Flight Control of Flexible Aircraft

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Outline

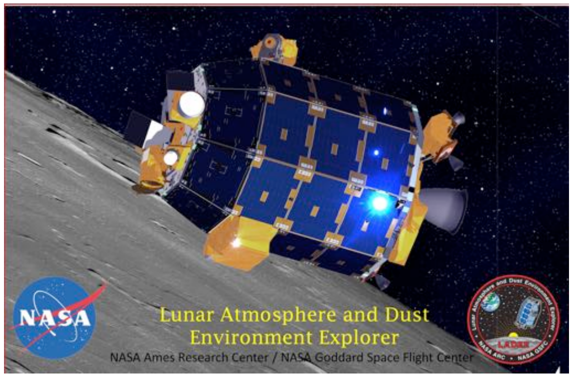
- **Introduction**
- **Performance Adaptive Aeroelastic Wing**
- **Aeroservoelasticity Modeling of Flexible Aircraft**
- **Multi-Objective Flight Control**
  - Real-Time Drag Minimization
  - Gust / Maneuver Load Alleviation
  - Adaptive Flutter Suppression
- **X-56A Collaboration**
- **Other Collaborations**

Advanced Control and Evolvable Systems Group

- Advanced Control and Evolvable Systems (ACES) Group within the Intelligent Systems Division (code TI) has 21 researchers, 13 with Ph.D.

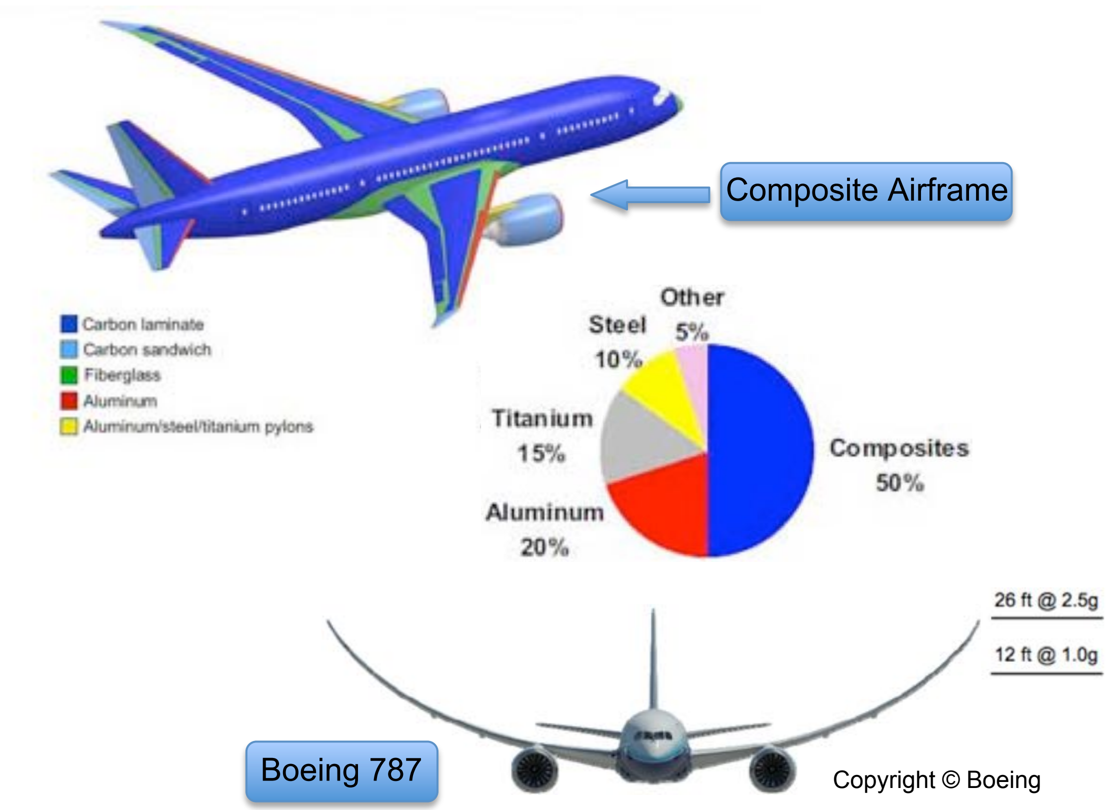
- Conduct GNC research and multidisciplinary fixed-wing vehicle dynamic modeling and simulations

- More than 90% research supports aeronautics with some space-related GNC



Introduction

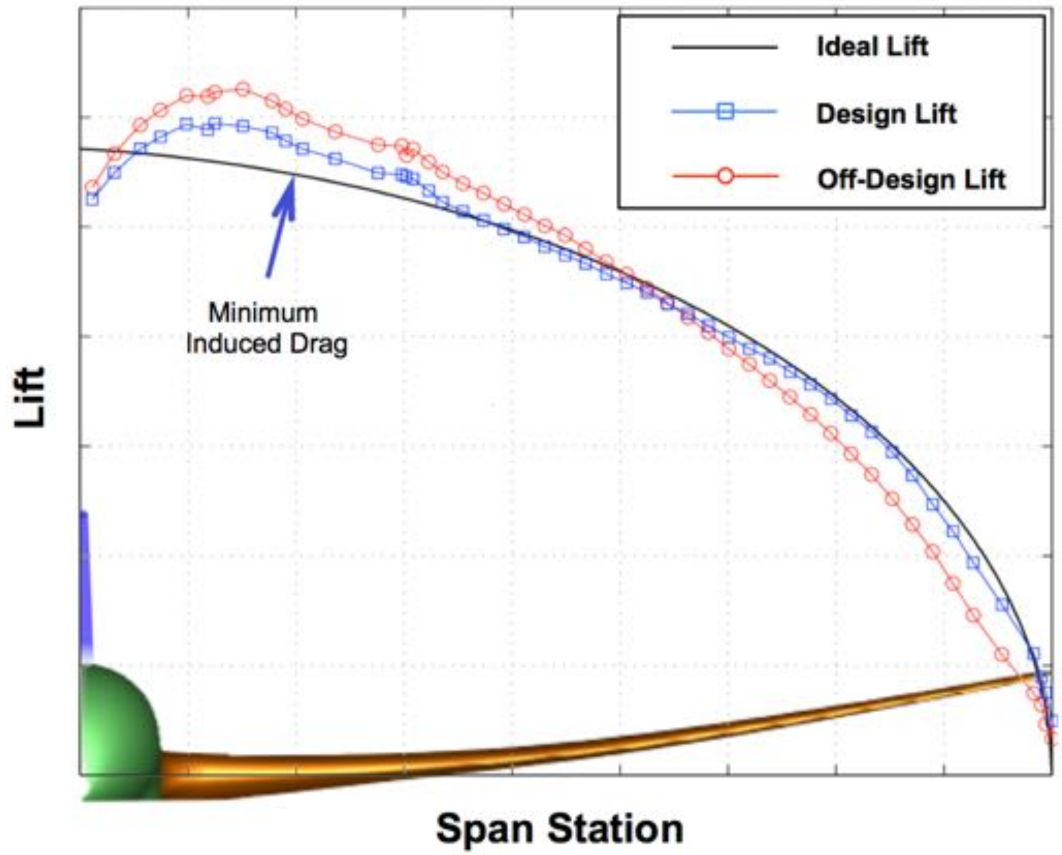
- **Composite wing technology in modern passenger aircraft affords weight reduction but also causes increased wing flexibility**



High-Aspect Ratio Truss-Braced Wing

Impact on Aerodynamics

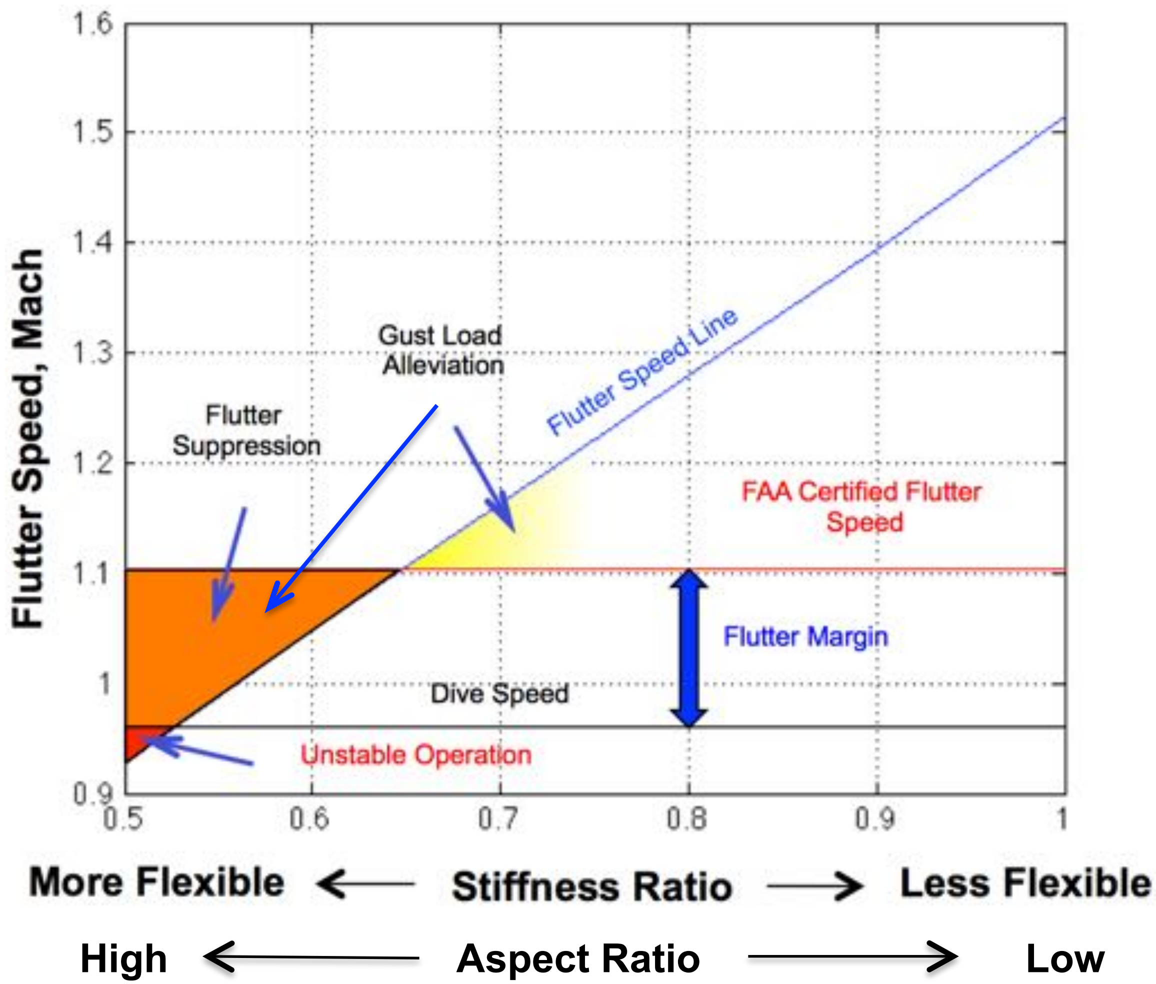
- **Increased wing deflection impacts optimal span load at off-design, causing increase in drag**



Increased drag leads to increased fuel consumption

Impact on Flight Load, Stability and Control

- **Increased wing flexibility causes reduced flutter margin, aeroservoelastic interactions with dynamics and control, and increased gust response**

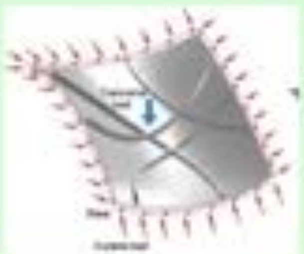


AATT Project Research Themes

Based on Goal-Driven Advanced Concept Studies

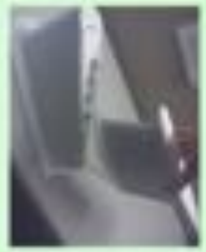
Goals Metrics (N+3)	Noise	Emissions (LTO)	Emissions (cruise)	Energy Consumption
	Stage 4 – 52 dB cum	CAEP6 – 80%	2005 best – 80%	2005 best – 60%

Goal-Driven Advanced Concepts (N+3)

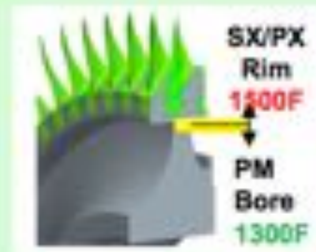


1. Lighter-Weight Lower Drag Fuselage

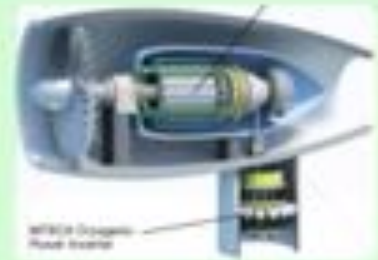
2. Higher Aspect Ratio Optimal Wing



3. Quieter Low-Speed Performance



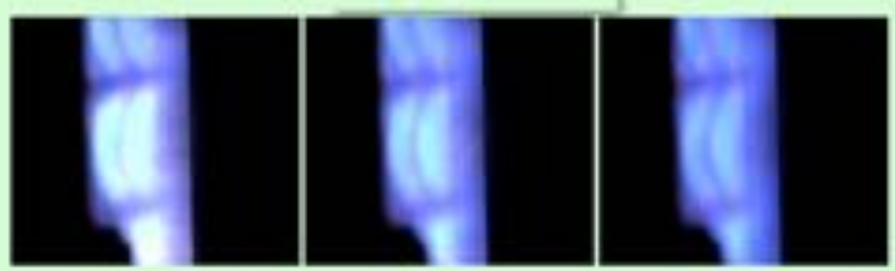
4. Cleaner, Compact Higher BPR Propulsion



5. Hybrid Gas-Electric Propulsion

6. Unconventional Propulsion Airframe Integration

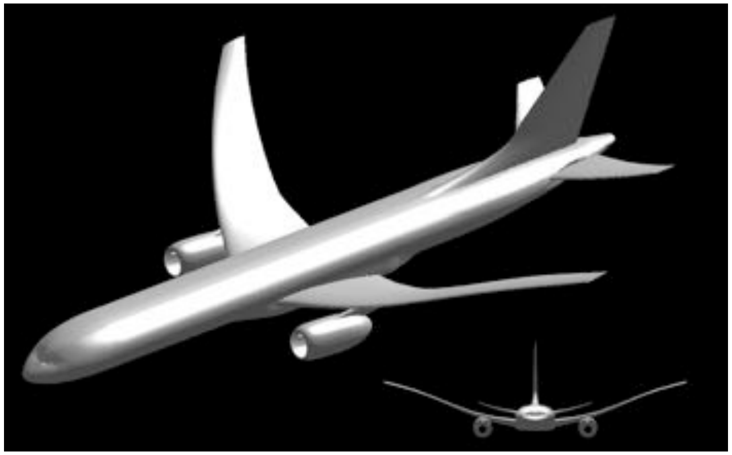
7. Alternative Fuel Emissions



Research Themes with Investments in both Near-Term Tech Challenges and Long-Term (2030) Vision

Performance Adaptive Aeroelastic Wing Research

- **Multidisciplinary design analysis optimization (MDAO) capabilities for development of advanced adaptive wing technology concepts**



