National Aeronautics and Space Administration

NASA Demo of Multi-Objective Flight Control for Drag Minimization and Load Alleviation

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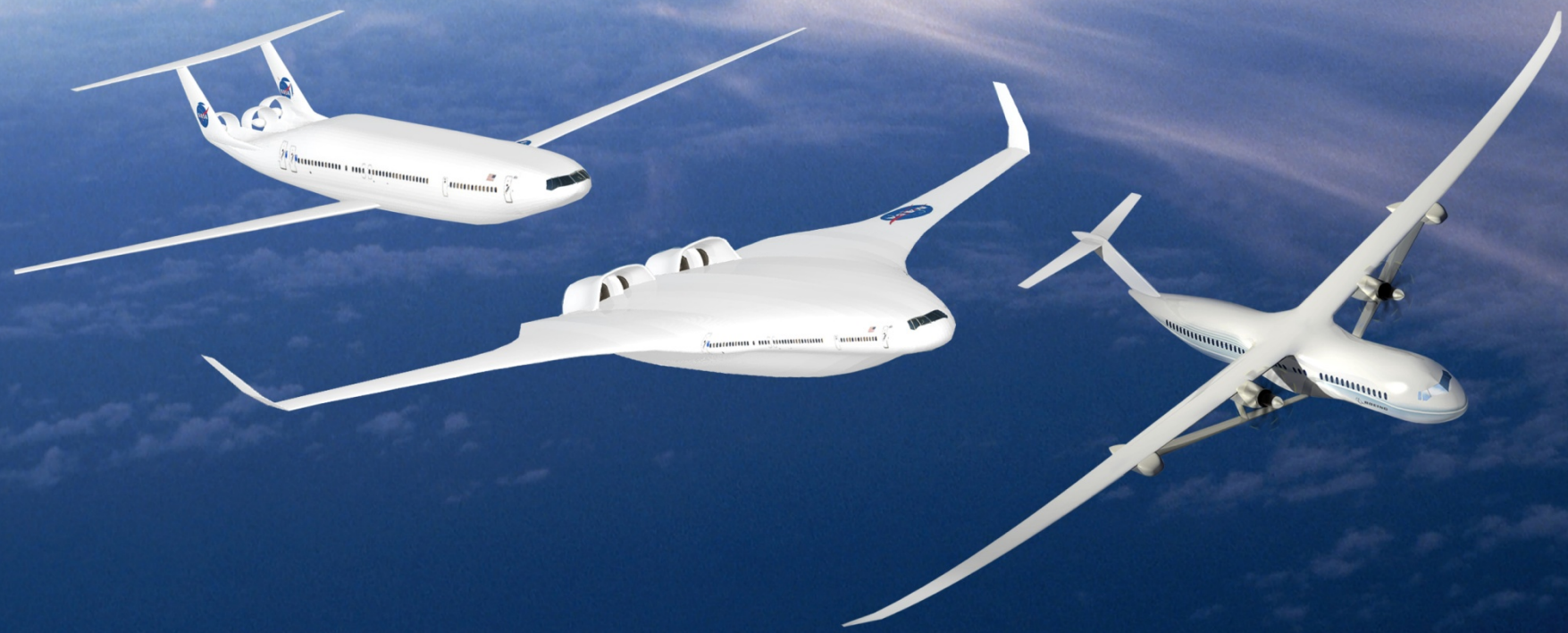
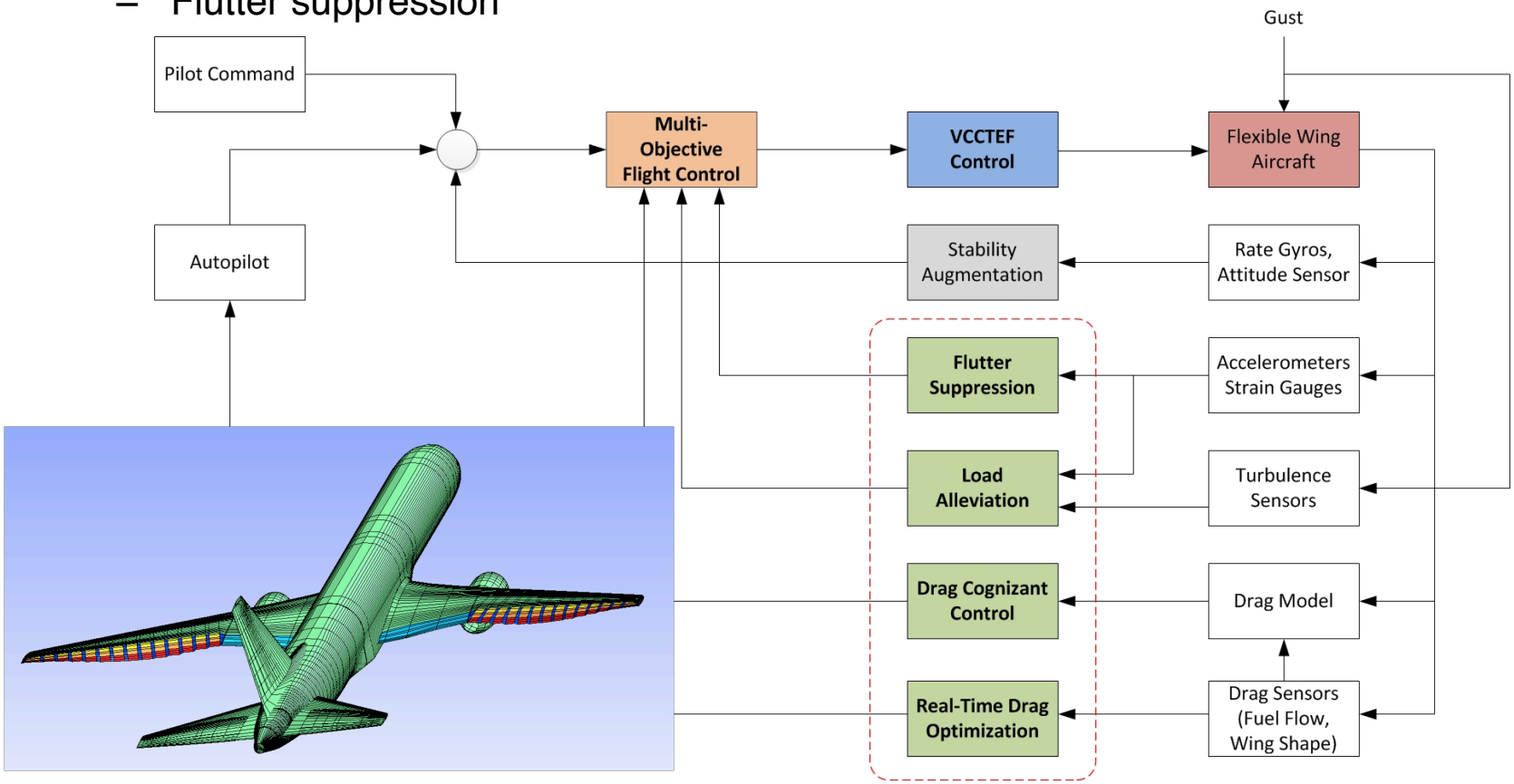


