Flutter Control

UNIVERSITY OF MICHIGAN

Part 1: Control of Flexible Aircraft

Fuel Efficient Aircraft Design

- Breguet Range Equation

$$\text{Range} = V\, I_{sp}\, \frac{L}{D}\, \ln\left(\frac{m_{\text{takeoff}}}{m_{\text{landing}}}\right)$$

- Improve fuel efficiency by
  - Improving engine efficiency
  - Reducing drag with longer, more slender wings (high aspect ratio)
  - Reducing structural mass

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  - Reducing structural mass

- Adverse effects
  - Increased coupling of structural dynamics and rigid body motion
  - Increased coupling of aerodynamic loads and structural deformation
  - Reduced flutter margins

Flutter

Source: NASA Dryden Flight Research

Flight Demonstrators

Lockheed Martin/AFRL: Body Freedom Flutter (BFF)

Ref: Burnett, et al. AIAA 2010; Holm-Hansen, et al. AUVSI 2010.

Flutter Free FLight Envelope eXpansion for ecOnomical Performance improvement
Ref: https://flexop.eu/, PI: B. Vanek

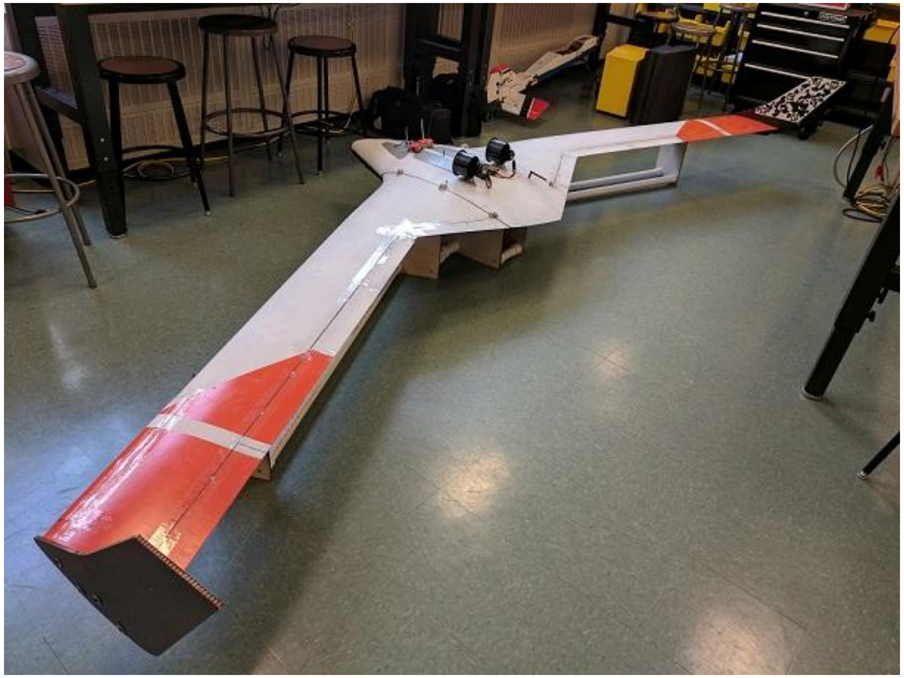
NASA/Lockheed Martin: X-56A Multi-Utility Tech. Testbed (MUTT)

Ref: Schaefer, ACGSC 2018.

Performance Adaptive Aeroelastic Wing (PAAW)

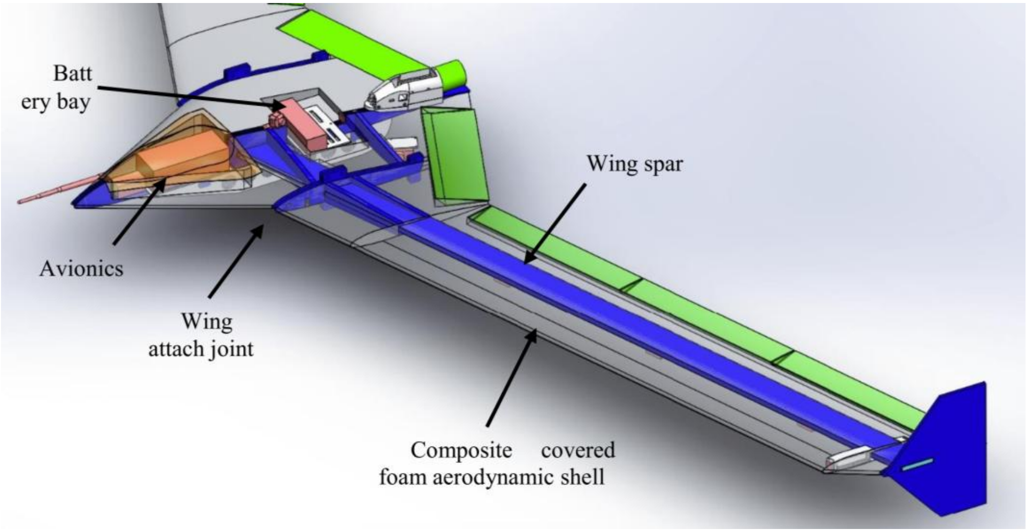
- Goal: Suppress flutter, control wing shape and alter shape to optimize performance
  - Funding: NASA NRA with Dr. Jeffrey Ouellette as Tech. Monitor
  - Team: UMN, VT, STI, CMSoft, Aurora, Schmidt & Assoc.

mAEWing1: BFF Replica
10ft wingspan, 14lbs



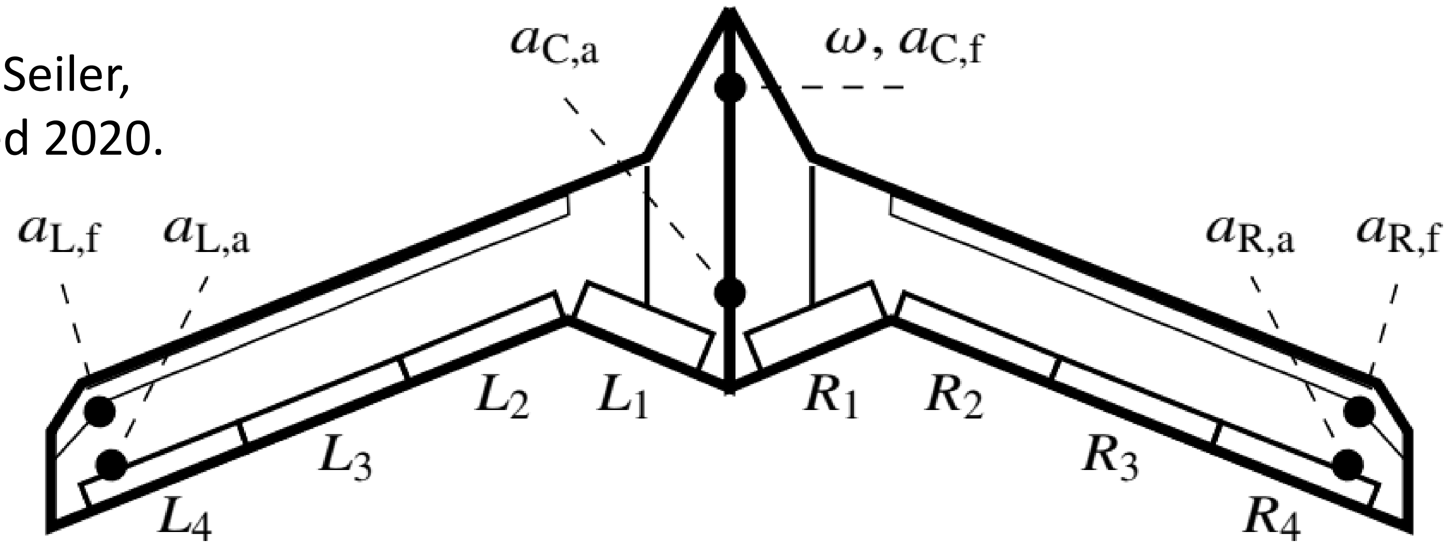
mAEWing2: Half-scale X-56A
14ft wingspan, 42lbs