Multi-Fidelity Modeling
- Multi-fidelity aero modeling (Cart3D, Overflow, Lava, Vorlax, Vspaero)
- Coupled FEM (Beam3D, NASTRAN) with aero codes
- Aeroelasticity / Aeroservoelasticity (ASE)

ASE – Flight Dynamics
- Coupled ASE – rigid aircraft flight dynamics
- Gust modeling
- Actuator dynamics of ASE control effectors

Control Effectors
- VCCTEF / continuous leading edge slat
- Distributed control surfaces
- Other novel concept

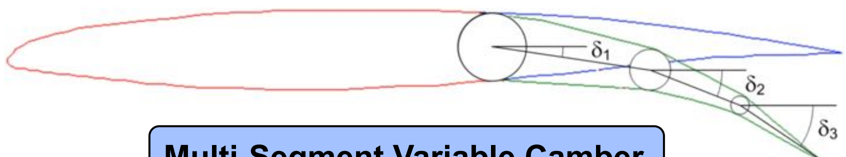
Multidisciplinary Optimization
- Aerodynamic design optimization for drag reduction
- MDO for drag minimization, load alleviation, and active ASE control

ASE Flight Control
- ASE control (flutter suppression, load alleviation)
- multi-objective flight control
- Real-time drag optimization

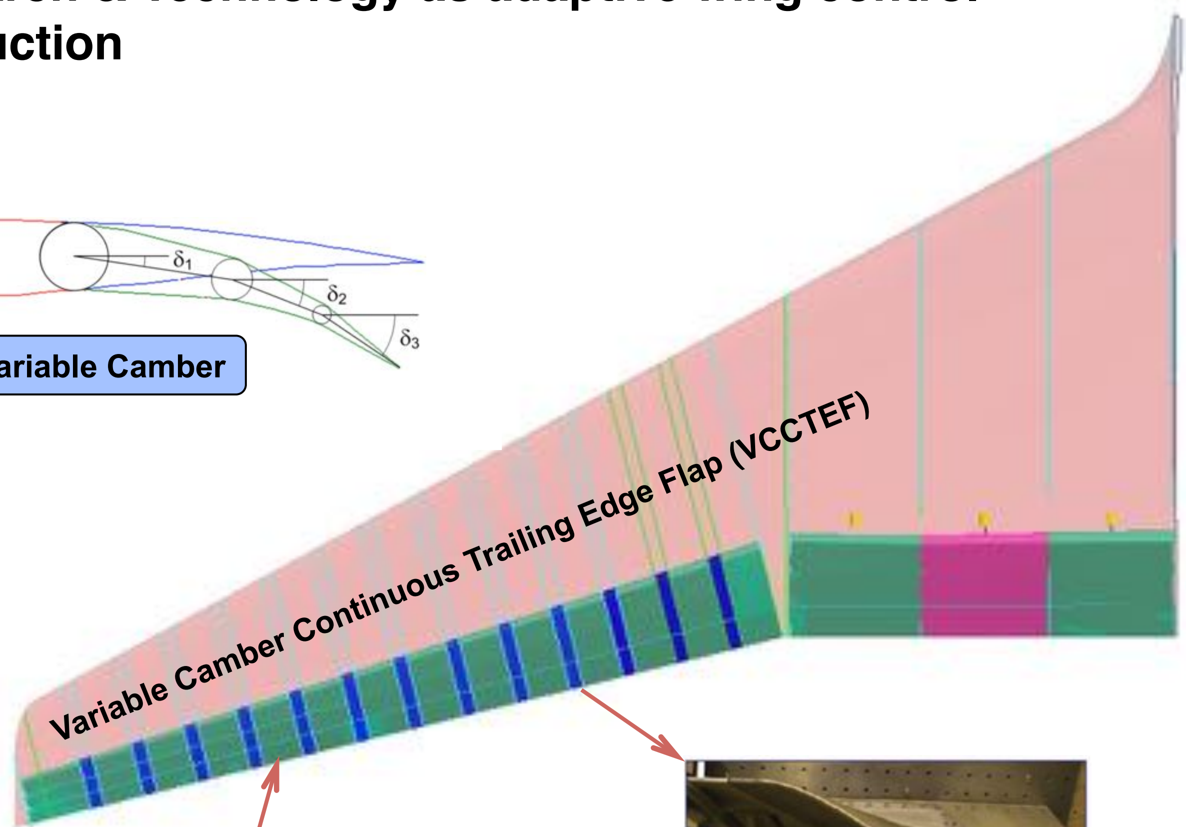
Performance Analysis
- Design trade-study
- Mission analysis / trajectory optimization to minimize fuel burn

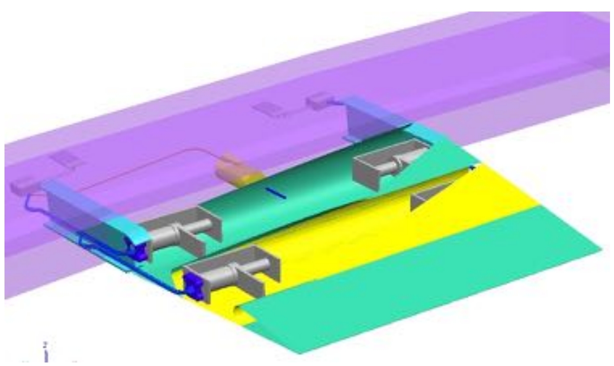
Performance Adaptive Aeroelastic Wing

- **Variable Camber Continuous Trailing Edge Flap (VCCTEF) developed by NASA and Boeing Research & Technology as adaptive wing control technology for drag reduction**



Multi-Segment Variable Camber





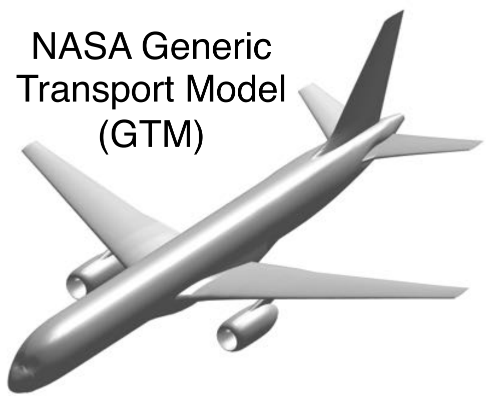
SMA and EMA Hinge Line Actuation

Individual Flap Deflection for Spanwise Lift Optimization

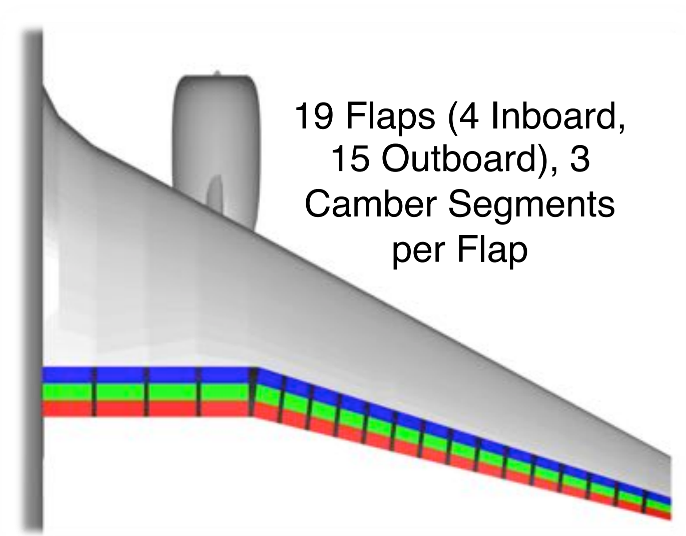
Conformal Mold Line Material ***for Gap Covering to Eliminate Flap Noise and Reduce Drag***

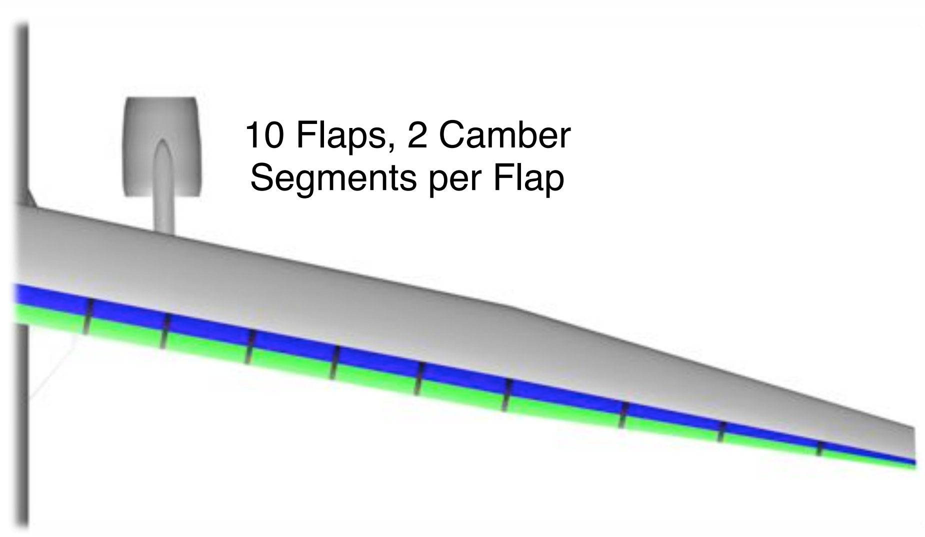
Flexible Wing High-Aspect Ratio Transport Models

- **Flexible conventional transport and next-generation Truss Brace Wing**



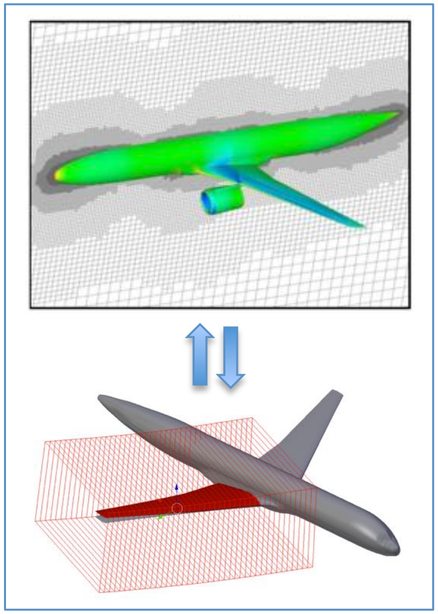
- **VCCTEF is equipped as an adaptive wing control technology**



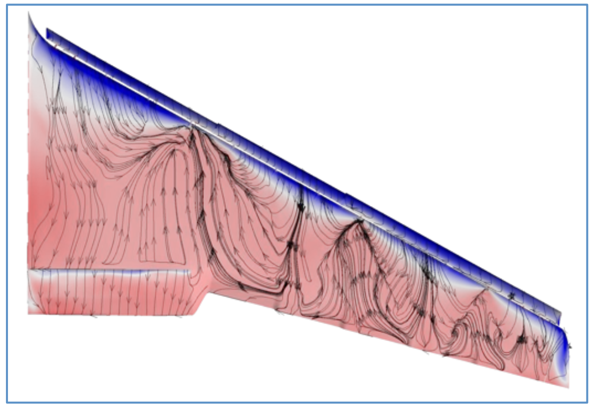


Multi-Fidelity Coupled Aerodynamic Tools

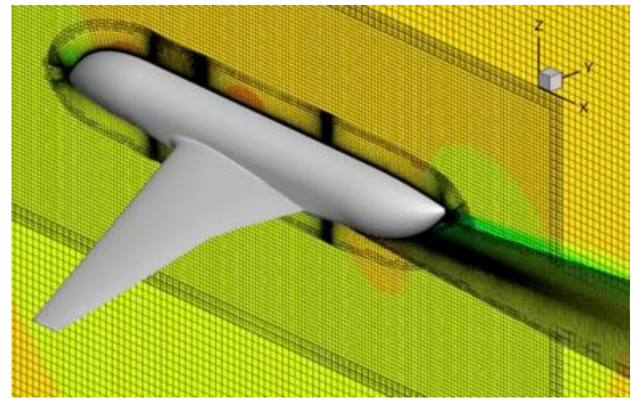
- **Right fidelity tools – Euler and high-fidelity RANS CFD for optimization and vortex-lattice with transonic and viscous flow corrections for MDAO**



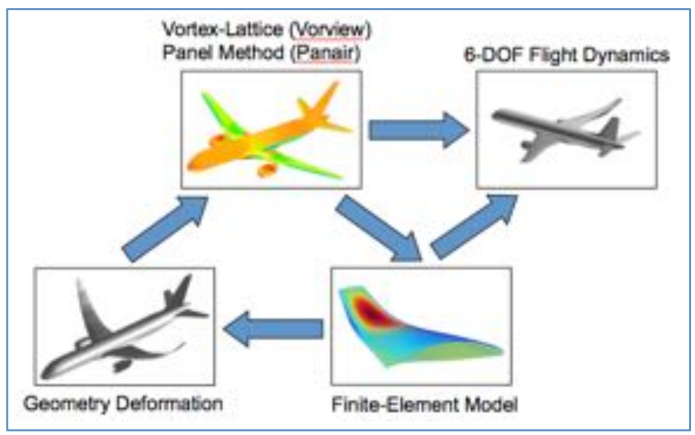
CART3D Static Aero-Structure



OVERFLOW Static Aero-Structure



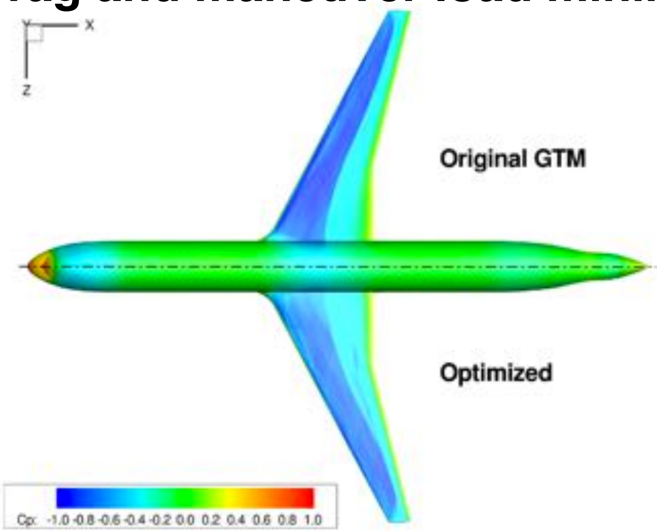
LAVA CFD



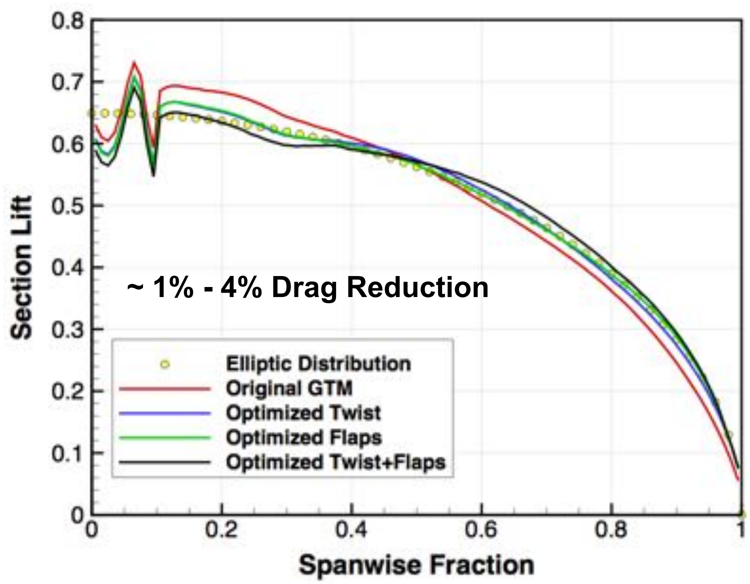
VORLAX Static & Dynamic FEM / NASTRAN

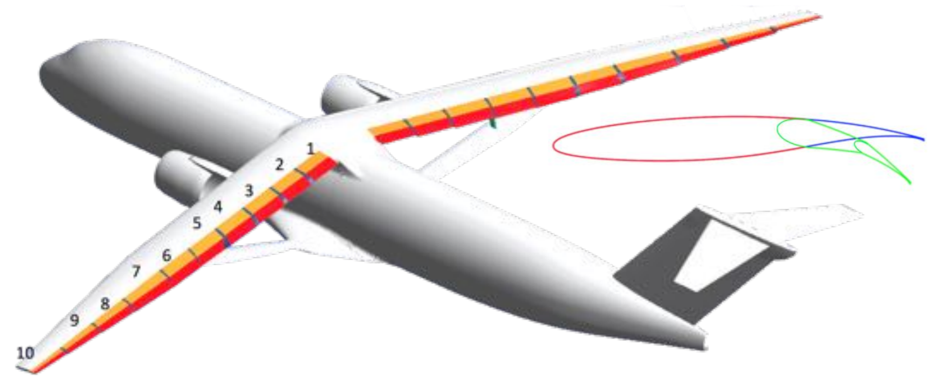
Drag and Maneuver Load Control Optimization