Agenda

- **Multi-Objective Flight Control**
- **Real-Time Drag Minimization**
- **Adaptive Flutter Suppression**

Multi-Objective Flight Control

- **Multi-functional flight control surfaces such as VCCTEF allow new possibilities in flight control to achieve multiple objectives simultaneously**
  - Roll control and high lift requirements
  - Drag reduction during cruise and maneuvers
  - Gust and maneuver load alleviation
  - Flutter suppression



Multi-Objective Flight Control

- **ASE state-space model**

$$\dot{x}_r = A_{rr}x_r + A_{re}x_e + B_r u_r + w_r$$

$$\dot{x}_e = A_{er}x_r + A_{ee}x_e + B_e u_e + w_e$$

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

- **Objectives**
  - Command tracking

$$z = Fx_r \to r$$

  - Drag reduction during cruise and maneuvers

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

  - Maneuver load alleviation

$$\Delta M = M_x x + M_u u + M_w w_e$$

  - Modal suppression / gust load alleviation due to gust disturbance w_r and w_e

$$x_e \to 0$$

Multi-Objective Flight Control

- **Multi-objective LQG optimal control**

$$J = J_r + J_e$$

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

$$J_e = \lim_{t_f \to \infty} \frac{1}{2} \int_0^{t_f} \left(x_e^\top Q_e x_e + u_e^\top R_e u_e + q_D \Delta C_D + \Delta M^\top q_M \Delta M \right) dt$$

- **Observer-based adaptive disturbance estimation**

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

$$\boxed{\begin{aligned} \dot{\hat{w}}_r^\top &= -\Gamma_r e^\top P \\ \dot{e} = \dot{x}_c - \dot{x}_r &= A_c e + A_{re}(\hat{x}_e - x_e) + \tilde{w}_r \end{aligned}}$$

$$\boxed{\begin{aligned} \dot{\hat{w}}_e^\top &= -\Gamma_e \frac{\partial J^\top}{\partial \hat{w}_e^\top} = -\Gamma_e \epsilon^\top M_w \\ \epsilon &= M_x \hat{x} + M_u u + M_w \hat{w}_e - \Delta M \end{aligned}}$$

Multi-Objective Flight Control

- **Multi-objective flight control laws**

$$u = K_x \hat{x} + K_r r + K_w \hat{w} + \Lambda_0$$

$$K_x = -\bar{R}^{-1}\left(B^\top W + \frac{1}{2} q_D C_{D_{xu}}^\top + q_M M_u^\top M_x\right)$$

$$K_r = -\bar{R}^{-1} B^\top V$$

$$K_w = -\bar{R}^{-1}\left(B^\top T + q_M M_u^\top M_w E\right)$$

$$\Lambda_0 = -\bar{R}^{-1}\left(B^\top S + \frac{1}{2} q_D C_{D_u}^\top\right)$$