mAEWing1 Sensor/Actuator Configuration

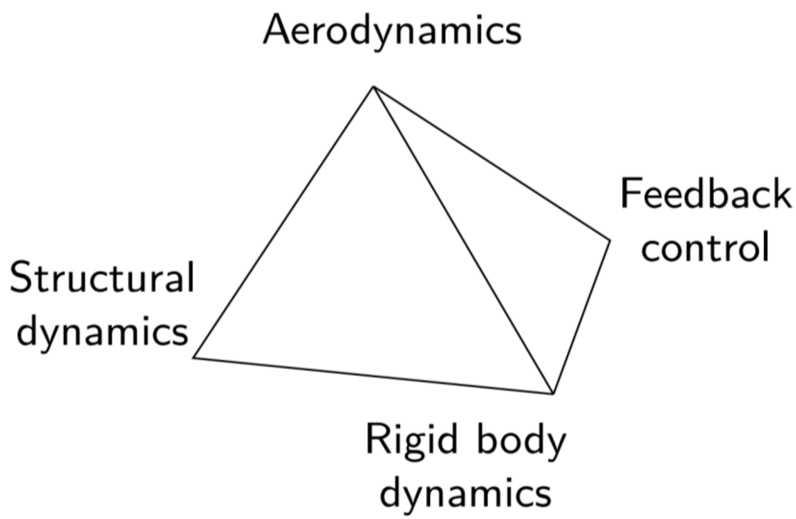


Ref: Regan & Taylor, AIAA 2016-1747

Ref: Theis, Pfifer, & Seiler, AIAA JGCD, accepted 2020.



Modeling for Aeroservoelastic Systems



[Cooper & Wright 2015; Collar 1946]

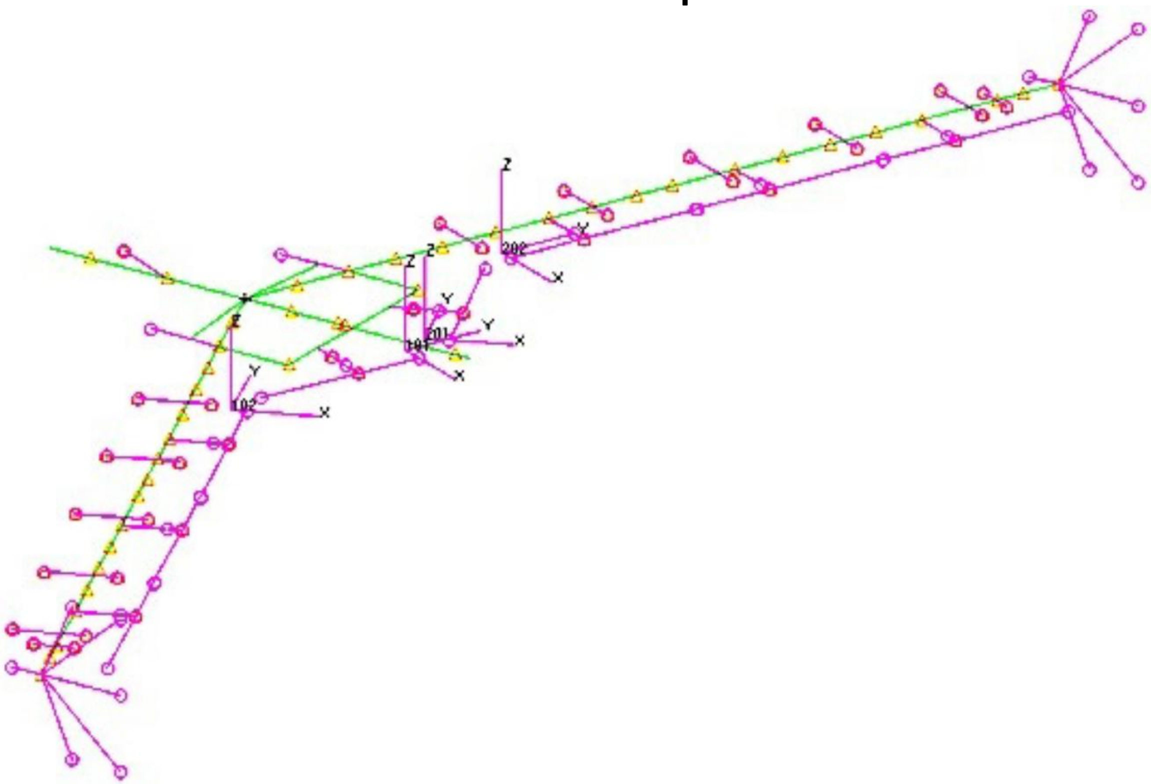
A variety models are required at different levels of fidelity for flutter analysis, control design, etc.

Lower Fidelity ⟷ Higher Fidelity

- Flight Dynamics (Schmidt)
- Control-oriented Panel Code (UMN/Gupta)
- IO Reduced-Order Model (STI/CMSoft)
- NASTRAN (VT)
- CFD/CSD (CMSoft)

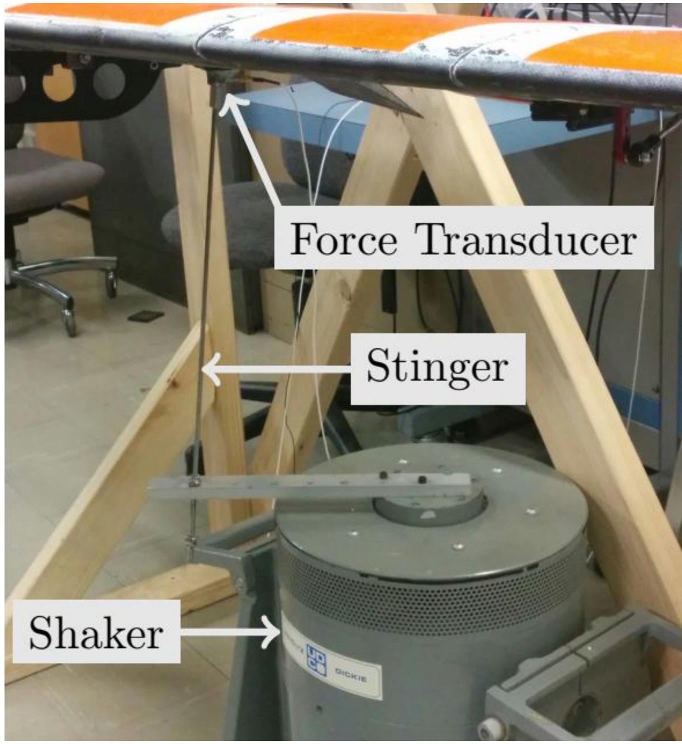
Control-Oriented Modeling

1. VT: Construct MSC NASTRAN model
   - Ref: Schmidt, Zhao, Kapania, AIAA 2016-1748
   - Finite-element model with rod / beam elements & unsteady aerodynamic model with double lattice.
   - Initial model from CAD and simple static test data from UMN