- **Drag and maneuver load minimization with VCCTEF**

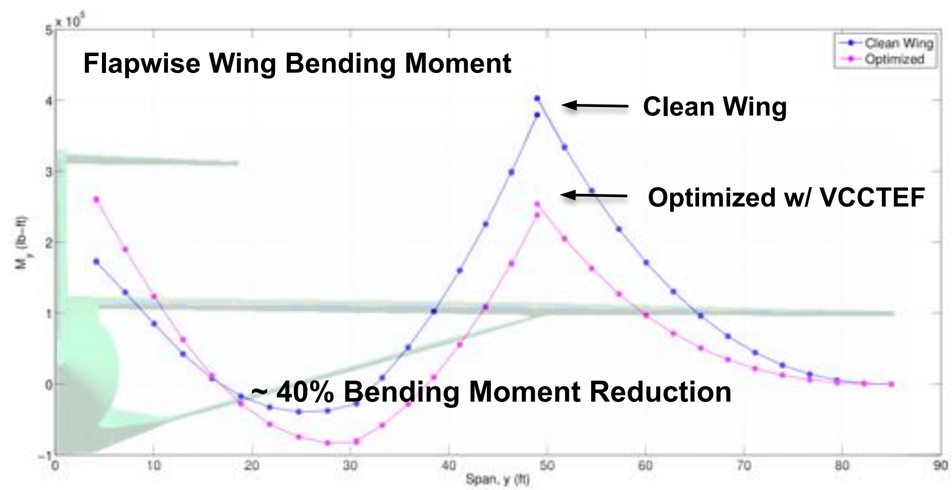


CART3D Aero-Structural Drag Minimization





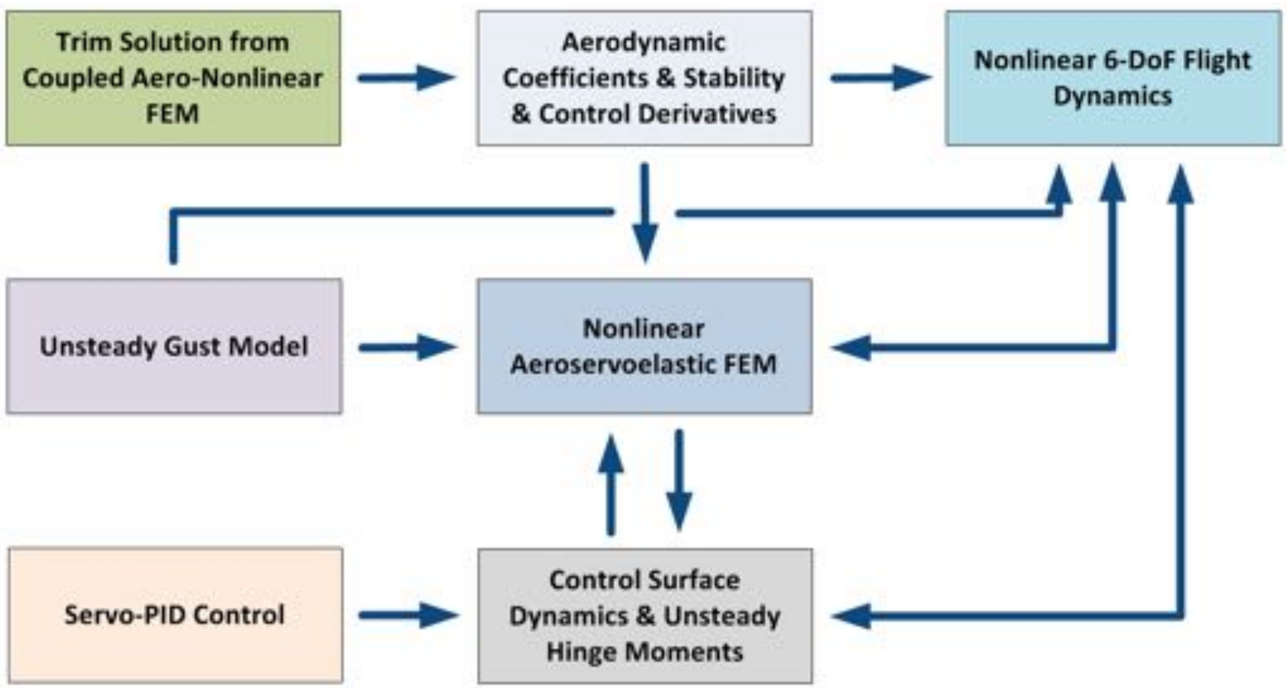
Coupled FEM-VORLAX Load Alleviation Optimization



Aeroservoelasticity

- **Gust and maneuver load responses are important design considerations for flexible wing transports**

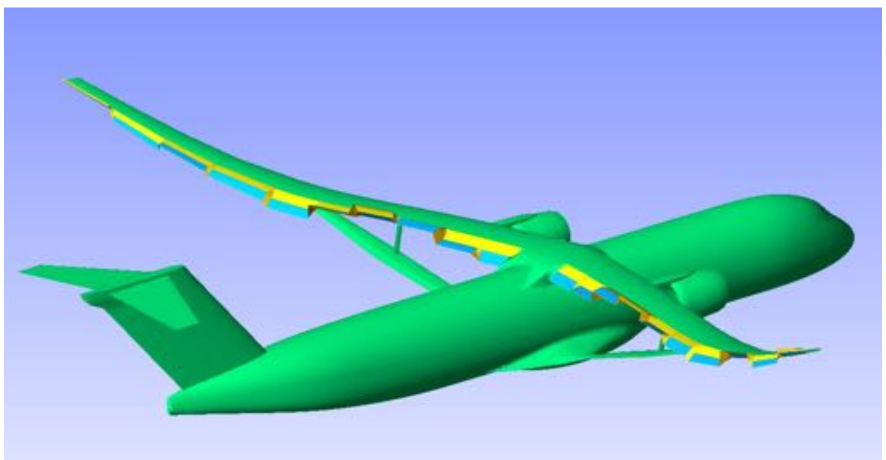
- **Integrated coupled ASE flight dynamics provides flight prediction capability of combined flexible vehicle stability and control response characteristics**

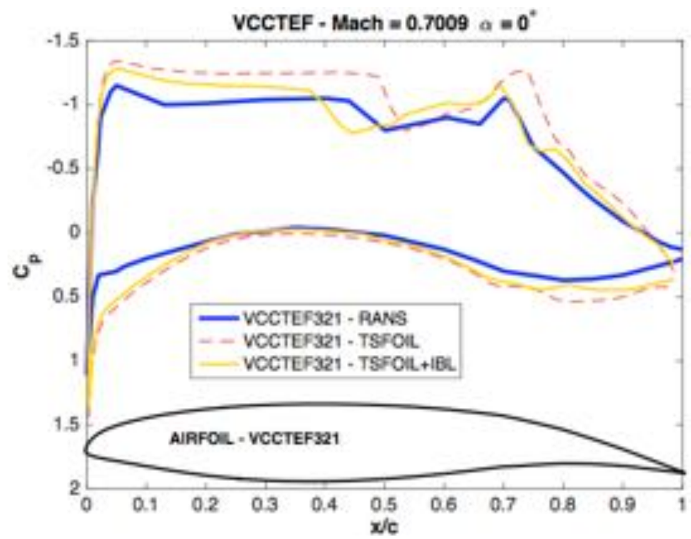


Integrated Coupled ASE Tool

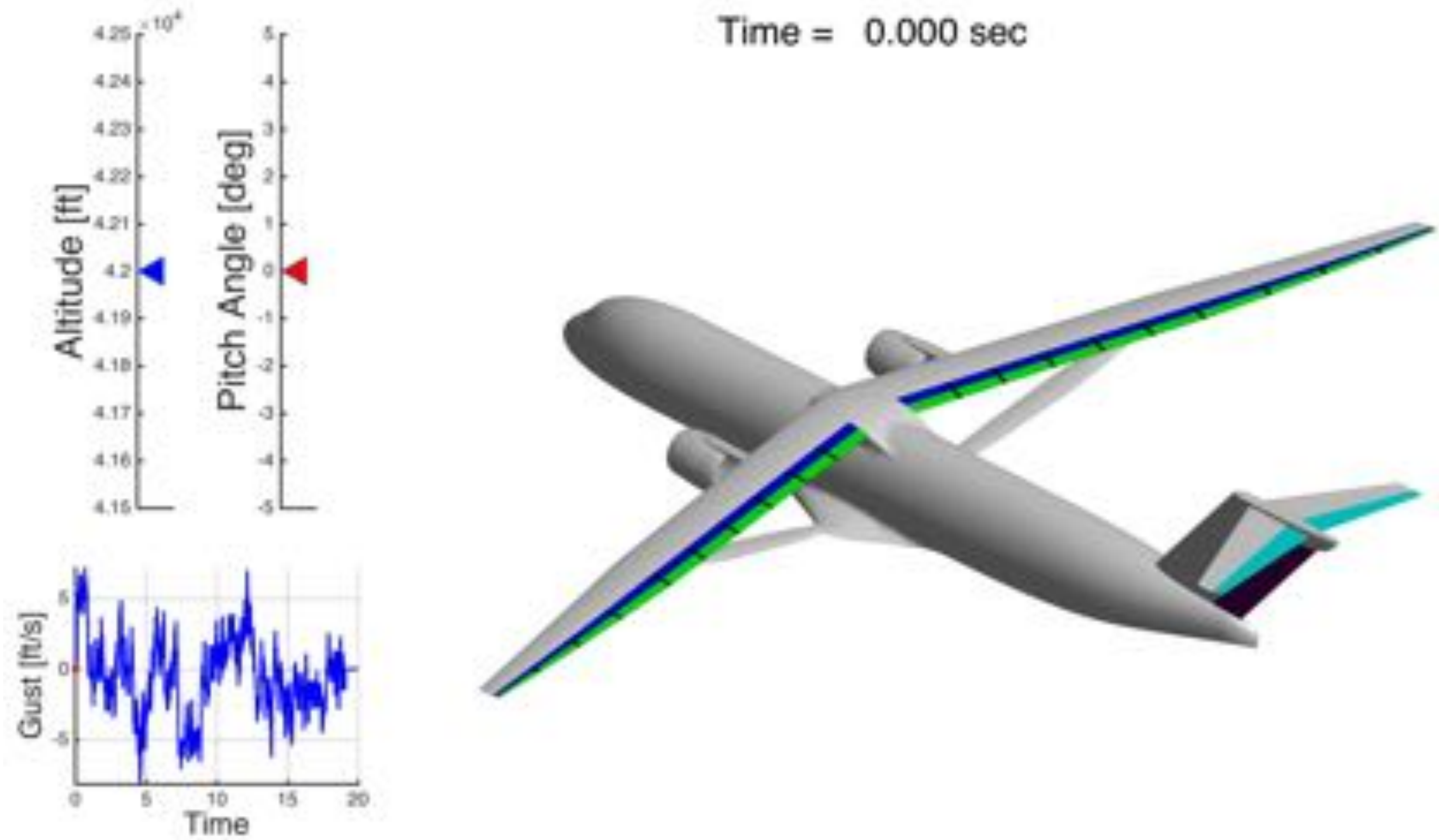
- **Integrated coupled ASE tool can rapidly generate nonlinear and linear ASE state space models with gust models and with transonic and viscous corrections**

$$\begin{bmatrix} M_{rr} & M_{re} & M_{r\delta} & M_{rs} \\ M_{er} & M_{ee} & M_{e\delta} & M_{es} \\ M_{\delta r} & M_{\delta e} & M_{\delta\delta} & M_{\delta s} \\ M_{sr} & M_{se} & M_{s\delta} & M_{ss} \end{bmatrix} \begin{bmatrix} \dot{x}_r \\ \dot{x}_e \\ \dot{x}_\delta \\ \dot{x}_s \end{bmatrix} = \begin{bmatrix} S_{rr} & S_{re} & S_{r\delta} & S_{rs} \\ S_{er} & S_{ee} & S_{e\delta} & S_{es} \\ S_{\delta r} & S_{\delta e} & S_{\delta\delta} & S_{\delta s} \\ S_{sr} & S_{se} & S_{s\delta} & S_{ss} \end{bmatrix} \begin{bmatrix} x_r \\ x_e \\ x_\delta \\ x_s \end{bmatrix} + \begin{bmatrix} T_r \\ T_e \\ T_\delta \\ T_s \end{bmatrix} u$$