$$W\bar{A} + \bar{A}^\top W - WB\bar{R}^{-1}B^\top W + \bar{Q} = 0$$

$$V = \left(\bar{A}^\top - WB\bar{R}^{-1}B^\top\right)^{-1} G_x^\top Q G_r$$

$$S = \left(\bar{A}^\top - WB\bar{R}^{-1}B^\top\right)^{-1}\left[-\frac{1}{2} q_D C_{D_x}^\top + \frac{1}{2} q_D \left(WB + \frac{1}{2} q_D C_{D_{xu}} + q_M M_x^\top M_u\right)\bar{R}^{-1} C_{D_u}^\top\right]$$

$$\bar{R} = R + q_D C_{D_{u^2}}^\top + q_M M_u^\top M_u$$

$$\bar{A} = A - \frac{1}{2} q_D B\bar{R}^{-1} C_{D_{xu}}^\top - q_M B\bar{R}^{-1} M_u^\top M_x$$

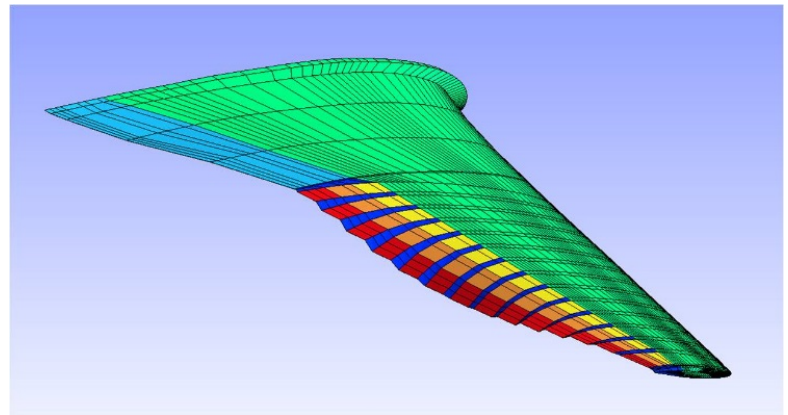
$$\bar{Q} = G_x^\top Q G_x + q_D C_{D_{x^2}}^\top + q_M M_x^\top M_x - \left(\frac{1}{2} q_D C_{D_{xu}}^\top + q_M M_u^\top M_x\right)^\top \bar{R}^{-1}\left(\frac{1}{2} q_D C_{D_{xu}}^\top + q_M M_u^\top M_x\right)$$

Virtual Control Variables

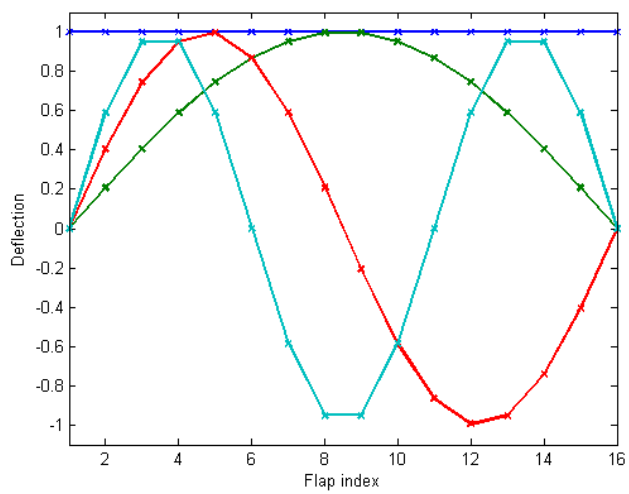
- **Elastomer limits relative deflection and rate**

$$|\delta_{i+1} - \delta_i| \leq \Delta\delta$$

$$\left|\dot{\delta}_{i+1} - \dot{\delta}_i\right| \leq \Delta\dot{\delta}$$



- **Flaps prescribed by sinusoidal or other shape function**
  - Constraints are satisfied
  - Reduction of control variables



$$\delta_i = A_0 + \sum_{n=1}^{N} A_n \sin \frac{(i-1)n\pi}{(m-1)}$$

Sensors for Drag and Load Estimation

- **Drag estimation requires model and sensors**
  - Fuel flow meter correlation
  - Fiber optic shape sensors
  - Strain gauges for wing tip deflections

- **Load alleviation requires model and sensors**
  - Wing root strain gauges for maneuver load estimation
  - Strain gauges for co-located gust load estimation
  - Lidar or leading edge pressure sensors for forward-looking gust load estimation