Control-Oriented Modeling

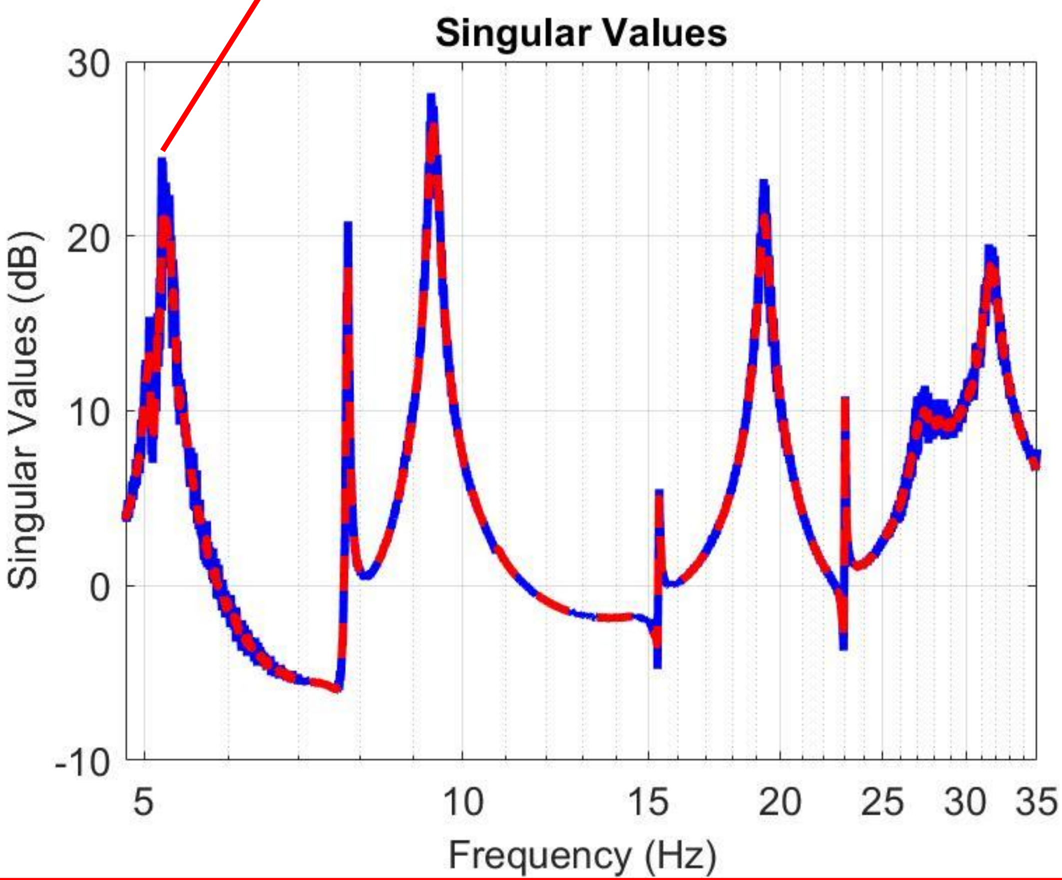
1. VT: Construct MSC NASTRAN model
2. VT/UMN: Update NASTRAN FEM with ground test data
   - Ref: Gupta, Seiler, Danowsky, AIAA 2016-1753
   - Matlab Demo: “Modal Analysis of a Flexible Flying Wing Aircraft”, Demonstrates frequency domain fitting in System ID Toolbox

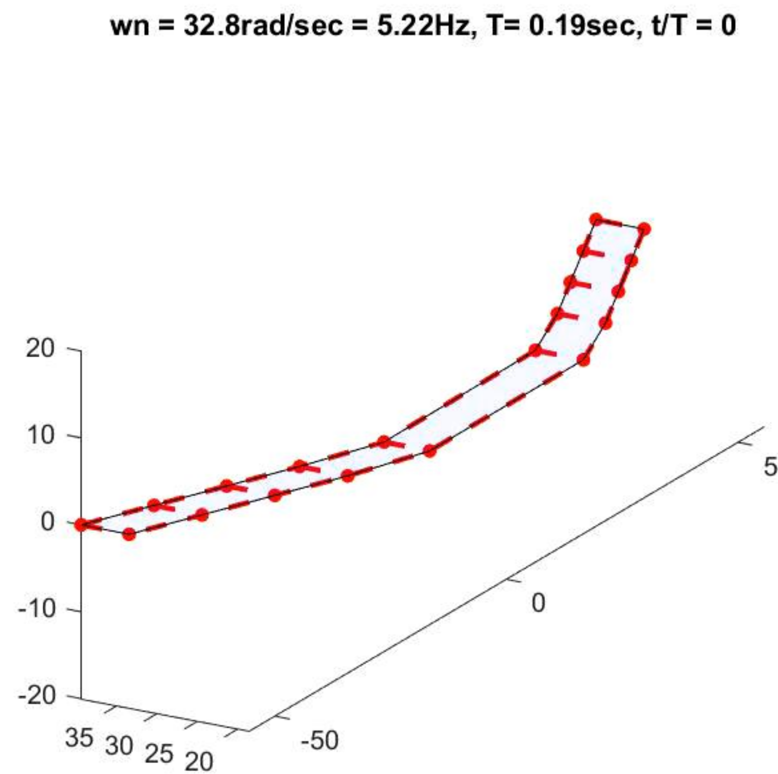


Control-Oriented Modeling

1. VT: Construct MSC NASTRAN model
2. VT/UMN: Update NASTRAN FEM with ground test data

First structural mode at 33.6rad/sec~=5.4Hz





Control-Oriented Modeling

1. VT: Construct MSC NASTRAN model
2. VT/UMN: Update NASTRAN FEM with ground test data
3. VT: Obtain mode shapes & frequencies from NASTRAN
   - Ref: Schmidt, Zhao, Kapania, AIAA 2016-1748

Symmetric 1st Bending ~5-6Hz

Symmetric 1st Torsion ~12Hz

Symmetric 2nd Bending ~19.5Hz

Control-Oriented Modeling

1. VT: Construct MSC NASTRAN model
2. VT/UMN: Update NASTRAN FEM with ground test data
3. VT: Obtain mode shapes & frequencies from NASTRAN
4. Schmidt: Construct low-order flight dynamics model
   - Ref: Schmidt, Zhao, Kapania, AIAA 2016-1748
   - Ref: Schmidt, Journal of Aircraft, 2016.
   - Parameter-varying model constructed using mean-axes

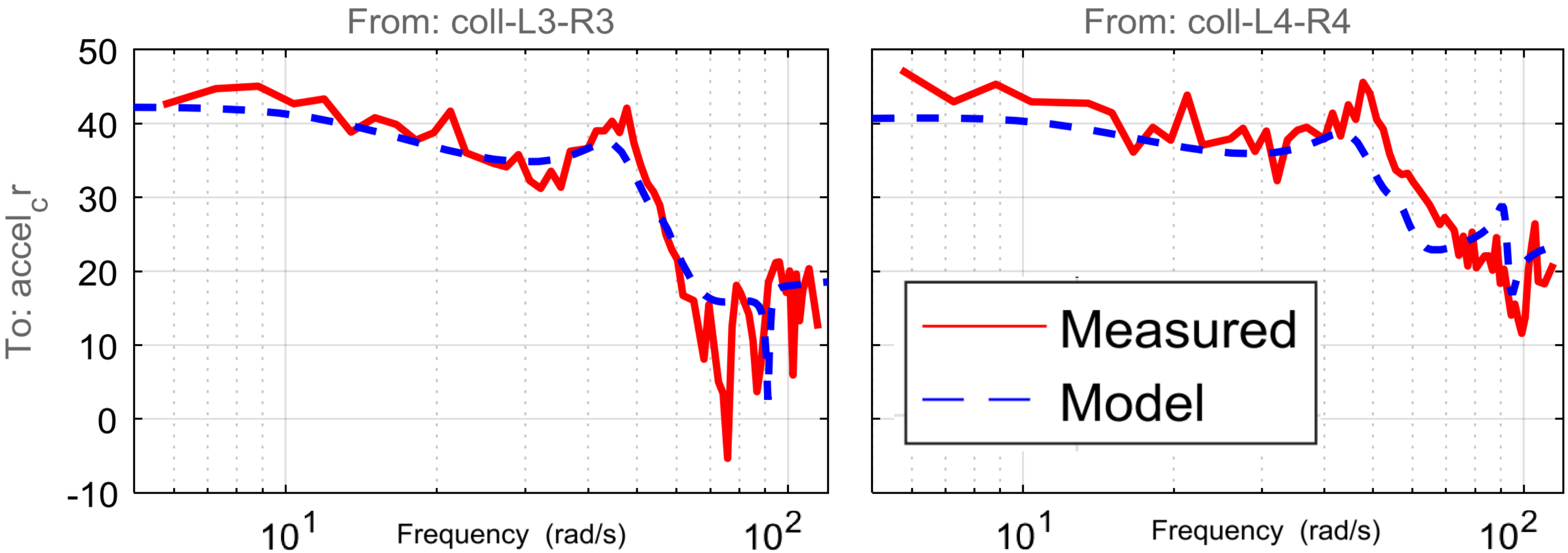
Model has longitudinal rigid body dyn. & three elastic modes

$$\dot{x} = A(V_\infty)x + B(V_\infty)u$$
$$y = C(V_\infty)x + D(V_\infty)u$$

where $x = [u \;\; \alpha \;\; \theta \;\; q \mid \eta_1 \;\; \dot{\eta}_1 \;\; \eta_2 \;\; \dot{\eta}_2 \;\; \eta_3 \;\; \dot{\eta}_3]^T$