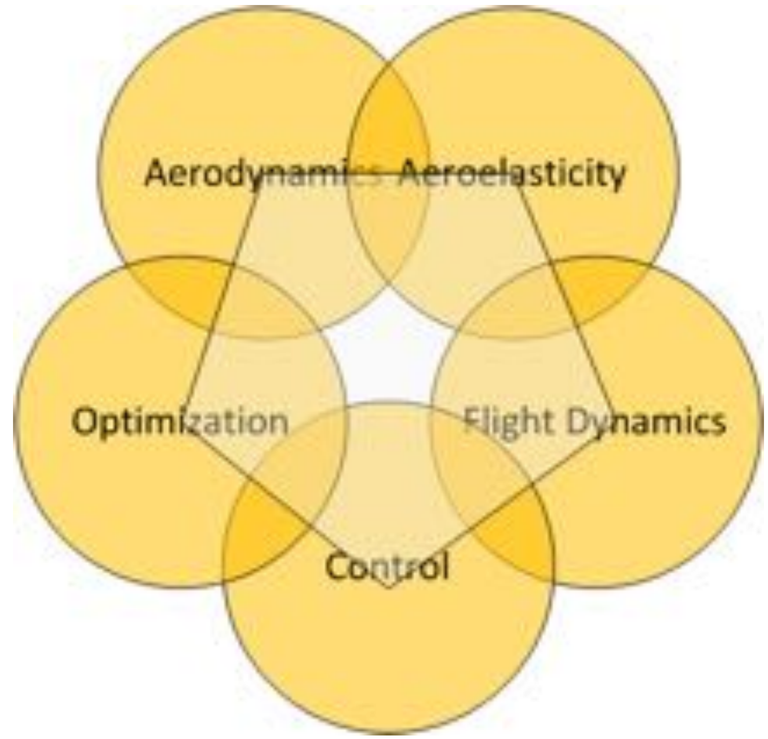


Simulations of Gust Response of Truss-Braced Wing



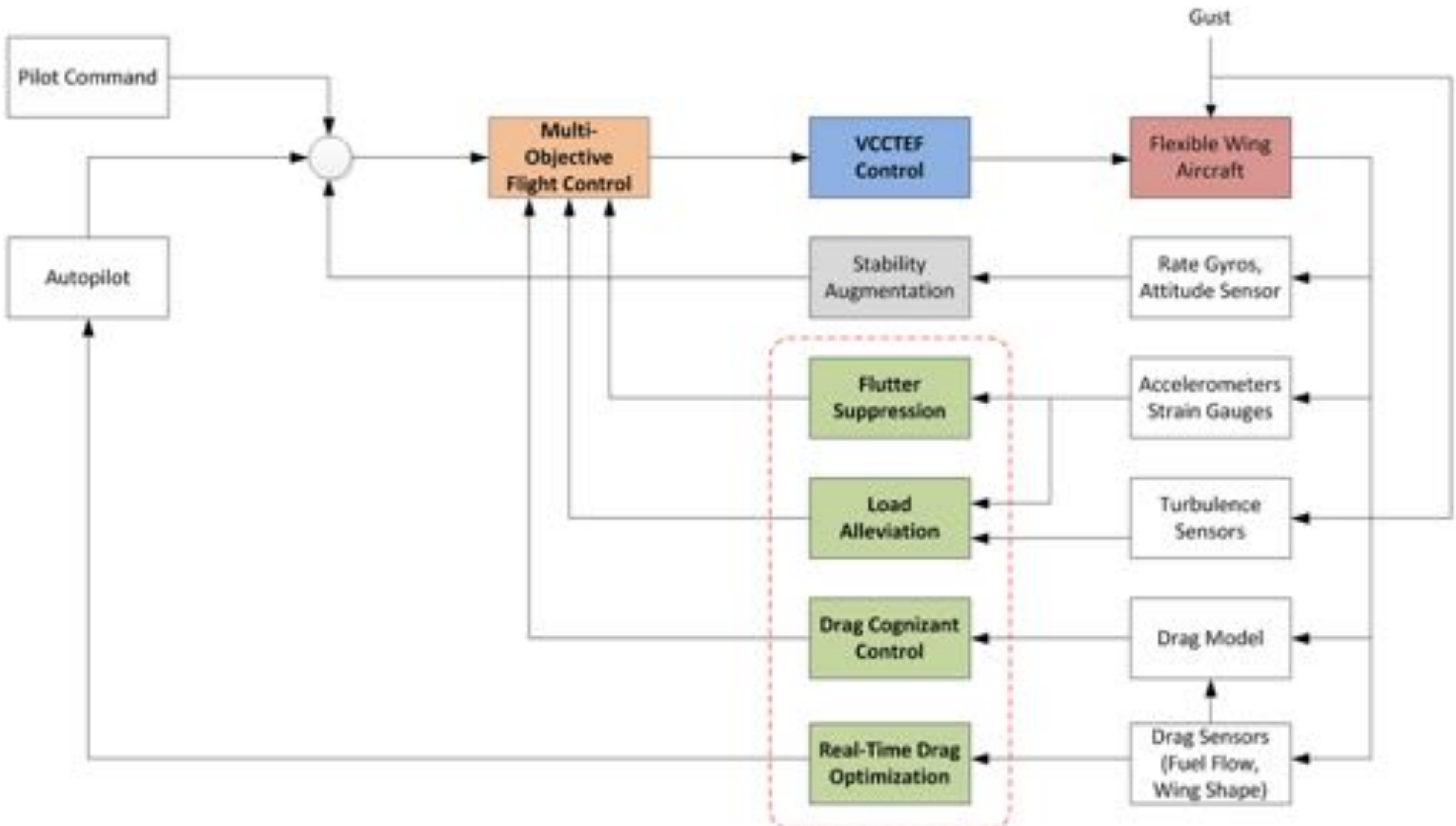
Multidisciplinary Flight Control

- **ASE flight control enables both adaptive wing performance and safe flight operation**
- **Increased aircraft performance can be realized by addressing multidisciplinary interactions in flight control design**
- **Integrated adaptive wing design by incorporating flight control in the MDAO cycle for weight and drag reduction**



Multi-Objective Flight Control

- **Multi-objective flight control, first introduced in 2012, takes advantage of multi-functional flight control surfaces such as VCCTEF to allow new capabilities in flight control to achieve multiple objectives simultaneously**



ASE State Space Model

- **ASE state space model with gust disturbance**

$$\dot{x} = Ax + Bu + w \;\Longrightarrow\; \begin{cases} \dot{x}_r = A_{rr}x_r + A_{re}x_e + B_r u_r + w_r \\ \dot{x}_e = A_{er}x_r + A_{ee}x_e + B_e u_e + w_e \end{cases}$$

- **Output equation for accelerometers**

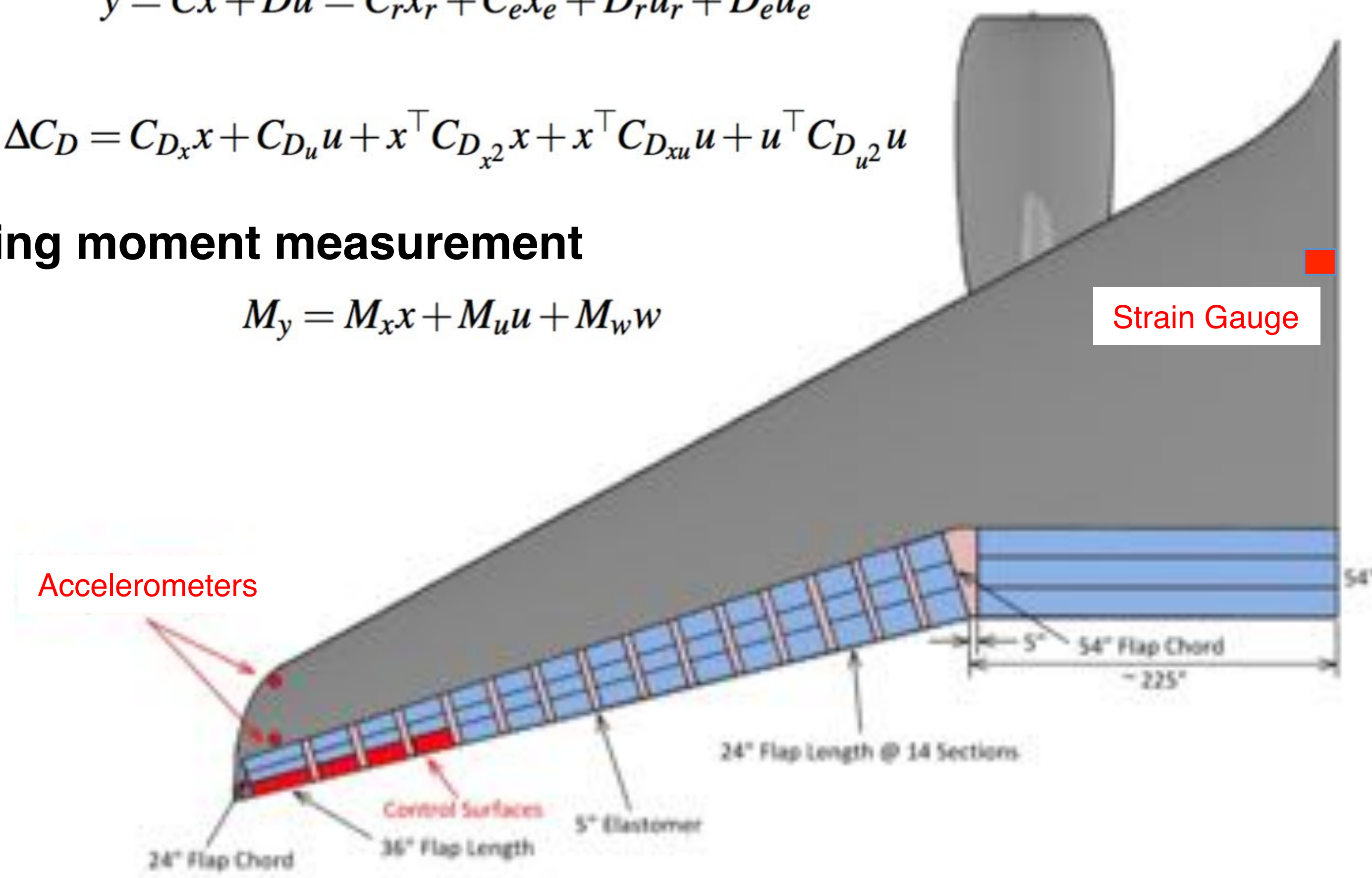
$$y = Cx + Du = C_r x_r + C_e x_e + D_r u_r + D_e u_e$$

- **Drag model**

$$\Delta C_D = C_{D_x} x + C_{D_u} u + x^\top C_{D_{x^2}} x + x^\top C_{D_{xu}} u + u^\top C_{D_{u^2}} u$$

- **Wing root bending moment measurement**

$$M_y = M_x x + M_u u + M_w w$$



Multi-Objective Optimal Control

- **Multi-objective cost function**

$$J = J_r + J_e$$

$$J_r = \lim_{t_f \to \infty} \frac{1}{2} \int_0^{t_f} \left[(z - r)^\top \underbrace{Q_r}_{\text{Pilot Command Tracking}} (z - r) + u_r^\top R_r u_r \right] dt$$

$$J_e = \lim_{t_f \to \infty} \frac{1}{2} \int_0^{t_f} \left(x_e^\top \underbrace{Q_e}_{\text{ASE Mode Suppression}} x_e + u_e^\top R_e u_e + \underbrace{q_D}_{\text{Drag Minimization}} \Delta C_D + M_y^\top \underbrace{q_M}_{\text{Load Alleviation}} M_y \right) dt$$

- **Drag minimization and load alleviation multi-objective optimal control**

$$\boxed{\begin{gathered} u = K_x \hat{x} + K_r r + K_w \hat{w} + \Lambda_0 \\ K_x = -\bar{R}^{-1} \left(B^\top W + \frac{1}{2} q_D C_{D_{xu}}^\top + q_M M_u^\top M_x \right) \\ K_r = -\bar{R}^{-1} B^\top V_r \\ K_w = -\bar{R}^{-1} \left(B^\top V_w + q_M M_u^\top M_w \right) \\ \Lambda_0 = -\bar{R}^{-1} \left(B^\top V_0 + \frac{1}{2} q_D C_{D_u}^\top \right) \end{gathered}}$$

Adaptive Gust Estimation

- **Kalman filter state estimation of flexible aircraft dynamics**

$$\dot{\hat{x}}_e = A_{ee}\hat{x}_e + A_{er}x_r + L(y - \hat{y}) + B_e u_e + \hat{w}_e$$

- **Plant modeling error**

$$\varepsilon_r = \dot{\hat{x}}_r - \dot{x}_r = (A_{rr} + B_r K_{x_r})(\hat{x}_r - x_r) + A_{re}(\hat{x}_e - x_e) + \hat{w}_r - w_r$$

- **Wing root bending moment estimation error**

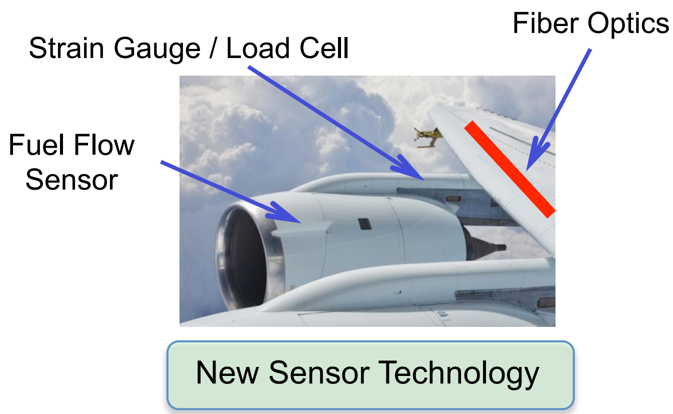
$$\varepsilon_M = \hat{M}_y - M_y = M_x\hat{x} + M_u u + M_{w_r}\hat{w}_r + M_{w_e}\hat{w}_e - M_y$$

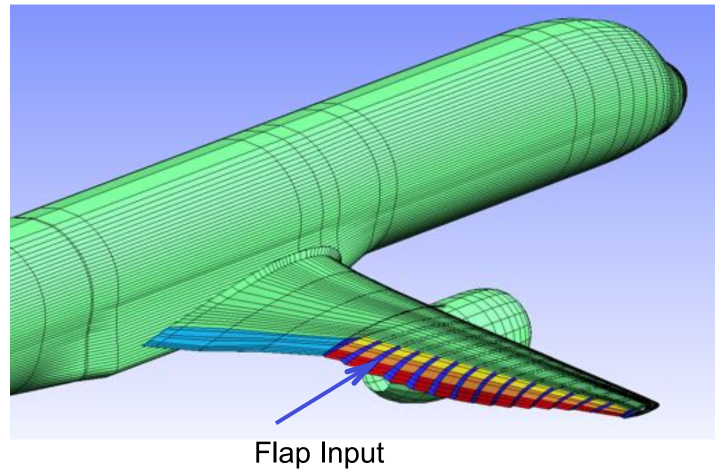
- **Least-squares gradient adaptive gust estimation**

$$\boxed{\begin{aligned} \dot{\hat{w}}_r^\top &= -\Gamma_{w_r}\frac{\partial J^\top}{\partial \hat{w}_r^\top} = -\Gamma_{w_r}\left(\varepsilon_r^\top + M_{w_r}\varepsilon_M^\top\right) \\ \dot{\hat{w}}_e^\top &= -\Gamma_{w_e}\frac{\partial J^\top}{\partial \hat{w}_e^\top} = -\Gamma_{w_e}M_{w_e}\varepsilon_M^\top \end{aligned}}$$