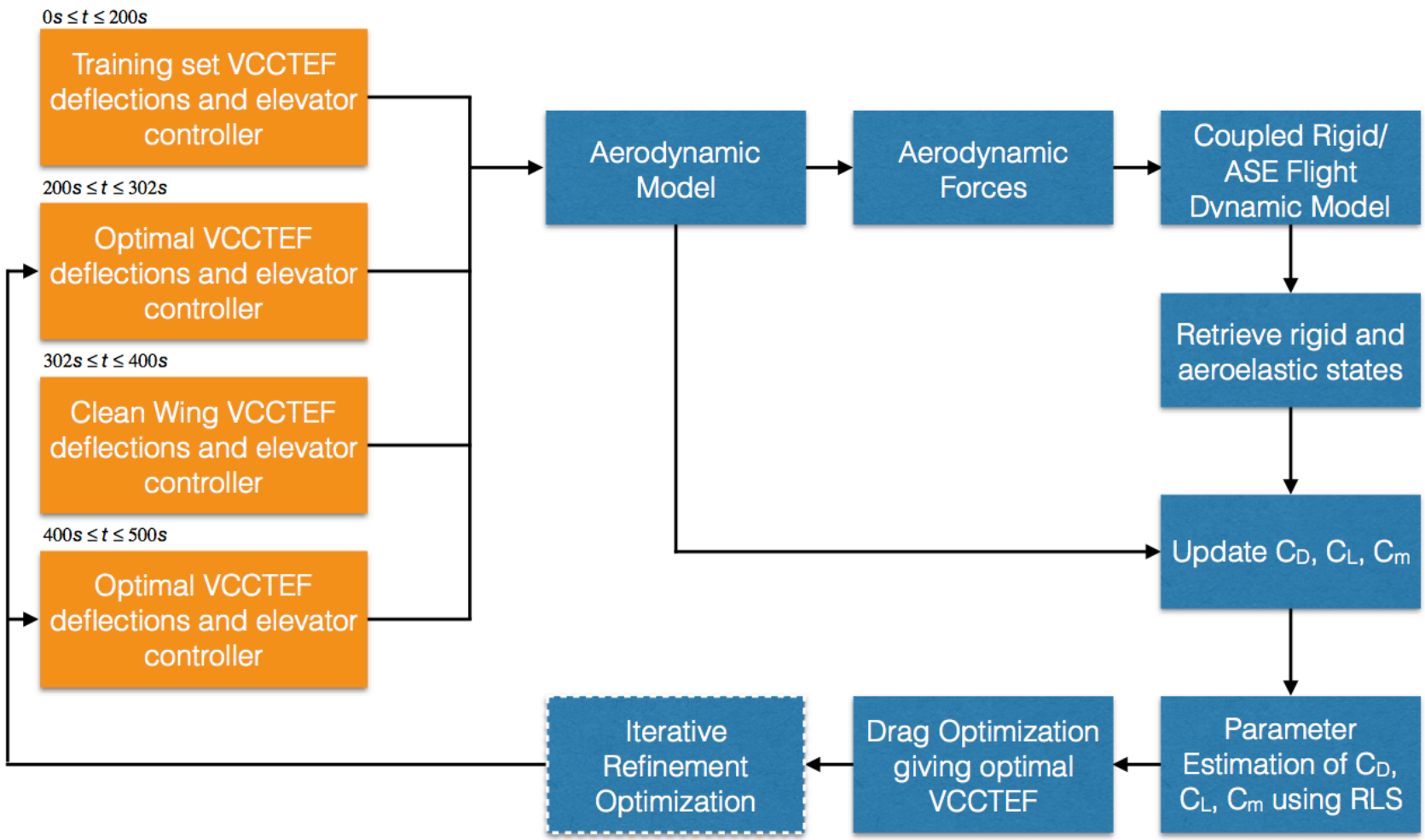
Real-Time Drag Minimization Control

- **Parametric aerodynamic model**

$$
\begin{aligned}
C_D = \; & C_{D_0} + C_{D_a} a + C_{D_\alpha} \alpha + C_{D_{w_t}} w_t + C_{D_{\theta_t}} \theta_t + C_{D_{\delta_e}} \delta_e + a^T C_{D_{a^2}} a + a^T C_{D_{a\alpha}} \alpha \\
& + a^T C_{D_{aw_t}} w_t + a^T C_{D_{a\theta_t}} \theta_t + a^T C_{D_{a\delta_e}} \delta_e + C_{D_{\alpha^2}} \alpha^2 + C_{D_{\alpha w_t}} \alpha w_t + C_{D_{\alpha\theta_t}} \alpha\theta_t \\
& + C_{D_{\alpha\delta_e}} \alpha\delta_e + C_{D_{w_t^2}} w_t^2 + C_{D_{w_t\theta_t}} w_t\theta_t + C_{D_{w_t\delta_e}} w_t\delta_e + C_{D_{\theta_t^2}} \theta_t^2 + C_{D_{\theta_t\delta_e}} \theta_t\delta_e \\
& + C_{D_{\delta_e^2}} \delta_e^2
\end{aligned}
$$

