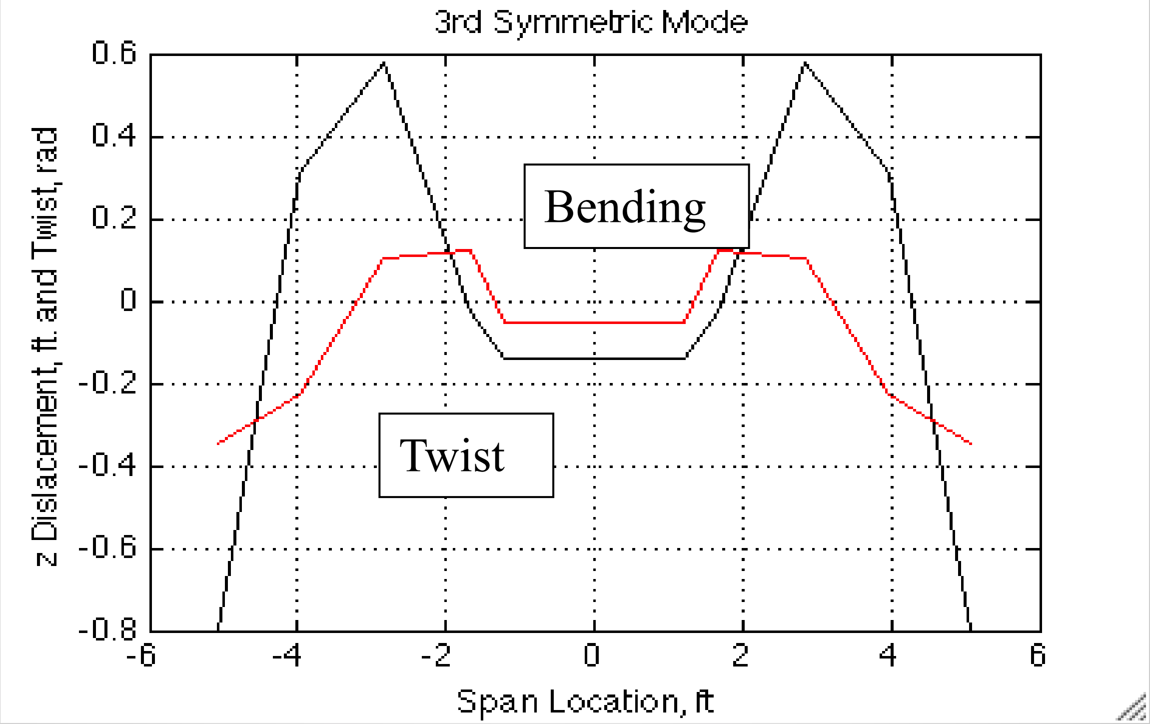
$$\mathbf{A} = \left[\begin{array}{cccc|ccccc}
X_u & X_\alpha & -g & X_q & 0 & 0 & \cdots & 0 & 0 \\
Z_u / \mathrm{U}_0 & Z_\alpha / \mathrm{U}_0 & 0 & 1 + Z_q / \mathrm{U}_0 & Z_{\eta_1} / \mathrm{U}_0 & Z_{\dot{\eta}_1} / \mathrm{U}_0 & \cdots & Z_{\eta_3} / \mathrm{U}_0 & Z_{\dot{\eta}_3} / \mathrm{U}_0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

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

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

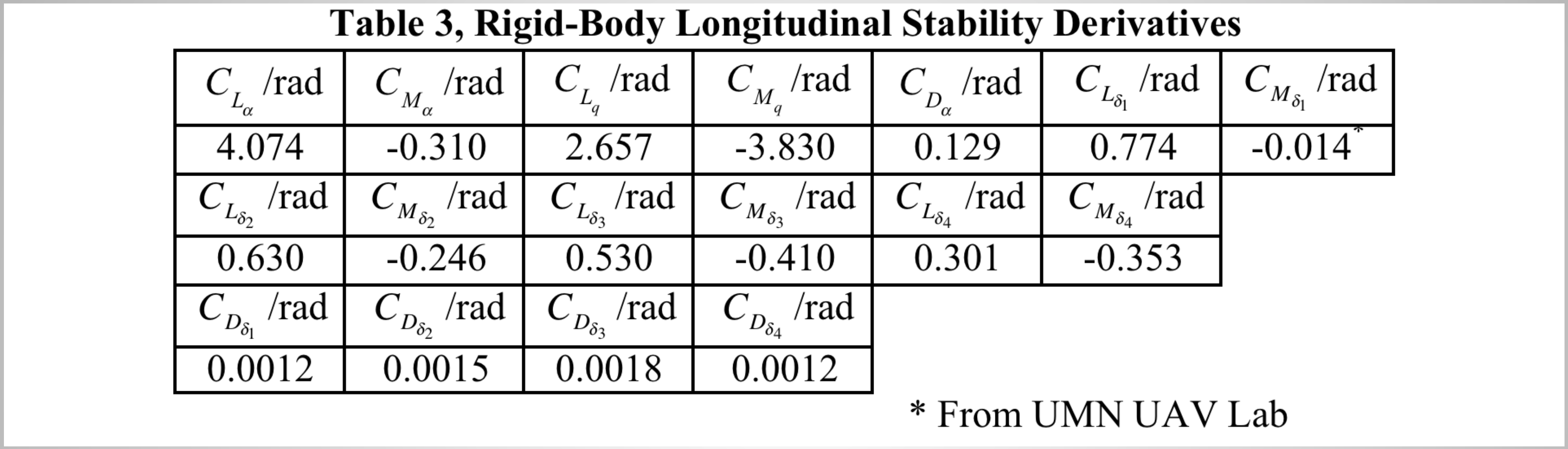


Table 3, Rigid-Body Longitudinal Stability Derivatives

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

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

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

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