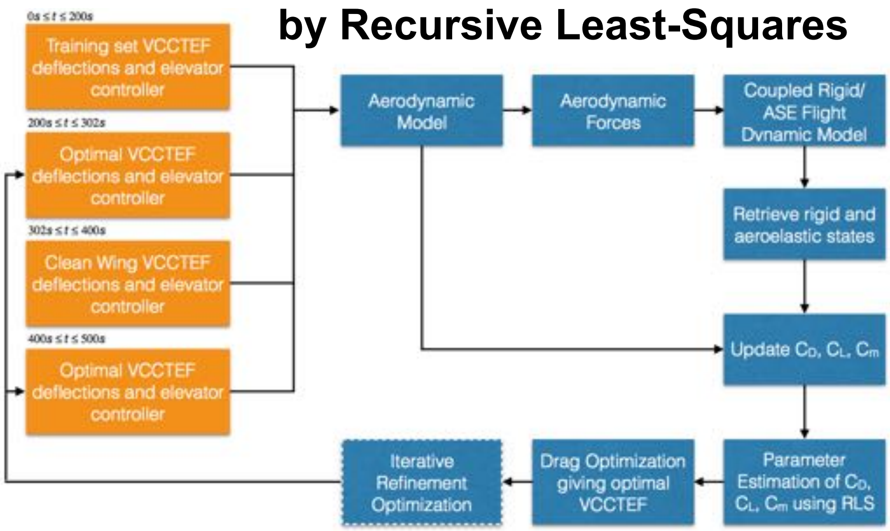
Real-Time Adaptive Drag Minimization Control

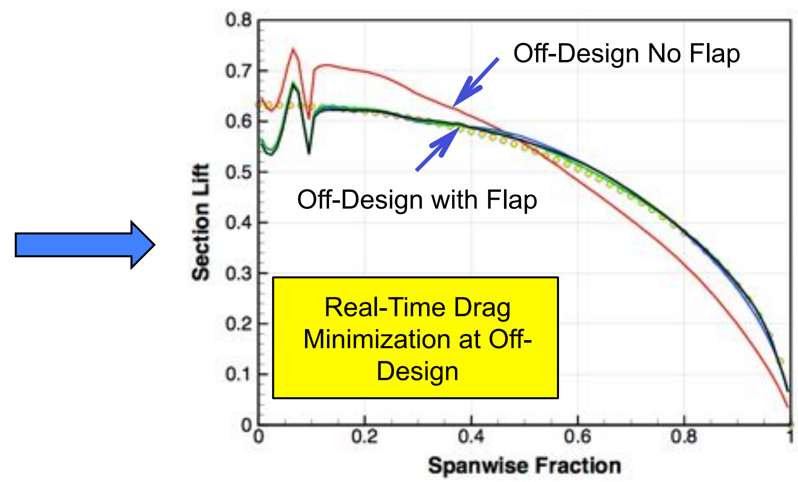
- **Real-time drag minimization is a technology that can truly harvest full potential of adaptive aeroelastic wing technology**





Real-Time Model Identification by Recursive Least-Squares

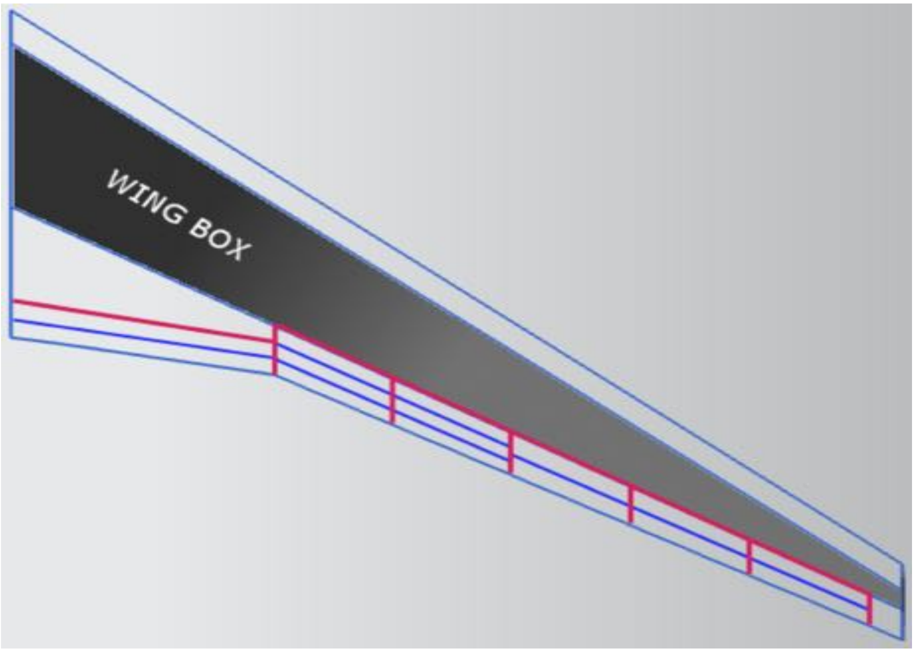




Adaptive Drag Optimization Wind Tunnel Test

- A wind tunnel test will be conducted in University of Washington Aeronautical Laboratory (UWAL) in FY17 to demonstrate adaptive drag optimization technique

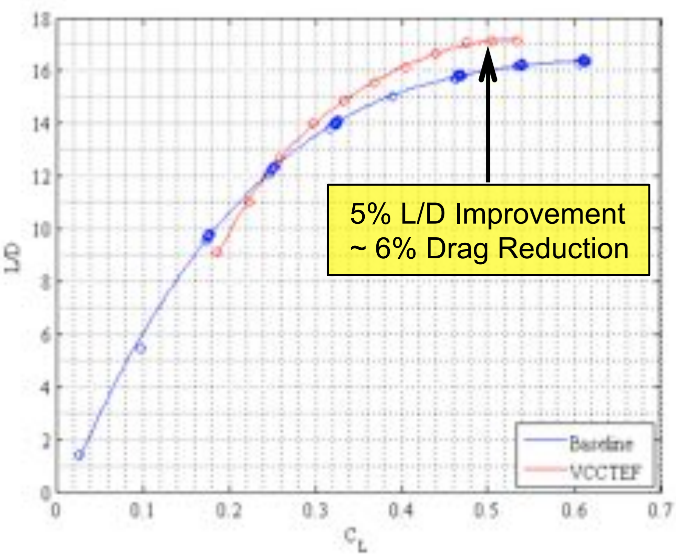
- Wind tunnel model will be a flexible CRM (Common Research Model) wing with 10% wing tip deflection

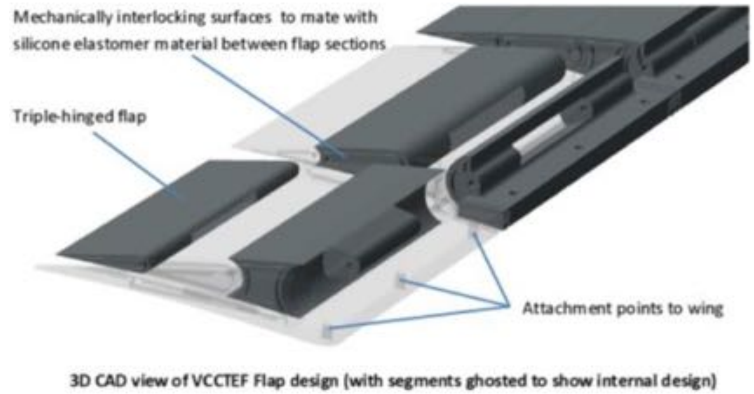


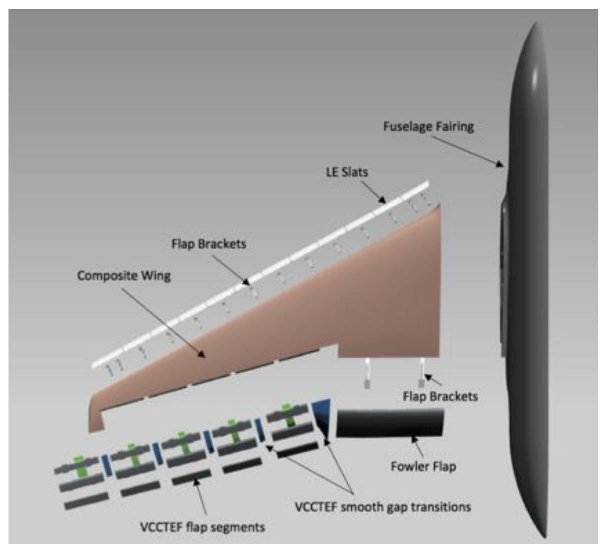
Wind Tunnel Tests

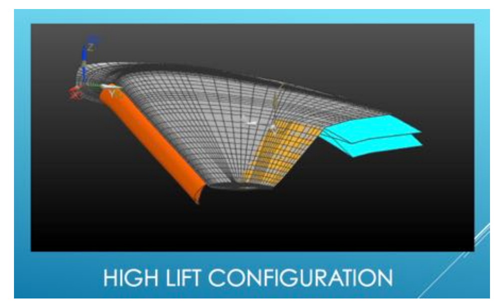
- **Two wind tunnel tests conducted in University of Washington Aeronautical Laboratory (UWAL) in August 2013 and July 2014**