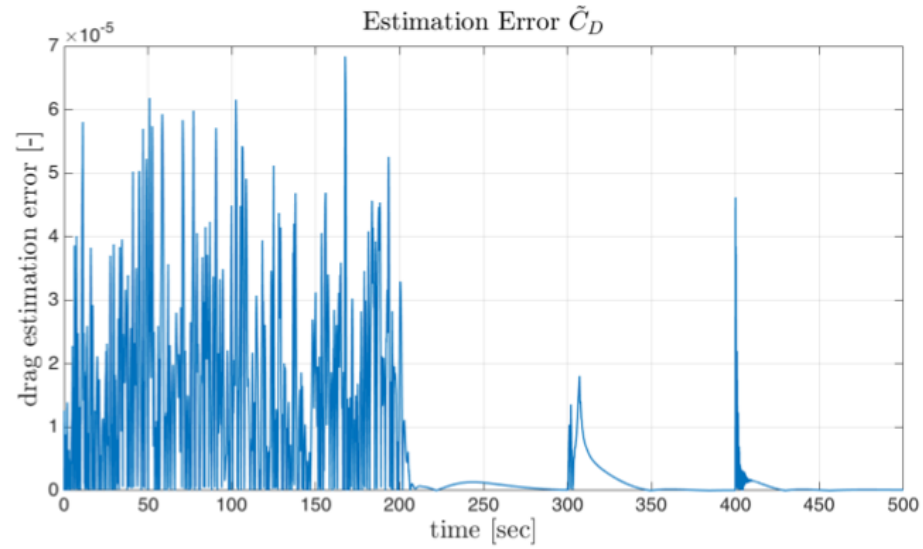
- **Real-time recursive least-squares parameter estimation with flap inputs**
- **Altitude-hold flight control to minimize aircraft motion**
- **Constrained adjoint-based optimization**
- **Iterative refinement optimization to prevent local minimum**