Control-Oriented Modeling

1. VT: Construct MSC NASTRAN model
2. VT/UMN: Update NASTRAN FEM with ground test data
3. VT: Obtain mode shapes & frequencies from NASTRAN
4. Schmidt: Construct low-order flight dynamics model
5. STI/UMN/Schmidt: Grey-box ID from flight tests
   - Ref: Danowsky, Schmidt, Pfifer, AIAA 2017-1394



Bode mag (dB) from symmetric L3/R3 and L4/R4 to center body accel

Control-Oriented Modeling

1. VT: Construct MSC NASTRAN model
2. VT/UMN: Update NASTRAN FEM with ground test data
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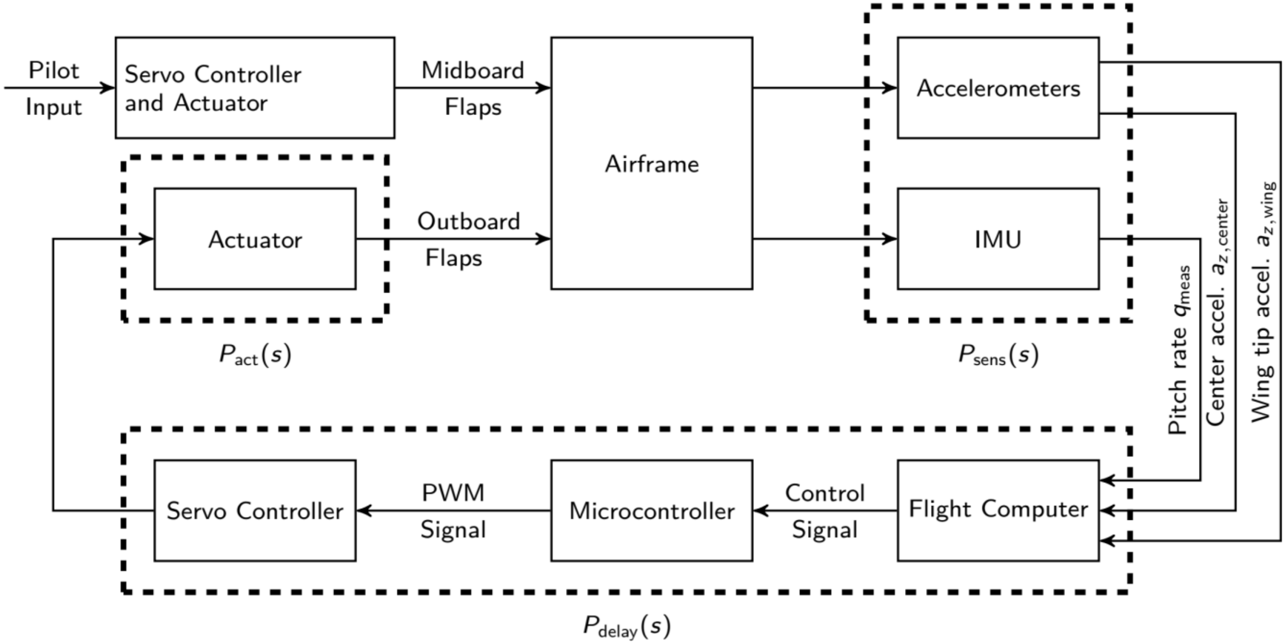
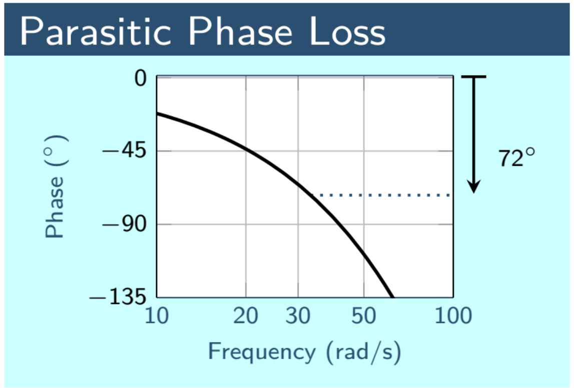
4. Schmidt: Construct low-order flight dynamics model
5. STI/UMN/Schmidt: Grey-box ID from flight tests

6. UMN: Component Modeling

- Ref: Theis, Pfifer, Seiler, AIAA 2016-1751





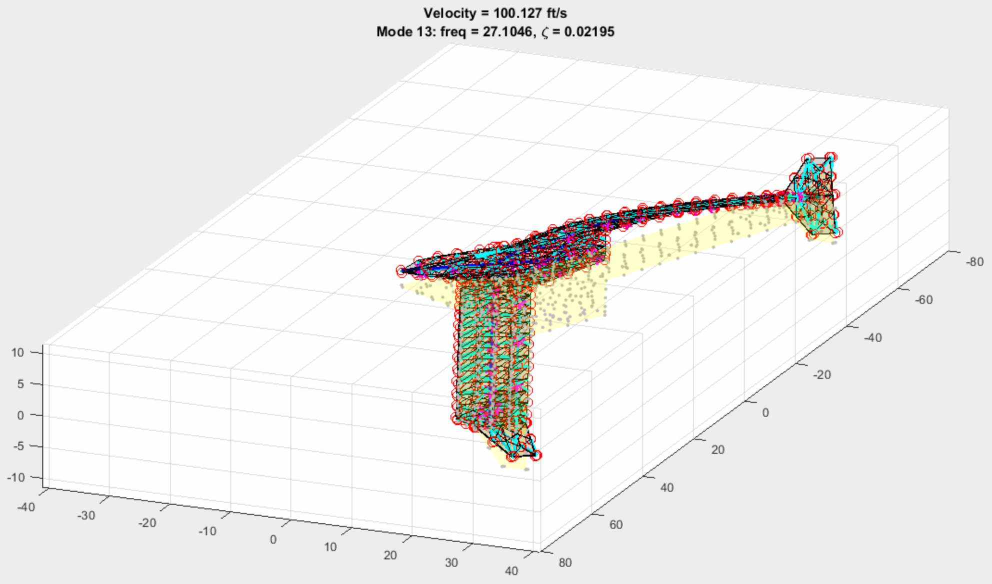
Open-Loop Flutter at ~30m/s

Model Predictions:

- Flight Dynamics (Schmidt): 29.1 m/s
- NASTRAN (VT): 29.5 m/s
- CFD/CSD (CMSoft): 30.8 m/s
- Input/Output Reduced Order Model (STI/CMSoft): 31.7m/s

Open-Loop Flutter at ~30m/s

Mode Shape: Coupling of rigid body short period and 1st symmetric wing bending.