Cruise Configuration Test in FY13



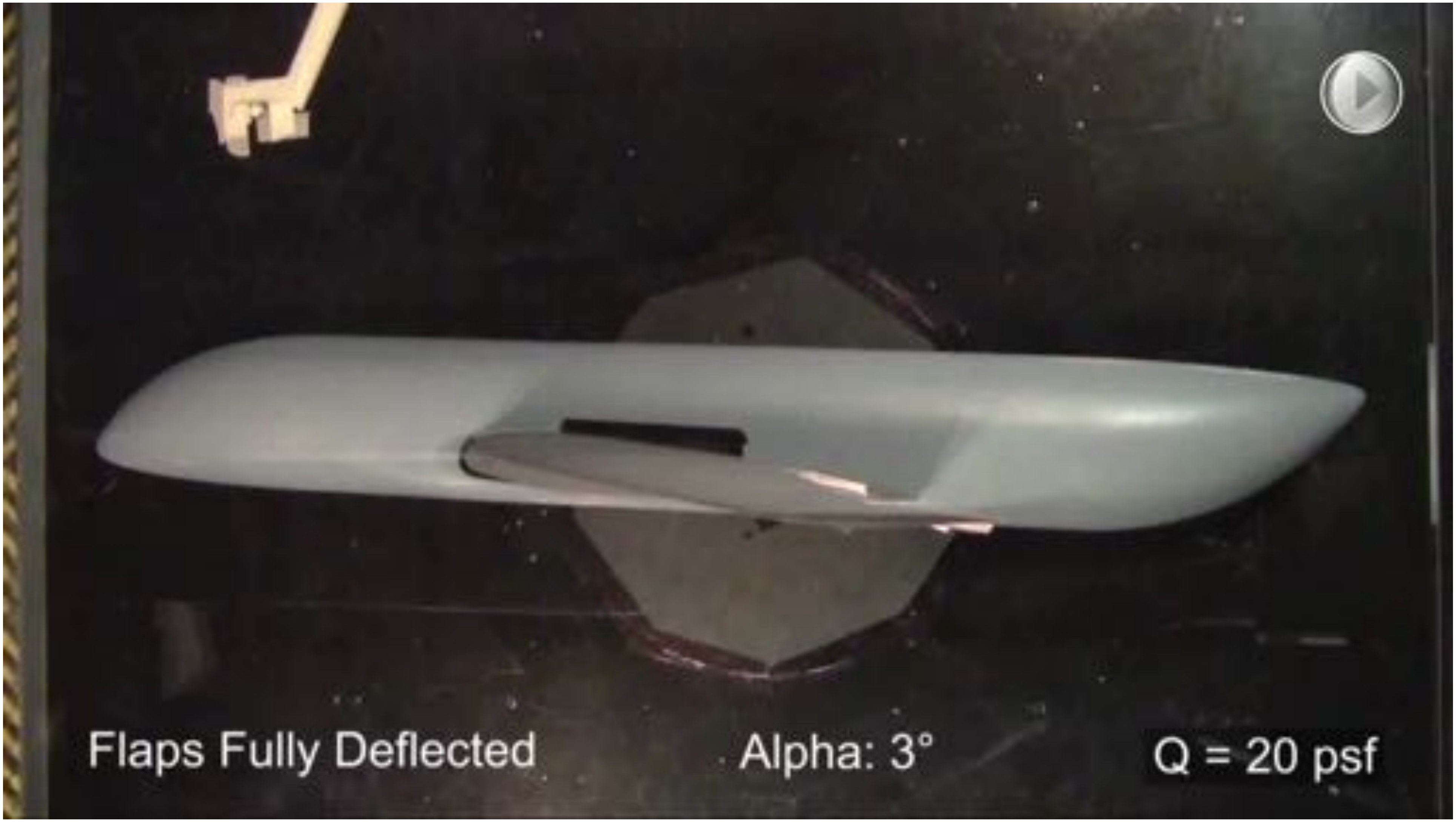




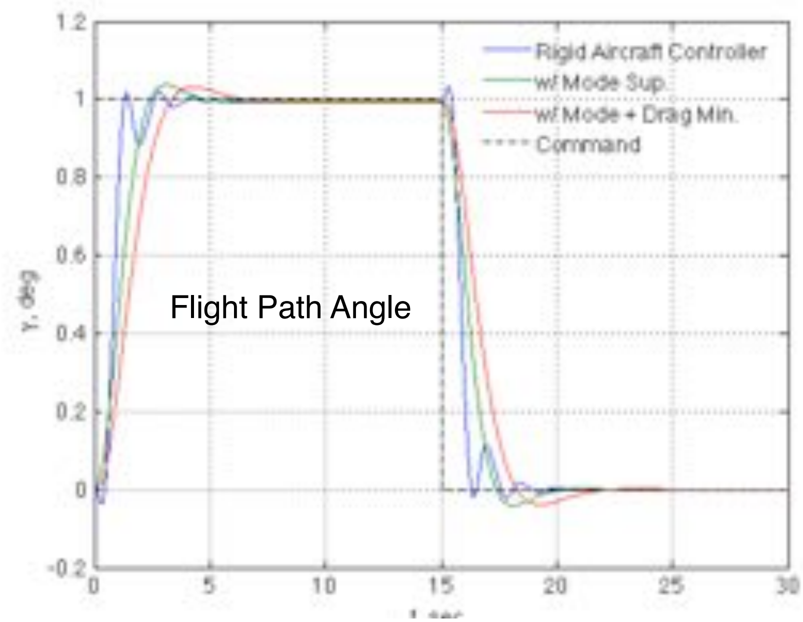


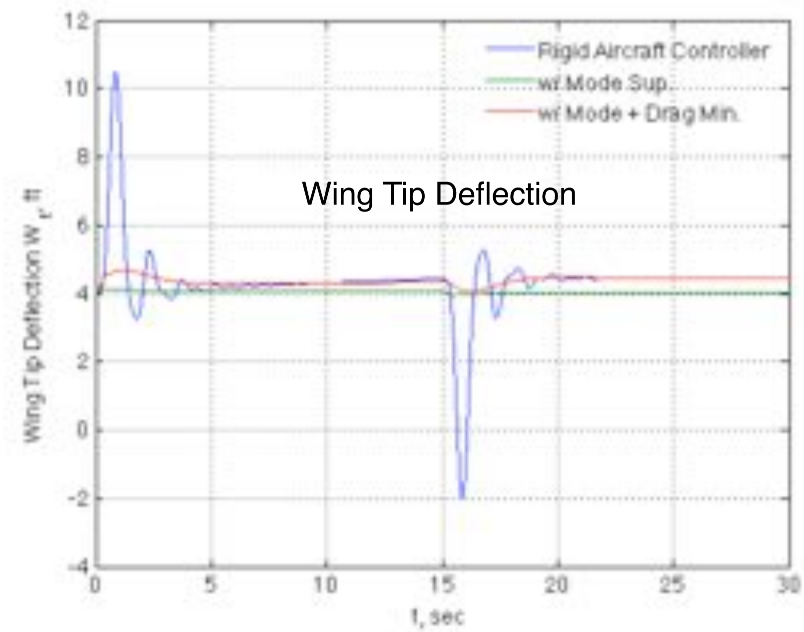
High-Lift Test in FY14

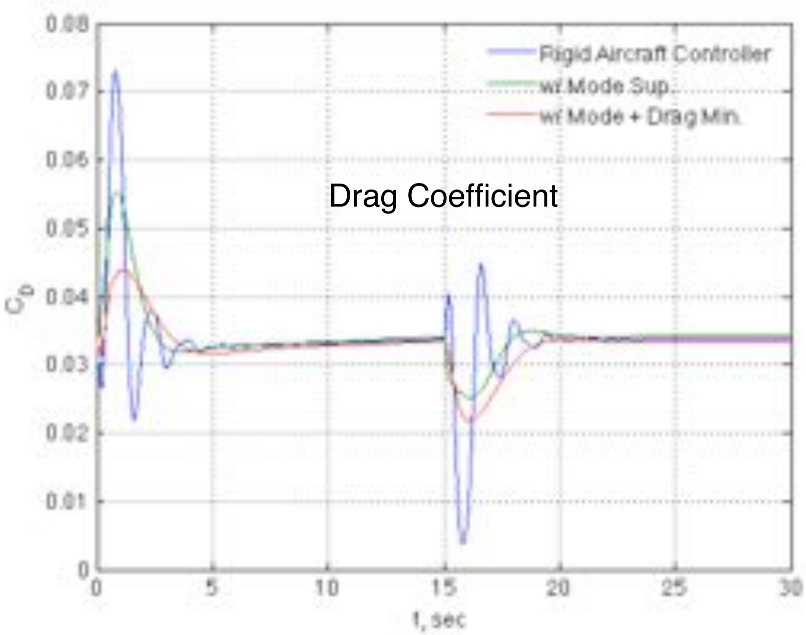
UWAL Test of Cruise Configuration

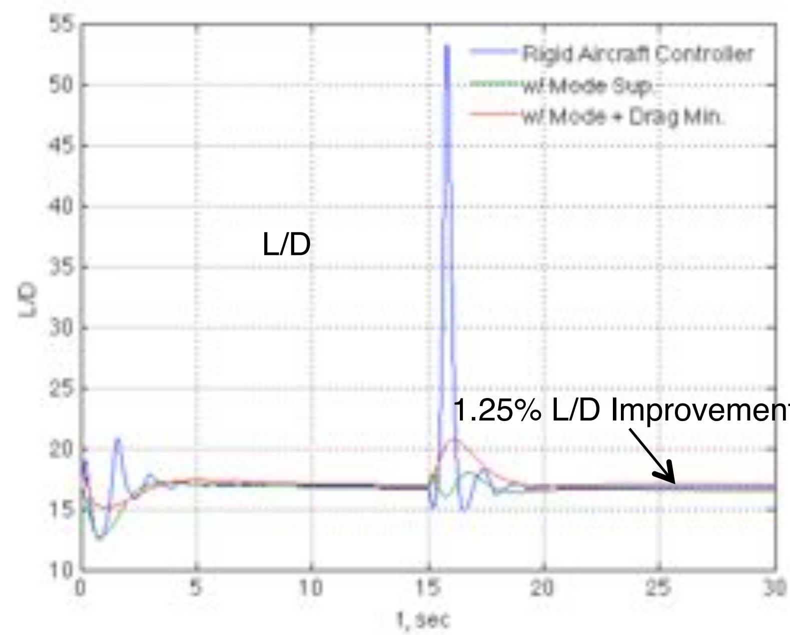


Flight Path Angle Control with Drag Minimization

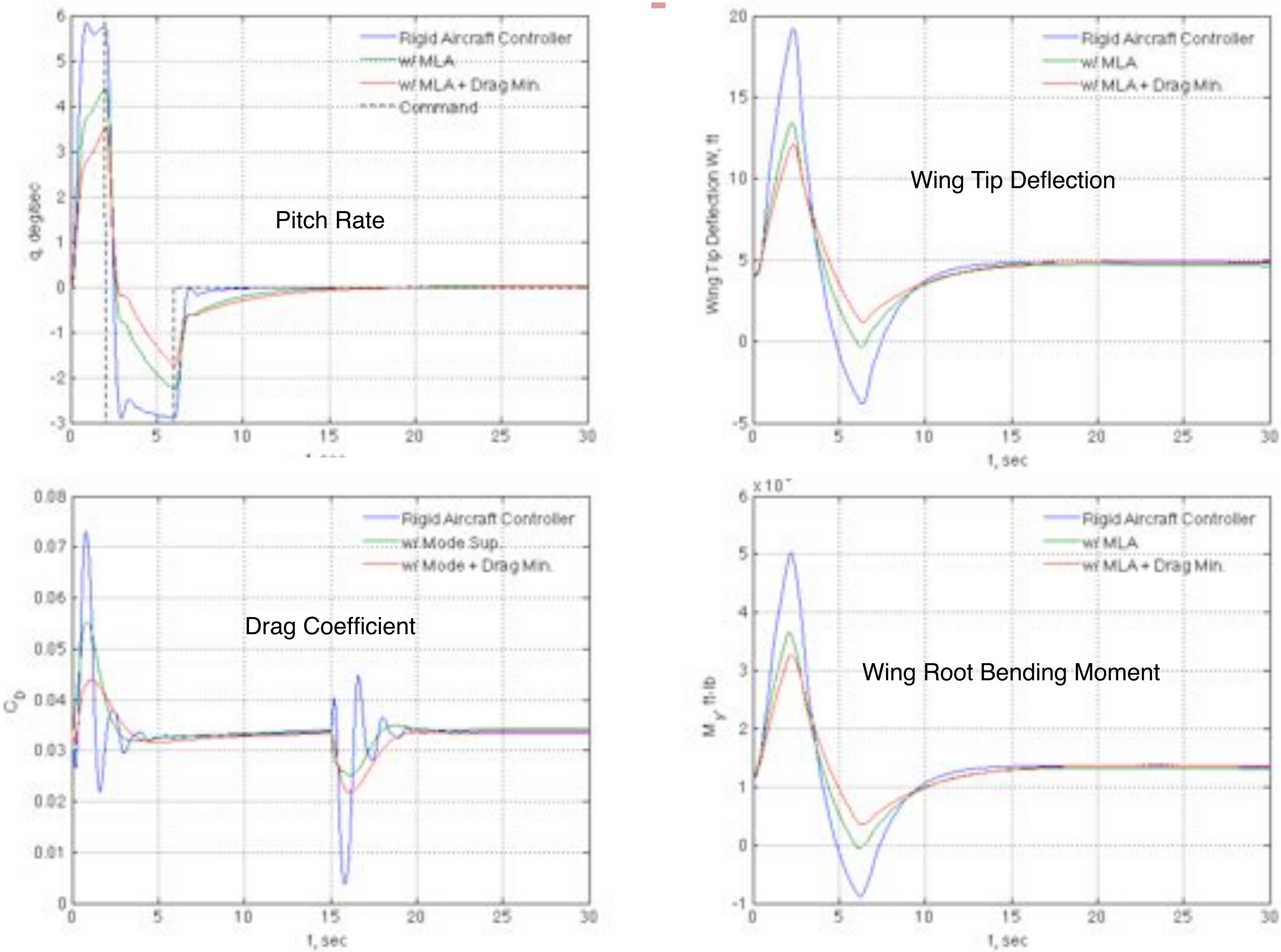




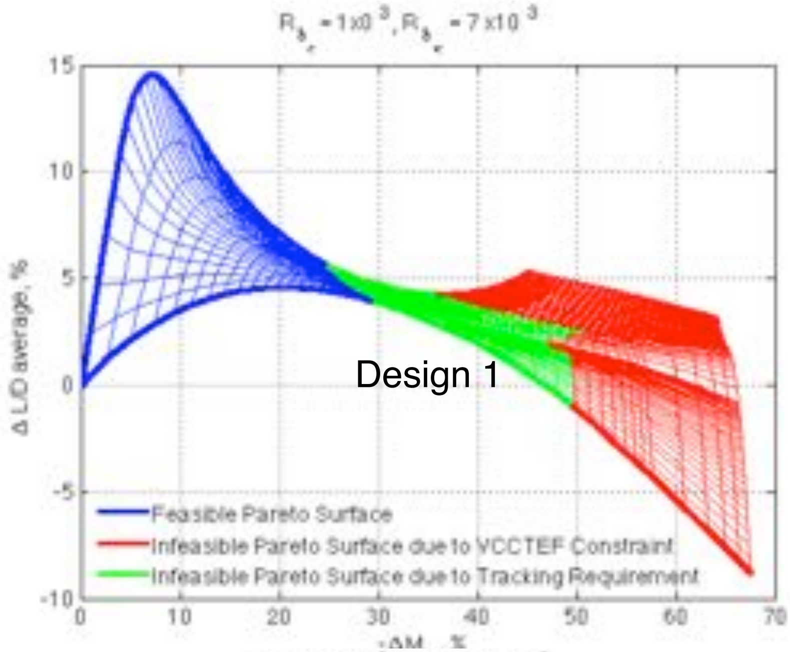




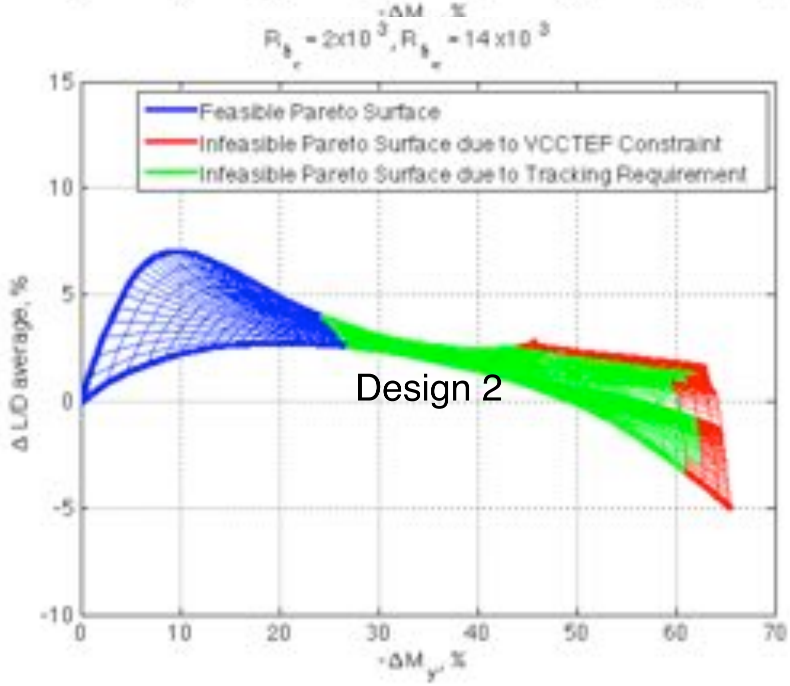
2.5 g Pull-Up Pitch Rate Control with Load Alleviation

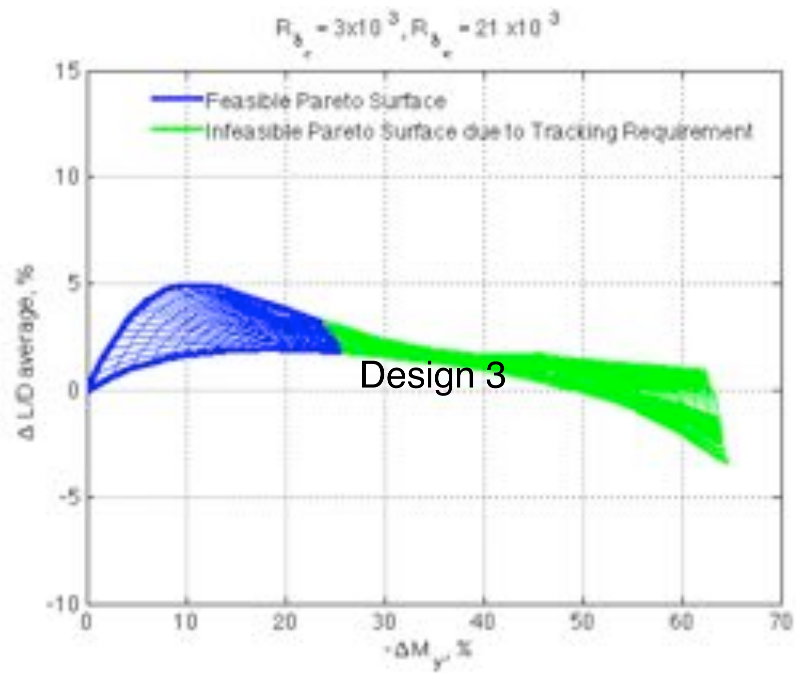


Pareto Frontier Multi-Objective Optimization Analysis



Design 1 provides best compromise between drag minimization and load alleviation





Aeroservoelasticity Control Conceptual Design Model

Intelligent Systems Division

NASA Ames Research Center

Adaptive Maneuver Load Alleviation

- **Many physical plants are designed to meet performance specifications or constraints. For example, aircraft wing structures are designed to meet certain load limits which cannot be exceeded in-flight.**
- **Conventional adaptive control generally does not take into account performance optimality.**
- **Physical plant performance optimization can achieve performance objective.**
- **Adaptive control with performance optimization has been developed in connection with time-varying modification of reference model**