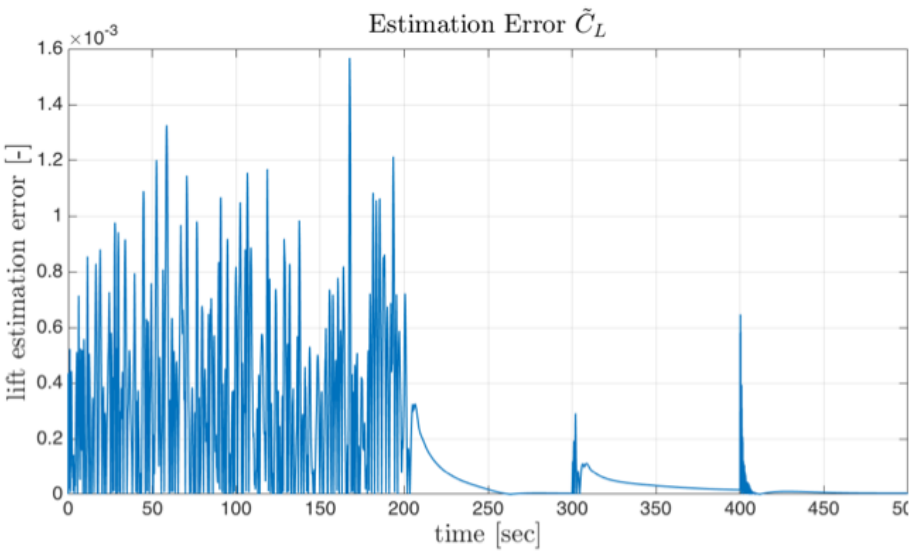
Real-Time Drag Minimization Control

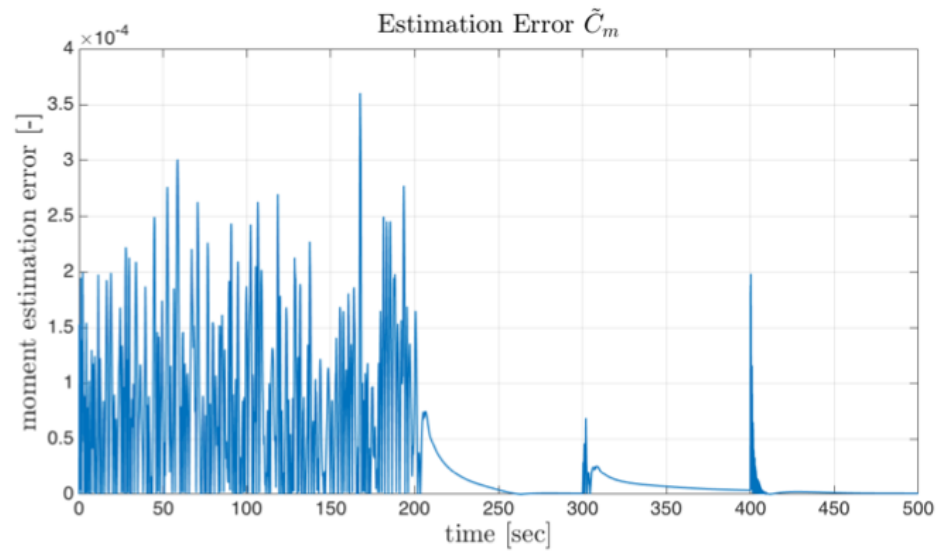


Simulations

Recursive Least Squares Coefficient Estimation Error





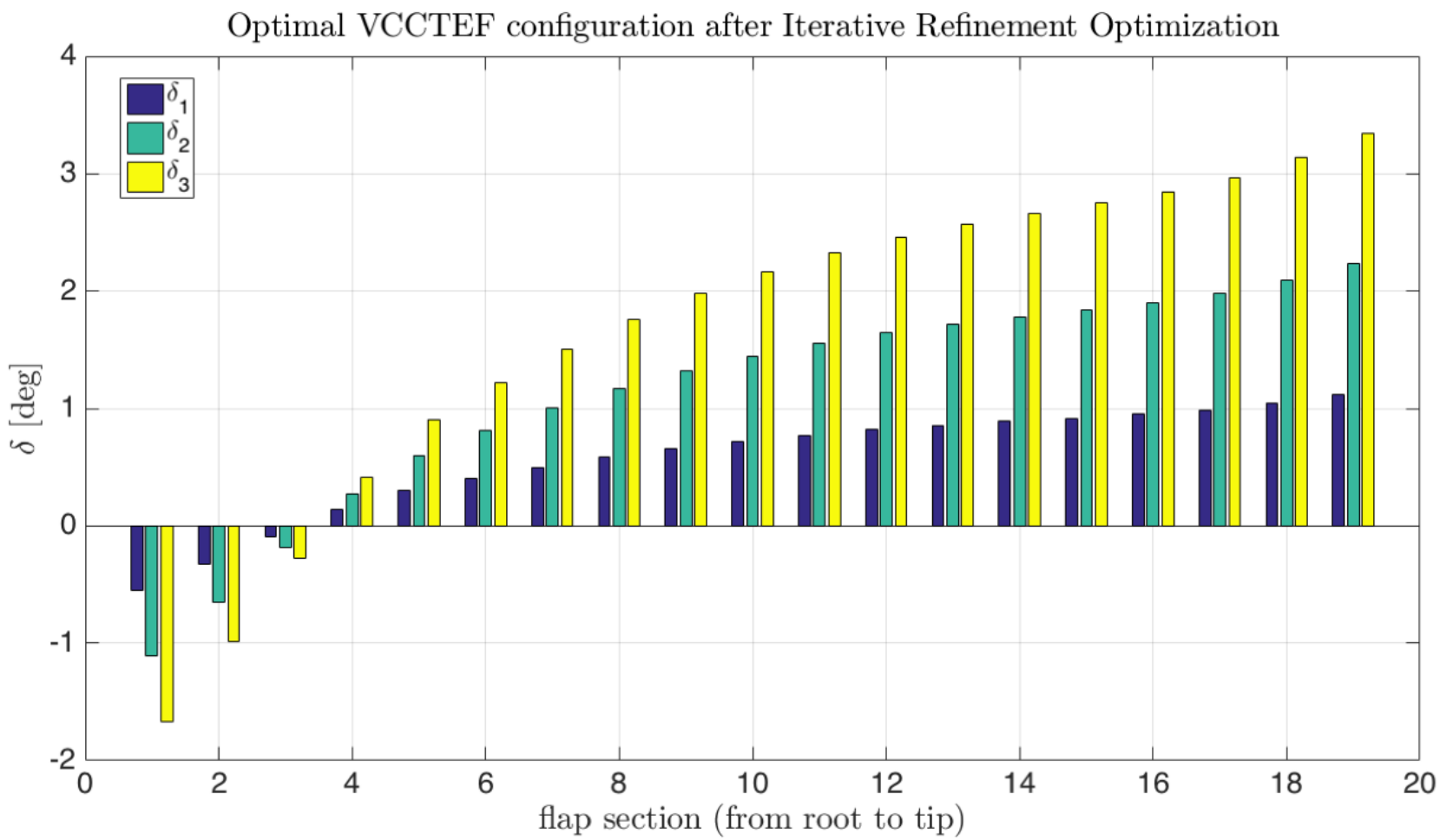


Simulations

Optimization Configuration and Results

	Clean Wing	Initial Optimal	Final Optimal
angle of attack [deg]	2.51	2.32	2.35
VCCTEF [deg]	0	$-1.5 < \delta < 3.6$	$-1.7 < \delta < 3.4$
elevator [deg]	-1.1	-1.9	-1.8
wing tip bending [ft]	3.1	3.4	3.4
wing tip twist [deg]	0.1	-0.1	-0.1
C_L [-]	0.4595	0.4595	0.4595
C_m [-]	-0.0042	-0.0042	-0.0042
C_D [drag count]	186.03	183.14	183.17

Simulations



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

- **Optimal Control Modification (OCM) adaptive law developed in 2008**
  - Optimal adaptive control theory

$$J = \frac{1}{2}\int_0^{t_f} (e-\Delta)^\top Q (e-\Delta)\, dt$$

$$\boxed{\dot{\Theta} = -\Gamma\Phi\left(e^\top P - \nu\Phi^\top\Theta B^\top P A_c^{-1}\right)B}$$

  - Asymptotic linear stability analysis well-suited for flutter suppression

Adaptive Flutter Suppression

- **Adaptive Linear Quadratic Gaussian control**

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

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

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

- **Asymptotic closed-loop system**

$$\dot{x} = Ax + B\bar{K}_x \hat{x} + \left(\frac{1}{\nu_x} + \frac{1}{\nu_y} \right) B \left(B^\top A_m^{-\top} P B \right)^{-1} B^\top P \hat{x}$$

$$\dot{\hat{x}} = \left[A + B\bar{K}_x + \left(\frac{1}{\nu_x} + \frac{1}{\nu_y} \right) P^{-1} A_m^\top P - LC \right] \hat{x} + LCx$$