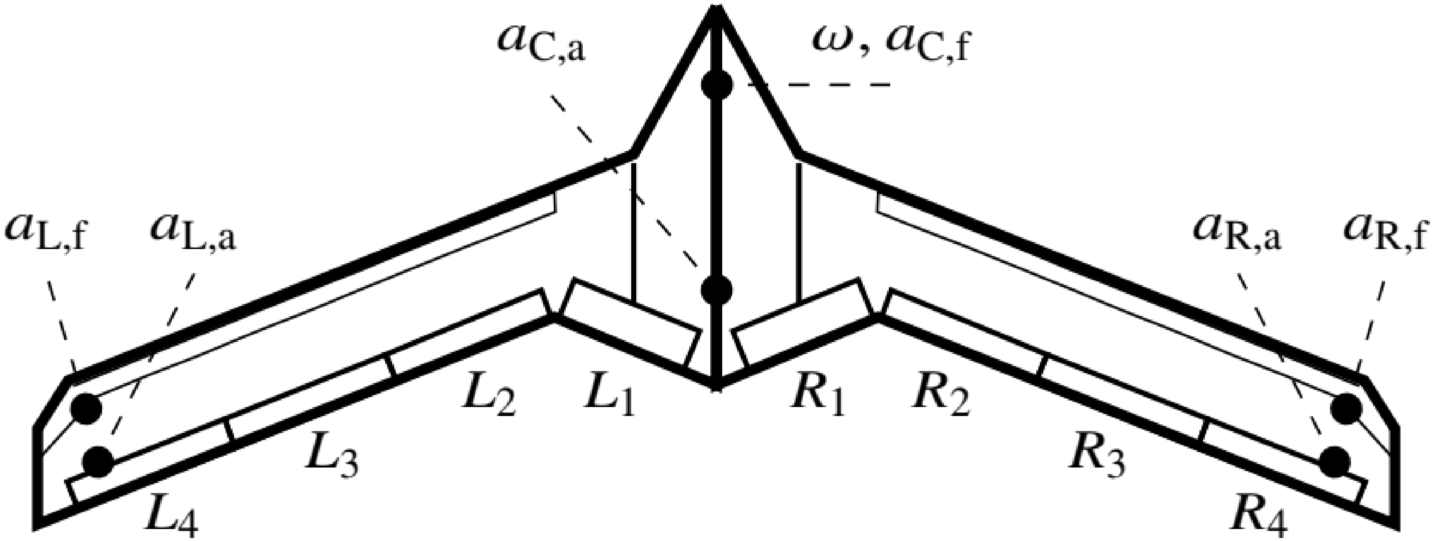
Mode shape from IOROM

Active Flutter Suppression

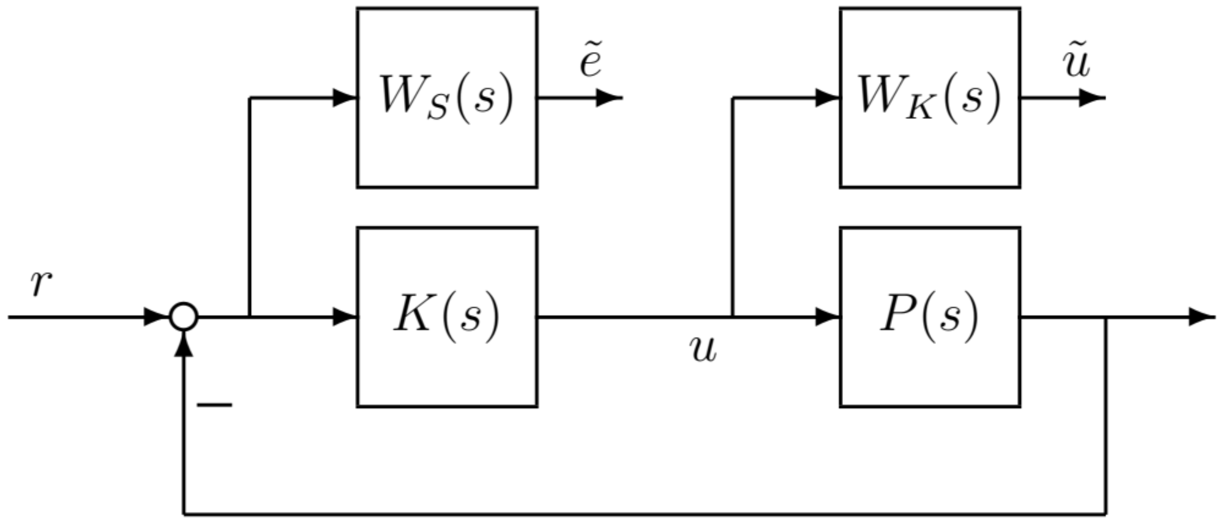
Design Objectives:

1. Maximize damping (or 1.' closed-loop flutter speed.)
2. Remain within actuator position/rate limits
3. Minimal interference with rigid-body autopilot
4. Robustness to model uncertainties

Approach: H_∞ Optimal Control with L1/R1/L4/R4 surfaces.



Brief Summary of H_∞ Optimal Control

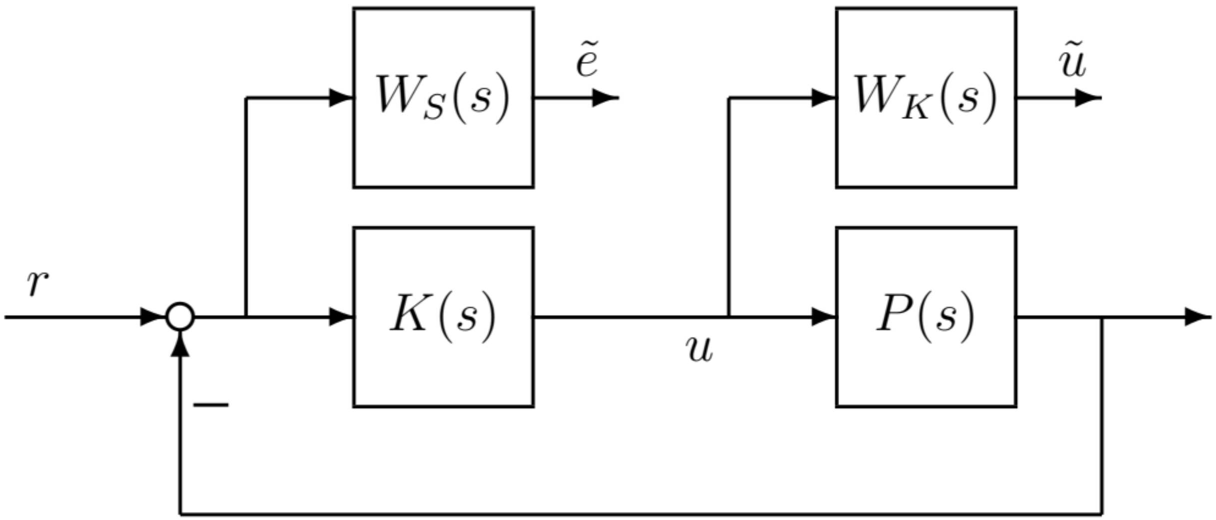


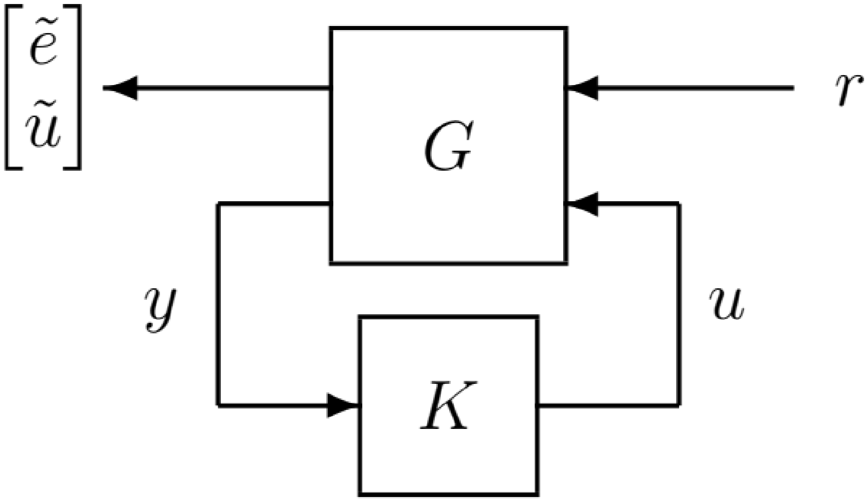
Goal (SISO): Find *K* to stabilize *P* and minimize

$$\sup_{\omega} |W_S(j\omega)S(j\omega)|^2 + |W_K(j\omega)K(j\omega)S(j\omega)|^2$$

Weights W_S and W_K selected to specify frequency-dependent tradeoffs.