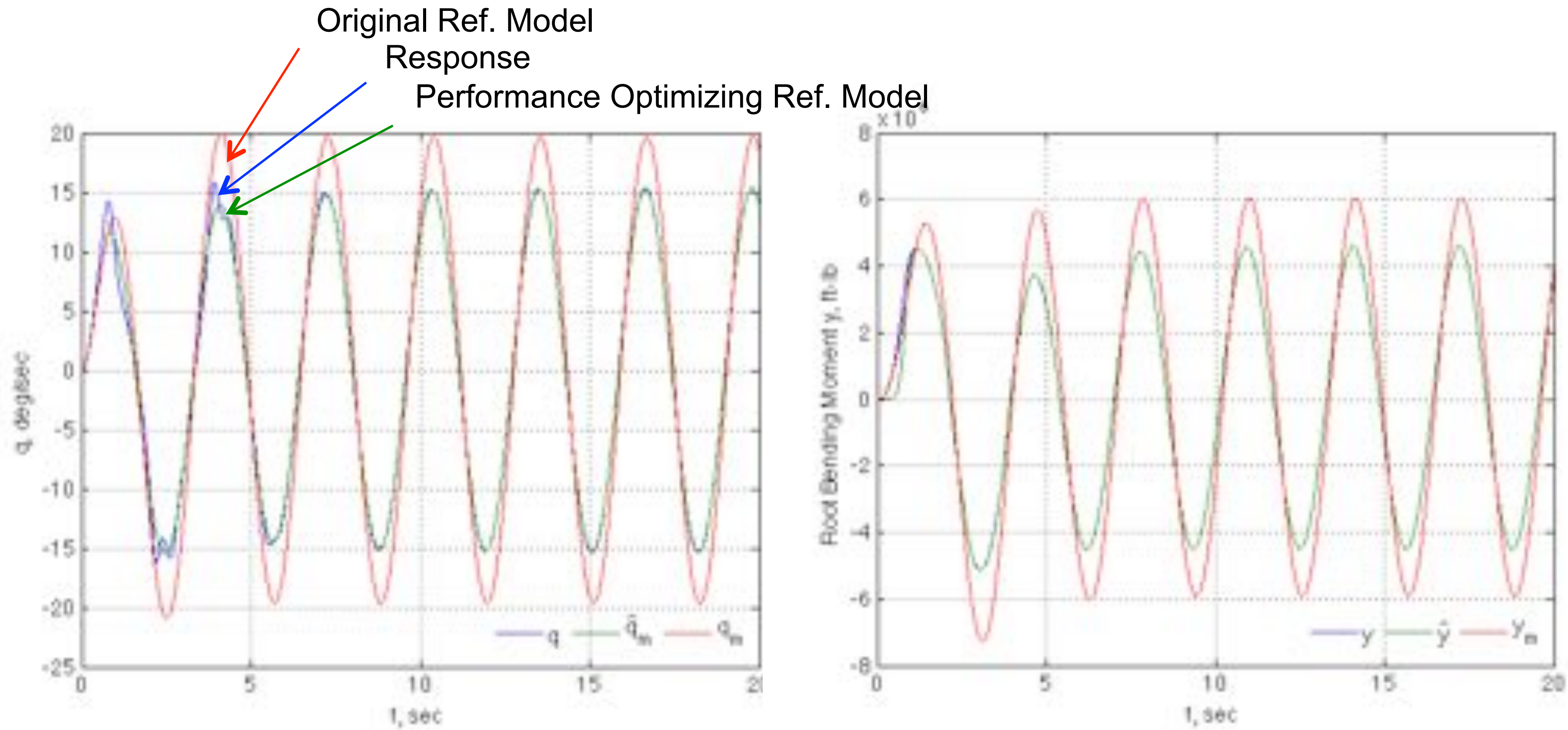
$$\dot{\hat{x}}_m = \left(A_m + B_p \bar{K}_x\right) \hat{x}_m + \left(B_m + B_p \bar{K}_r\right) r$$

$$\bar{K}_x = -\bar{R}^{-1} \left(B_p^\top W + \hat{D}_p^\top q \hat{C}\right)$$

$$\bar{K}_r = \bar{R}^{-1} B_p^\top \left(\bar{A}^\top - W B_p \bar{R}^{-1} B_p^\top\right)^{-1} W B_m$$

Adaptive Maneuver Load Alleviation

- **Simulations of flexible wing transport aircraft**



Pitch Rate

Wing Root Bending Moment

Adaptive Flutter Suppression

- **Aeroelastic uncertainty can degrade ASE flutter suppression control**
- **Adaptive control could be used to improve robustness to uncertainty – leverage previous adaptive flight control work on F-18 with Optimal Control Modification with NASA AFRC**

Flight Test of Optimal Control Modification in 2010

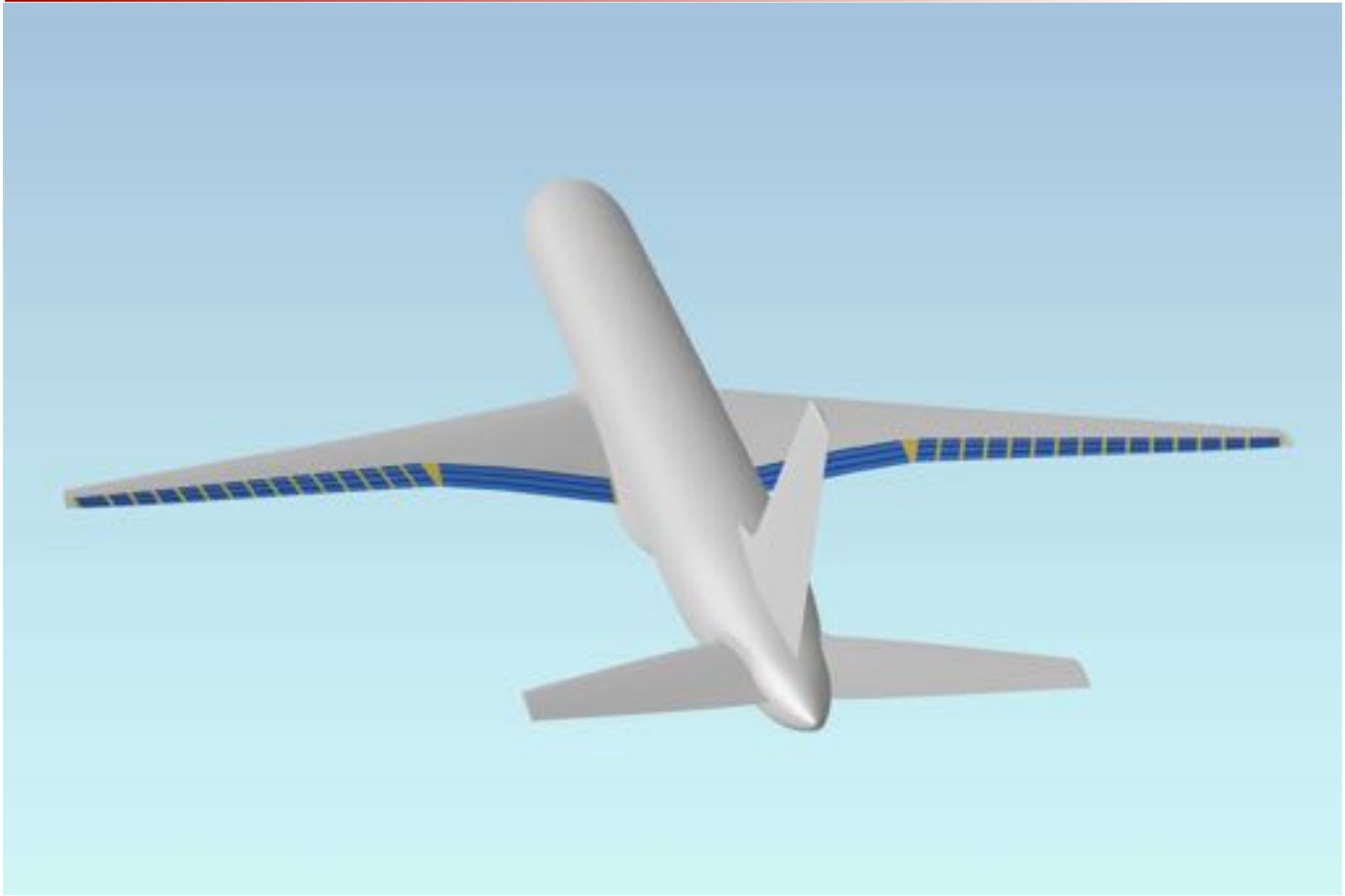
- **Adaptive Linear Quadratic Gaussian control**

$$u = \bar{K}_x \hat{x} + \Delta K_x \hat{x} + K_y (y - \hat{y})$$

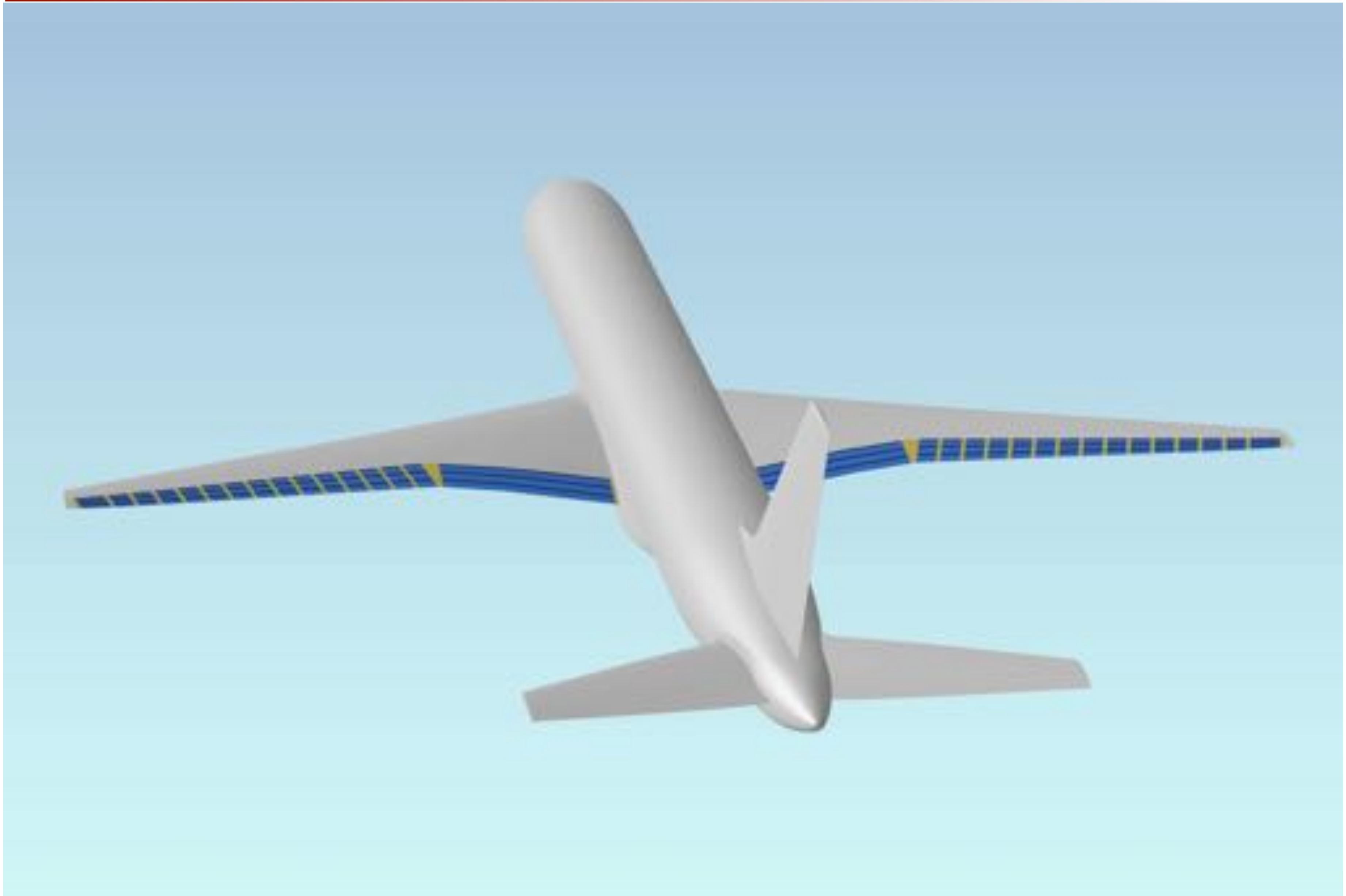
$$\Delta \dot{K}_x^\top = -\Gamma_x \hat{x} \hat{x}^\top \left(P - \nu_x \Delta K_x^\top B^\top P A_m^{-1} \right) B$$

$$\dot{K}_y^\top = -\Gamma_y (y - \hat{y}) \left[\hat{x}^\top P - \nu_y (y - \hat{y})^\top K_y^\top B^\top P A_m^{-1} \right] B$$

Flutter Animation



Flutter Suppression Animation



X-56A Flight Control Collaboration

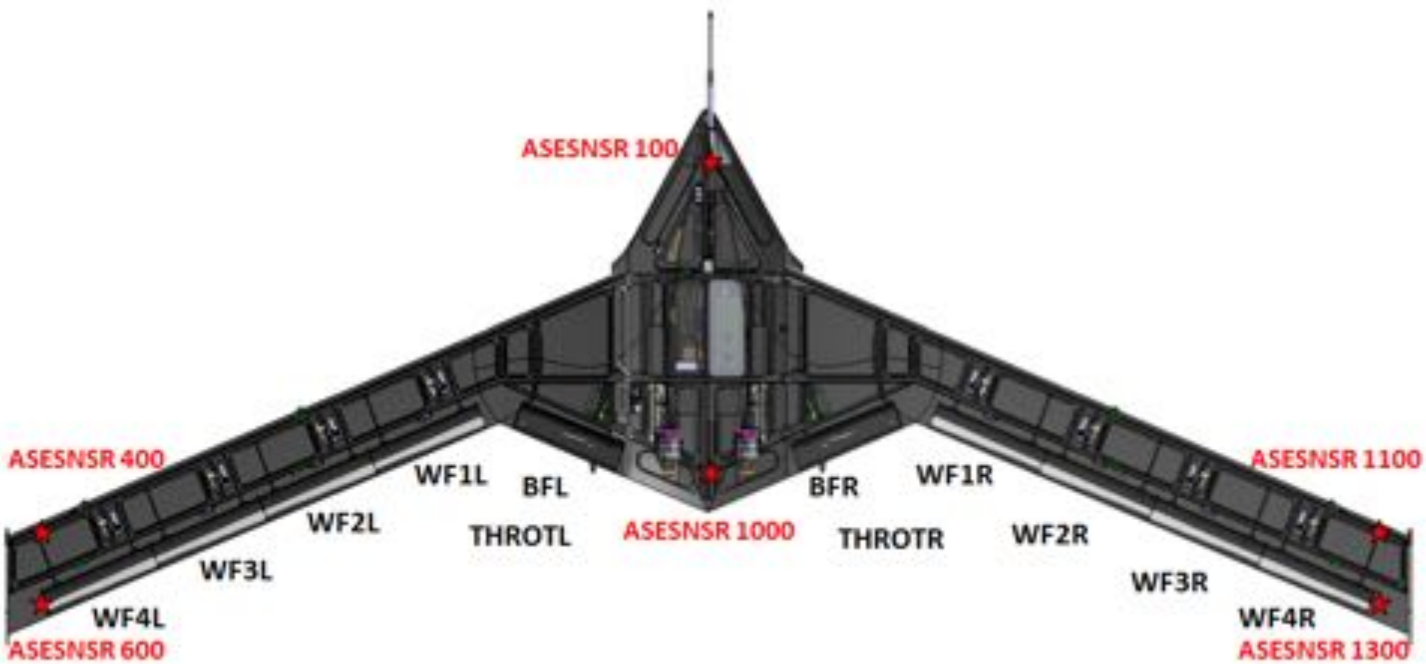
- **Collaboration with AFRC on X-56A flight control validation of ASE flutter suppression and multi-objective flight control**
  - POC: Steve Jacobson and Matt Boucher
  - AFRC sent ARC X-56A simulations on January 23, 2016 for control development