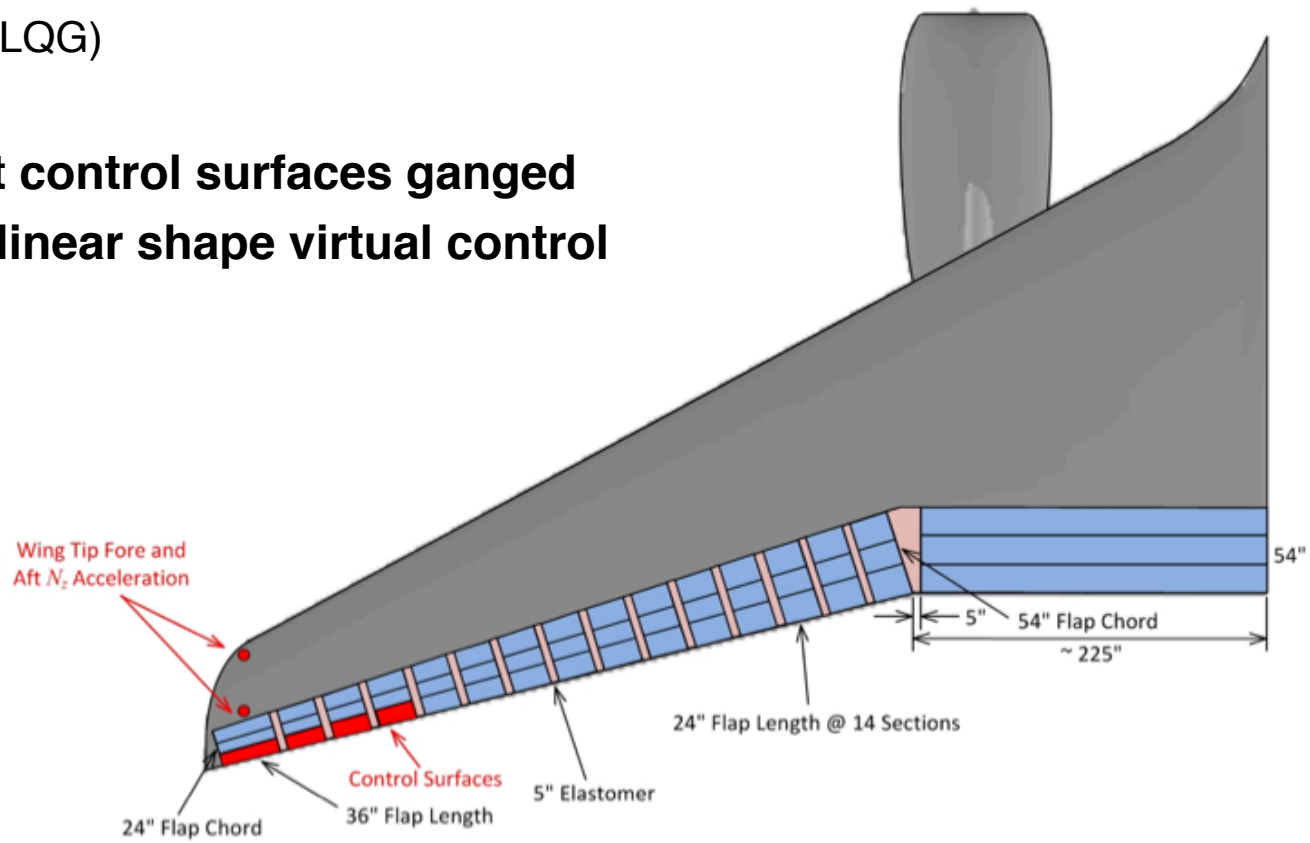
$$A_c = \begin{bmatrix} A & B\bar{K}_x + \left(\frac{1}{\nu_x} + \frac{1}{\nu_y} \right) B \left(B^\top A_m^{-\top} P B \right)^{-1} B^\top P \\ LC & A - LC + B\bar{K}_x + \left(\frac{1}{\nu_x} + \frac{1}{\nu_y} \right) B \left(B^\top A_m^{-\top} P B \right)^{-1} B^\top P \end{bmatrix}$$

  – Stability margins can be analyzed by singular perturbation model reduction to flutter mode of interest or MIMO singular-value or matrix measure methods