Brief Summary of H_∞ Optimal Control

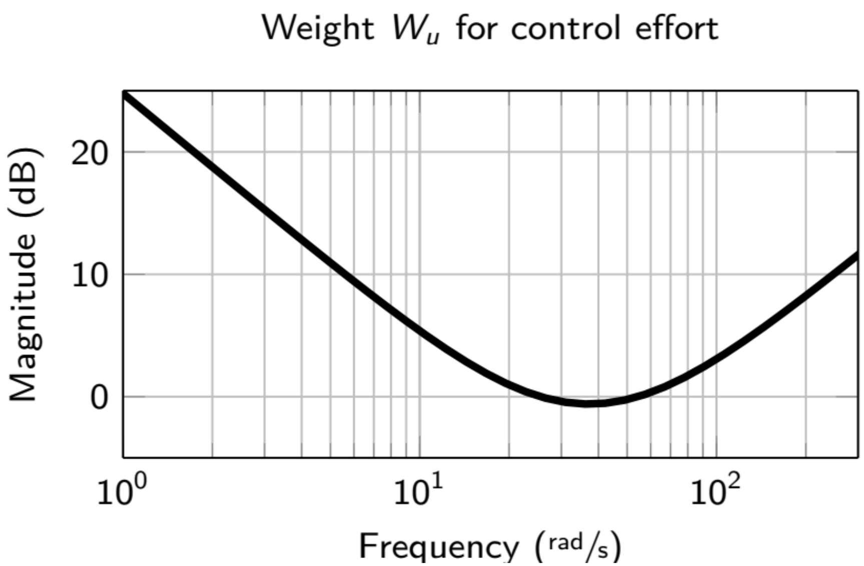


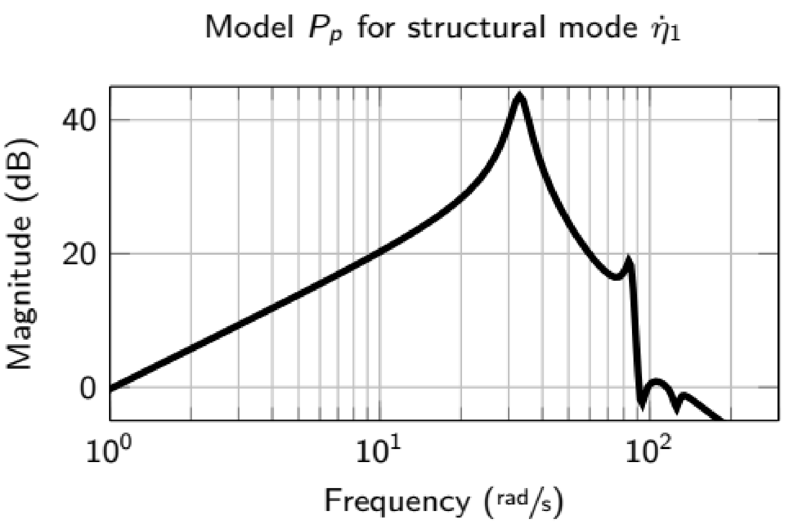


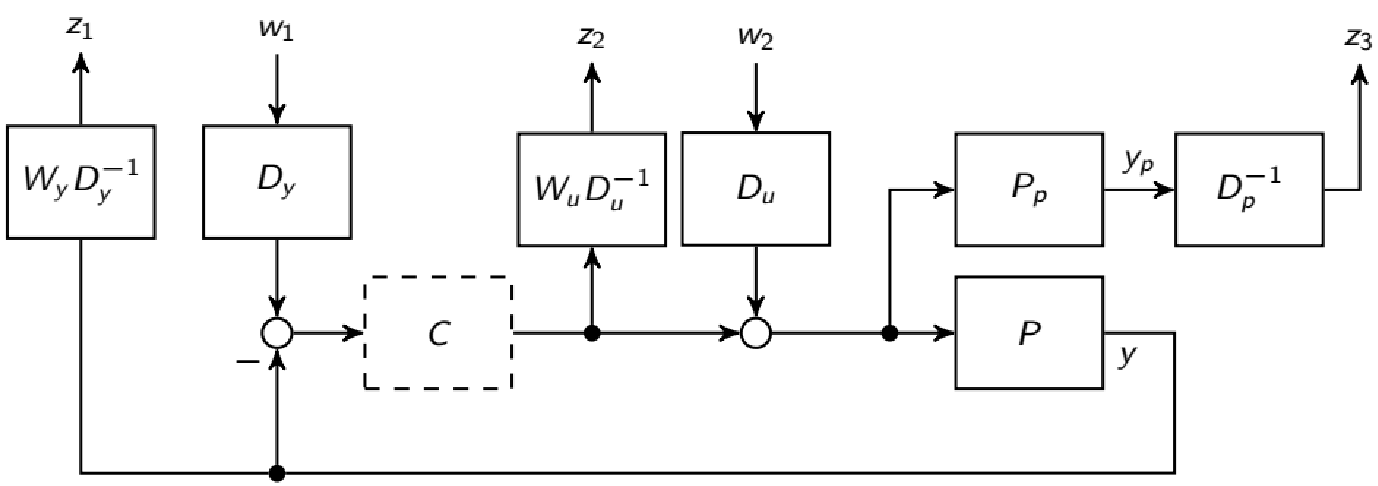
Goal: This is posed more generally as:

$$\inf_{K\, stabilizing} \|F_L(G,K)\|_\infty$$

H_∞ for Active Flutter Suppression

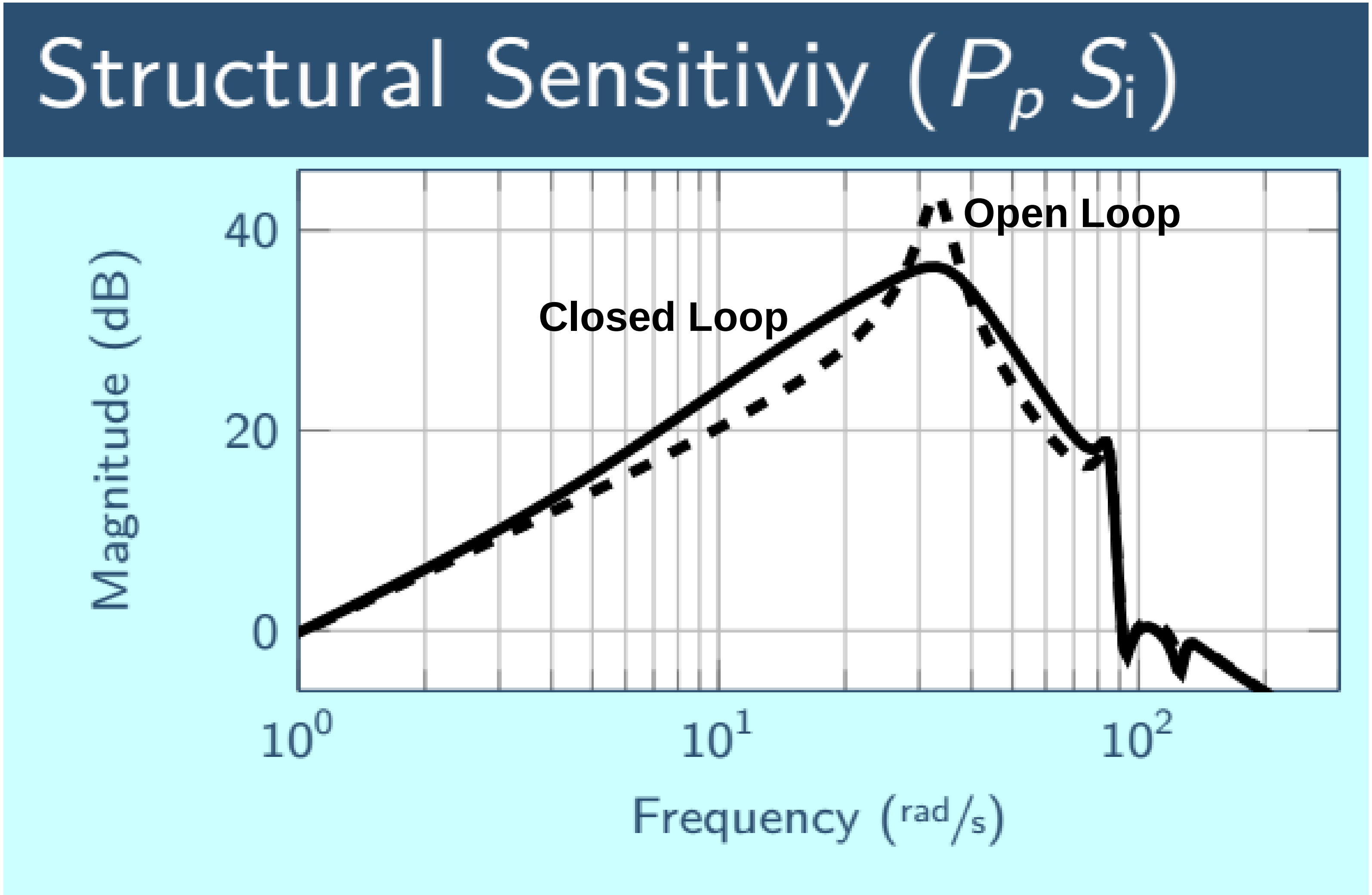




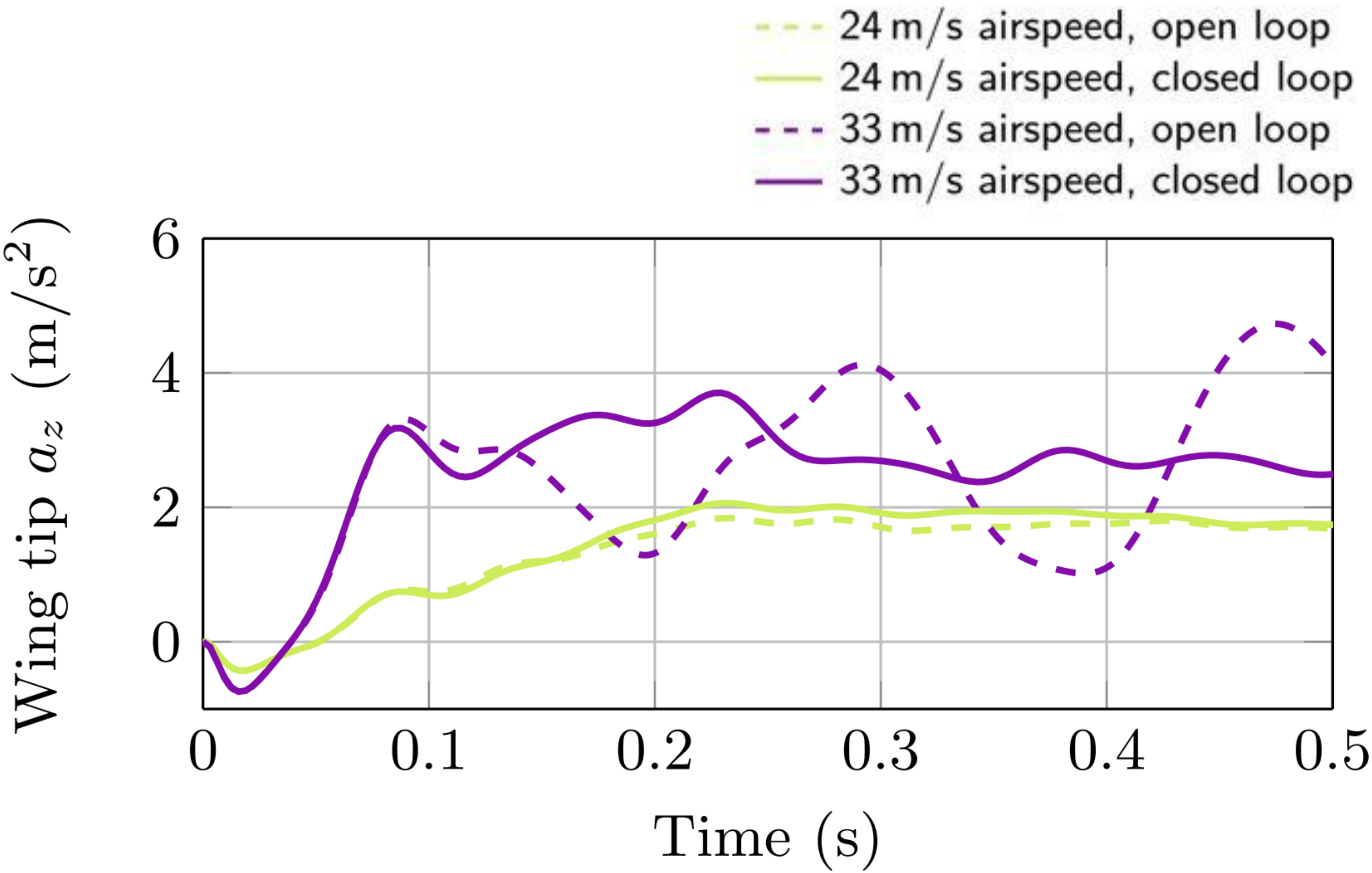


Refs: Theis, PhD 2018 & Theis, Pfifer, Seiler ('16 AIAA SciTech & JGCD)

Closed-Loop Performance



Closed-Loop Performance



Closed-Loop Flight Tests

- Three controllers designed to increase damping to BFF mode at 23m/s.
  - Hinf Controller (Retuned): Kotikalpudi, et al, AIAA 2018-3426
  - MIDAAS: Danowsky (STI), 2017-4353
  - Classical Controller: Schmidt, Journal of GCD, 2016.