X-56A with Interchangeable Wings

X-56A Model

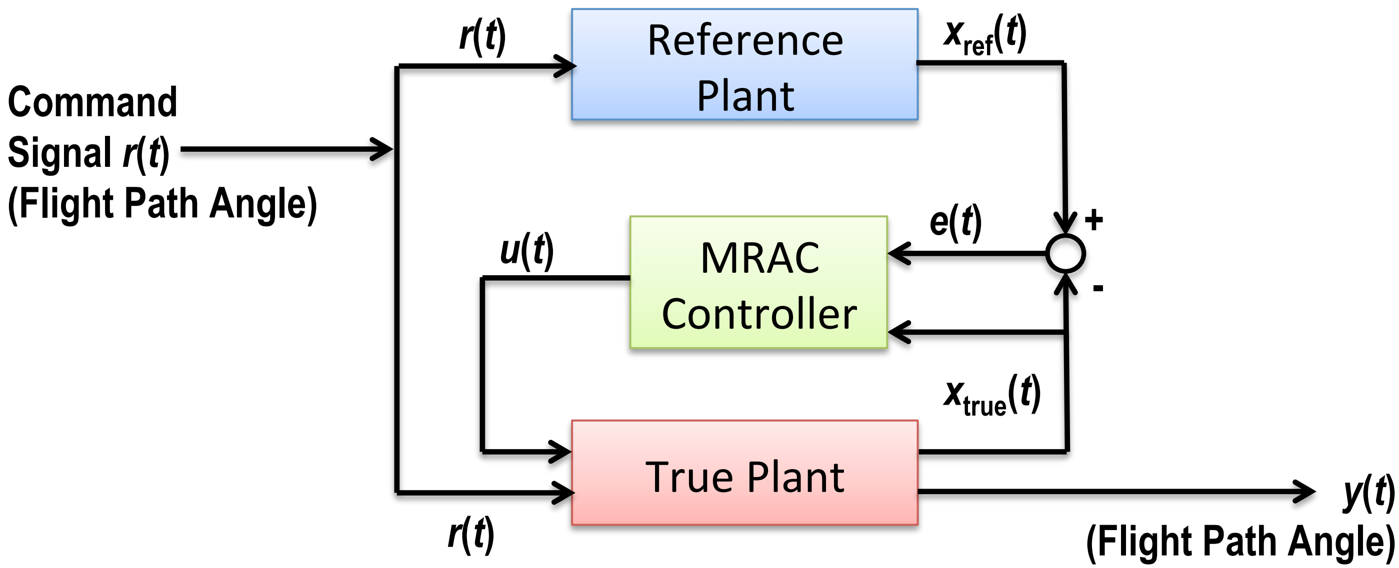
- **Reduced-order model for longitudinal dynamics**
  - 214 states including 5 rigid-body states $\{h, \theta, u, \alpha, q\}$, elastic and lag states for 25 elastic modes, and sensor and actuator dynamics
  - 16 outputs and 5 symmetric inputs including 1 body flap and 4 wing flaps per wing

- **Reduced-order reference model only includes 5 elastic modes and no sensor and actuator dynamics**



Adaptive Augmentation

- **LQR design for flight path angle control with adaptive augmentation for matched uncertainty**



$$u = \left(I - K_u^\top\right) K_x x - \Theta^\top \Phi\left(x\right)$$

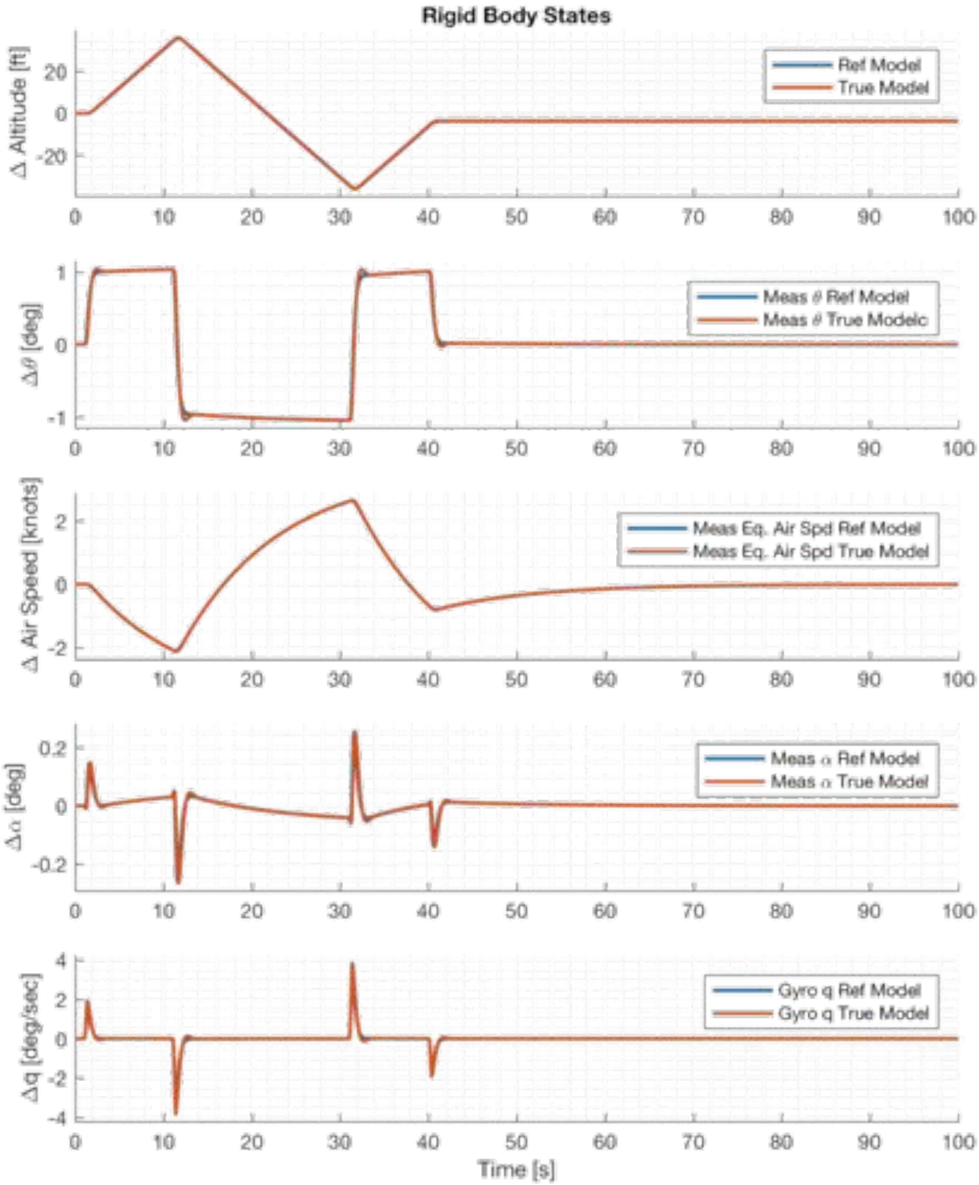
$$\dot{K}_u = -\Gamma_u K_x x \left(e^\top P - \nu_u x^\top K_x^\top K_u B^\top P A_m^{-1}\right) B$$

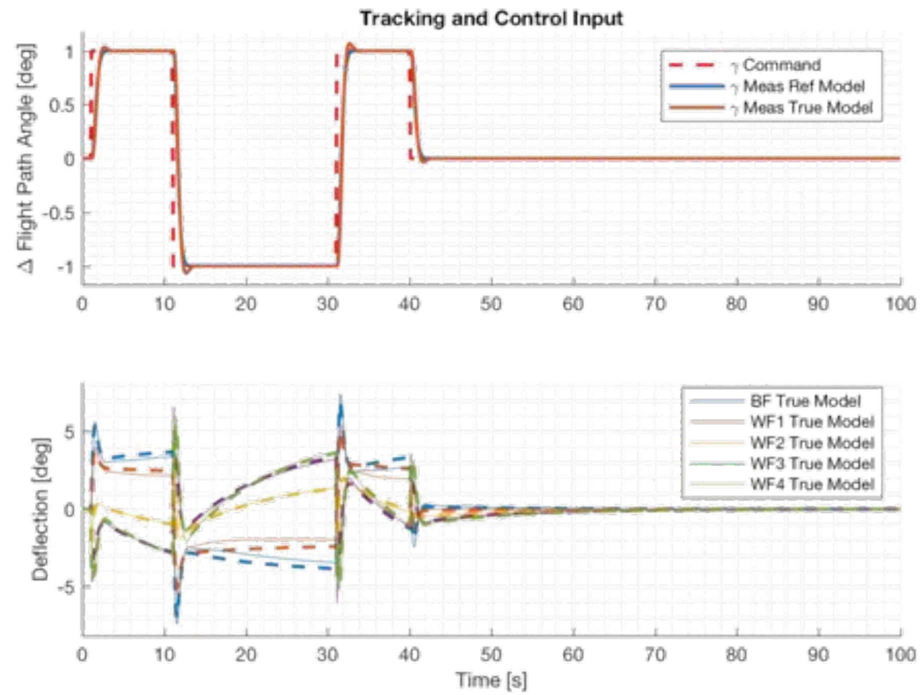
$$\dot{\Theta} = -\Gamma_\Theta \Phi\left(x\right) \left[e^\top P - \nu_u \Phi^\top\left(x\right) \Theta B^\top P A_m^{-1}\right] B$$

- **Demonstrate adaptive flutter suppression at two flight conditions on either side of flutter boundary without gain scheduling**

Simulations – Below Flutter Boundary

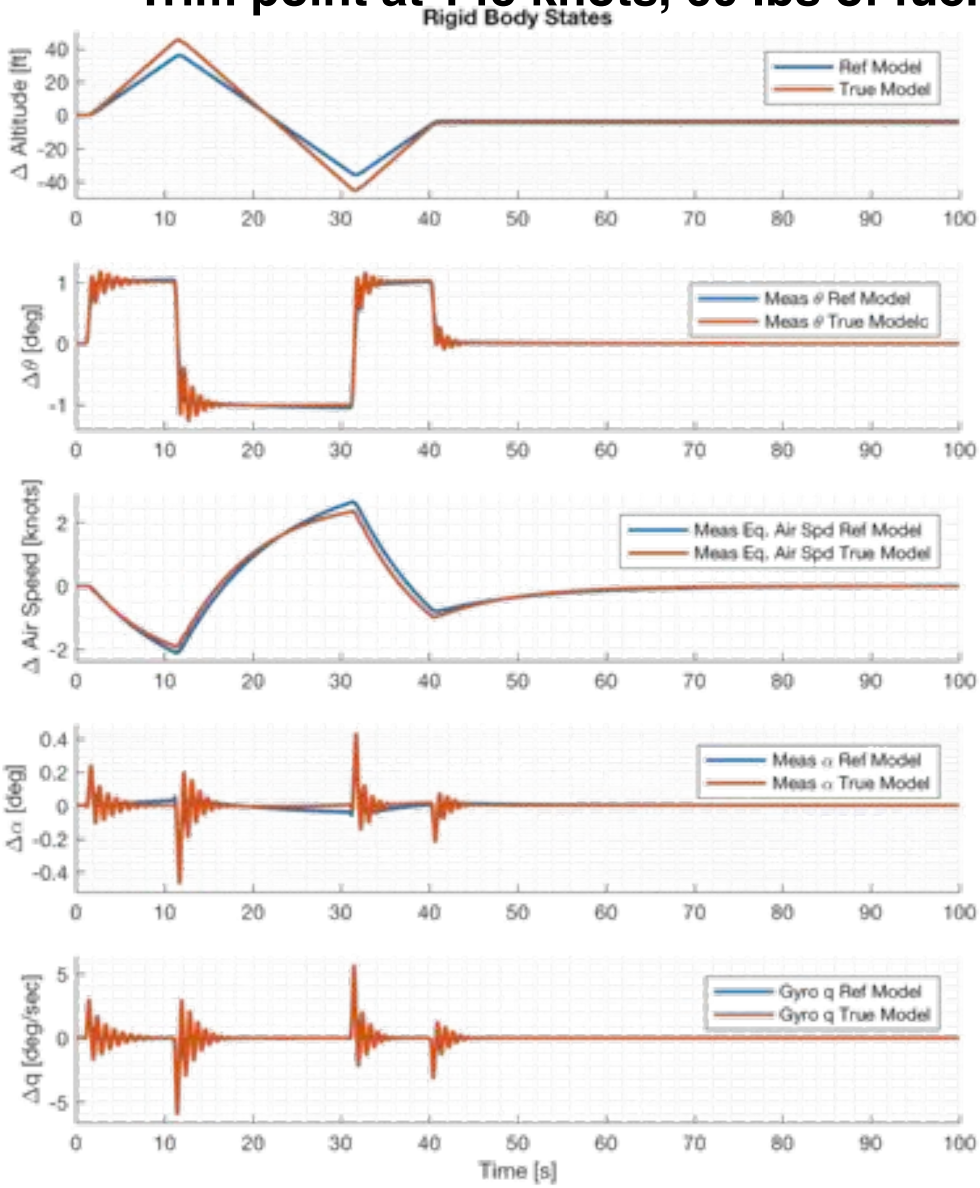
- **Reference model from flutter-free trim point at 115 knots, 60 lbs of fuel**

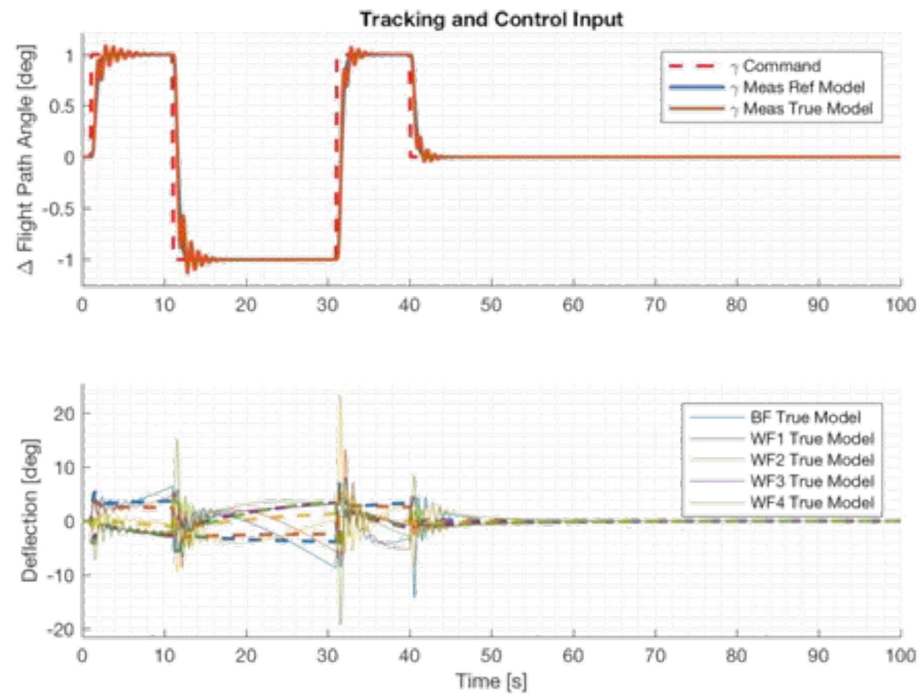




Simulations – Above Flutter Boundary

- **Trim point at 145 knots, 60 lbs of fuel above flutter boundary**





Adaptive control is able to stabilize flutter modes at different flight conditions without gain scheduling

Other Collaborations

- **NASA-funded EPSCoR project with Wichita State University "Active Wing Shaping Control for Morphing Aircraft"**
  - Wichita State University, Kansas University, and Missouri University of Science & Technology
  - FY15-18 performance period

- **Possible collaboration with Boeing Research & Technology on Integrated Adaptive Wing Technology Maturation NRA funded by AATT project**

Thank You