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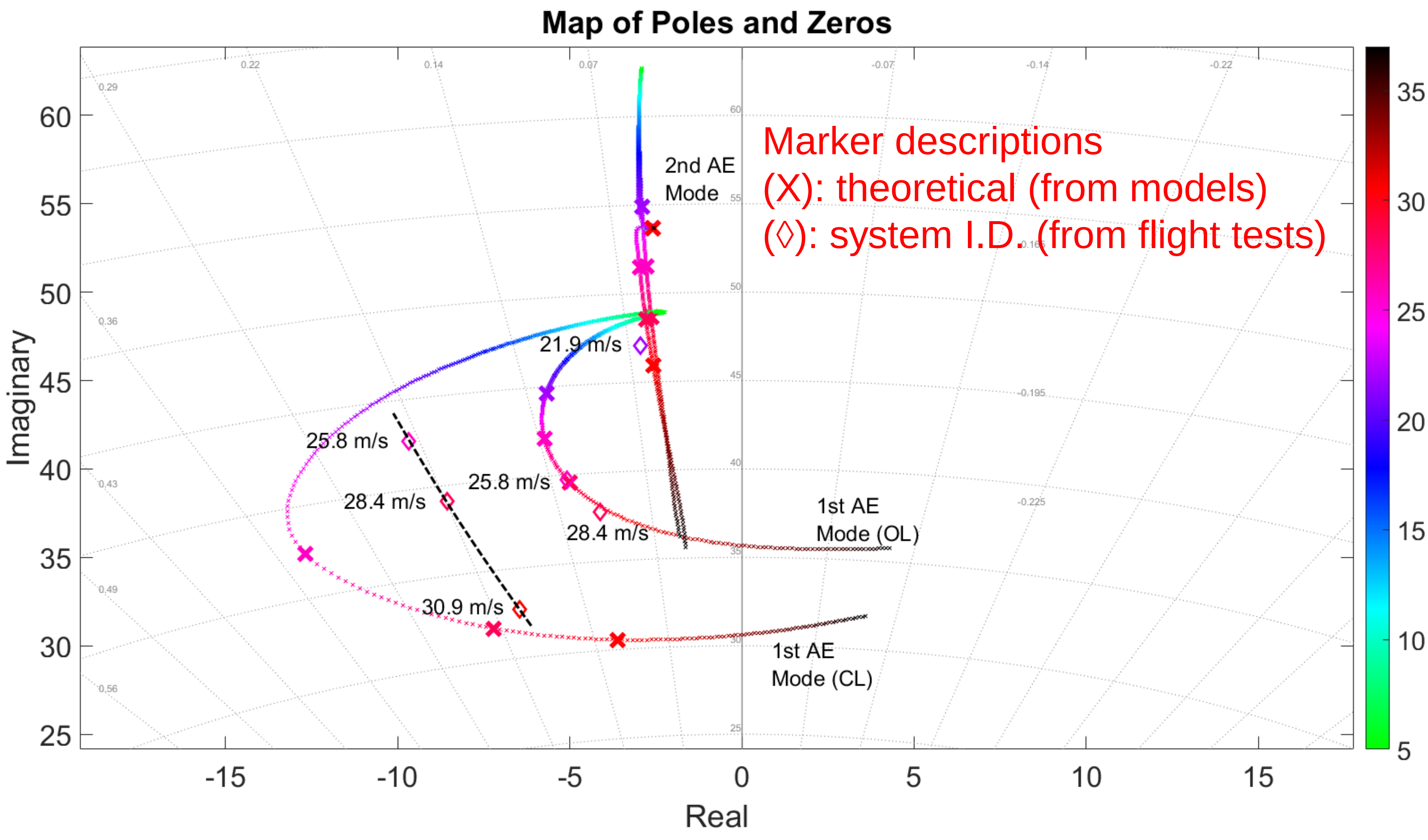
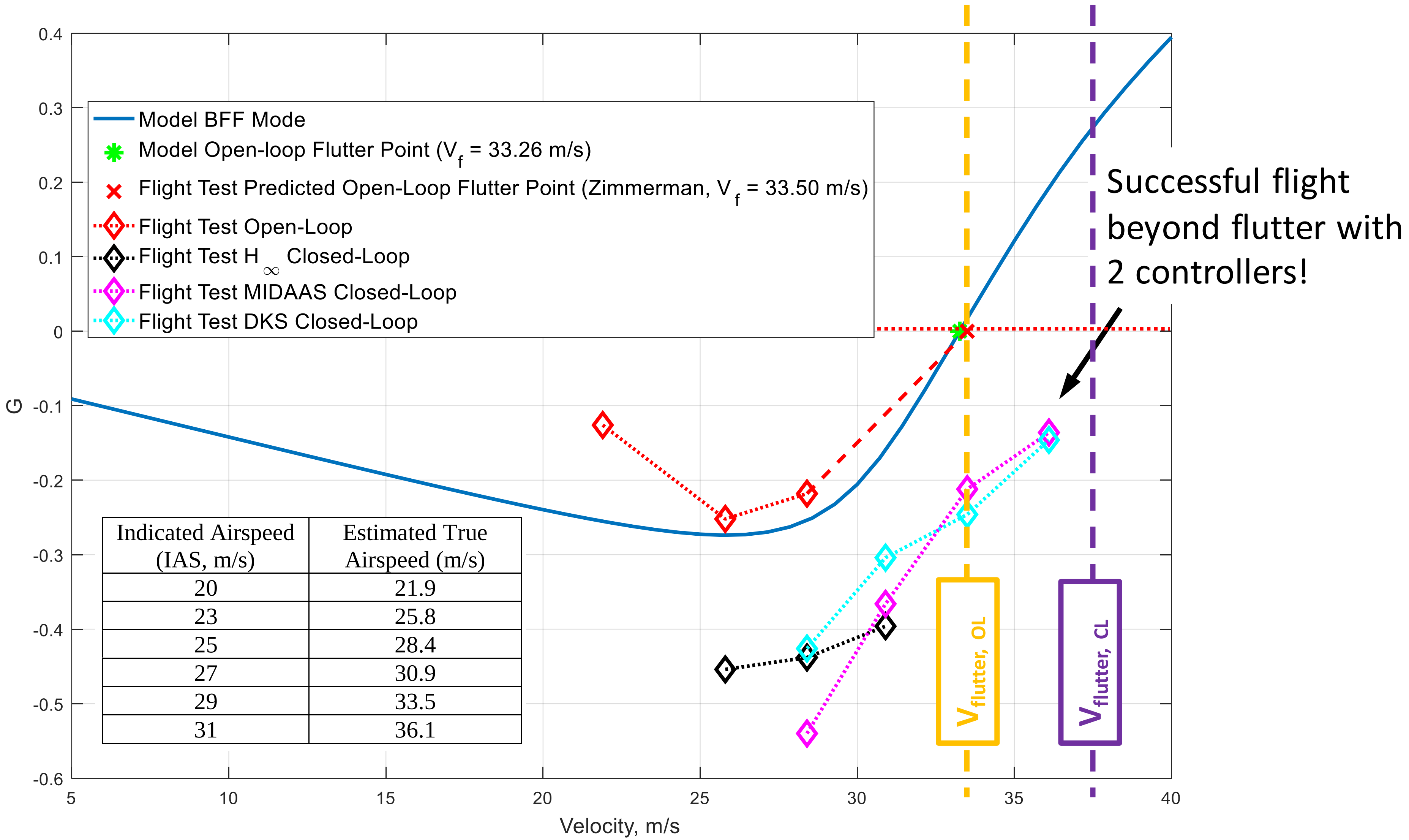
  - Classical Controller: Schmidt, Journal of GCD, 2016.

- Flight Tests
  - Ref: Danowsky, Kotikalpudi, Schmidt, Regan, Seiler, AIAA 2018-3427
  - Controllers tested at and above the designed airspeed.
  - All controllers added damping at the designed speed.
  - MIDAAS & classical designs flown above open-loop flutter speed.
  - Hinf controller did not increase flutter speed but this was an artifact of our design objective and flight test plan.

Pole Map for Retuned H_∞ Controller



Flight Test Summary



Indicated Airspeed (IAS, m/s)	Estimated True Airspeed (m/s)
20	21.9
23	25.8
25	28.4
27	30.9
29	33.5
31	36.1

Next Steps

- Robust Flutter Speed (RFS): Airspeeds where active flutter control has 6dB/45deg margins on all inputs & outputs
  - Metric for safe flight envelope with active flutter suppression
  - Current: Restrict envelope to 20% below (open-loop) flutter speed

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  - Current: Restrict envelope to 20% below (open-loop) flutter speed
- Redesigned 3 controllers to maximize robust flutter speed
  - Design complicated by second bending mode at higher speeds

- Preliminary Results:
  - H_∞ control achieves robust/absolute flutter speeds of 43/41 m/s
  - Similar but slightly lower speeds for MIDAAS & classical designs
  - Tested in sims (linear parameter varying model with actuator limits & nonlinear panel-based model)