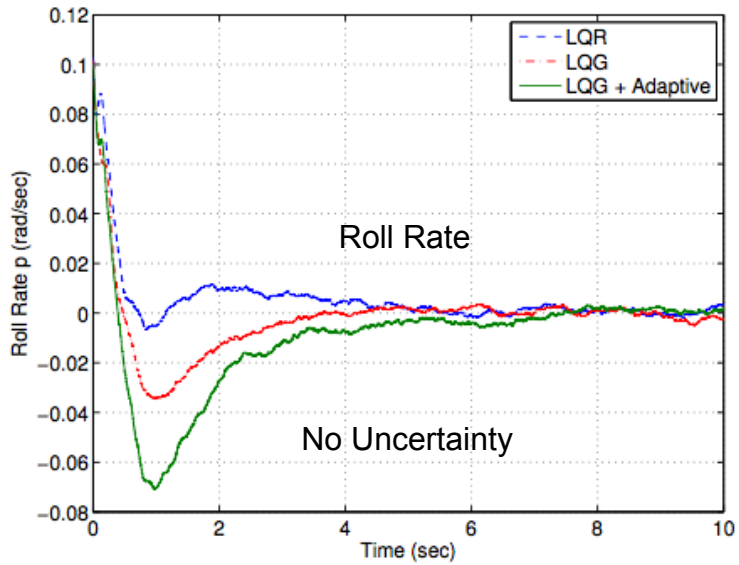
Sensing and State Estimation

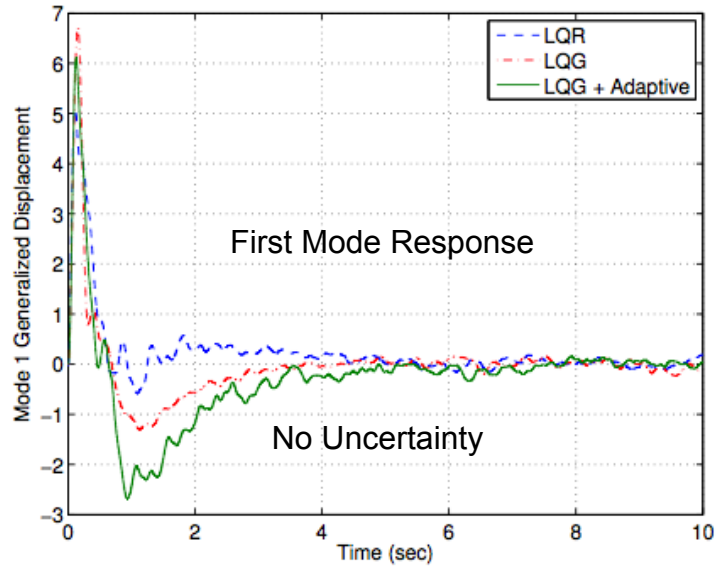
- **Measurement feedback for elastic states**
  - 2 accelerometers
  - Kalman filter (LQG)

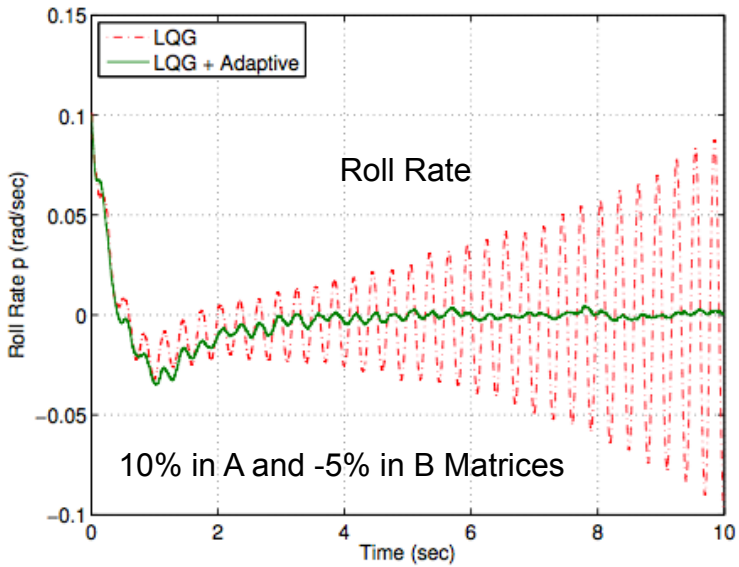
- **Four outermost control surfaces ganged together using linear shape virtual control**

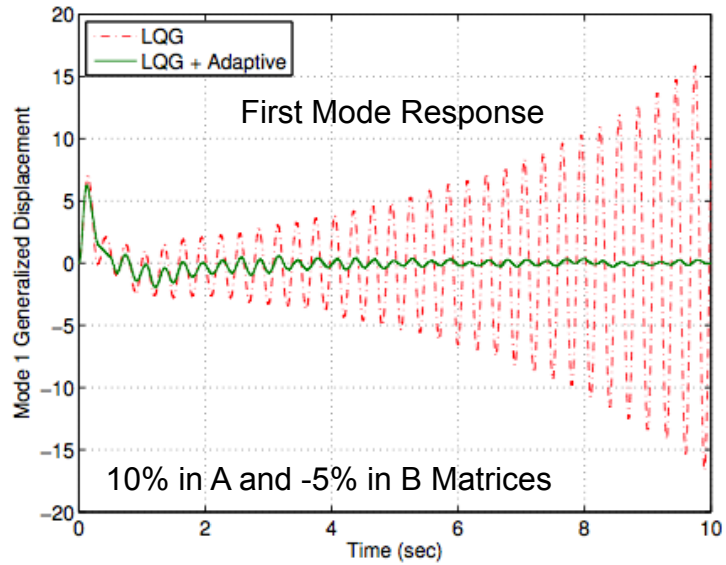


Flutter Suppression Simulations

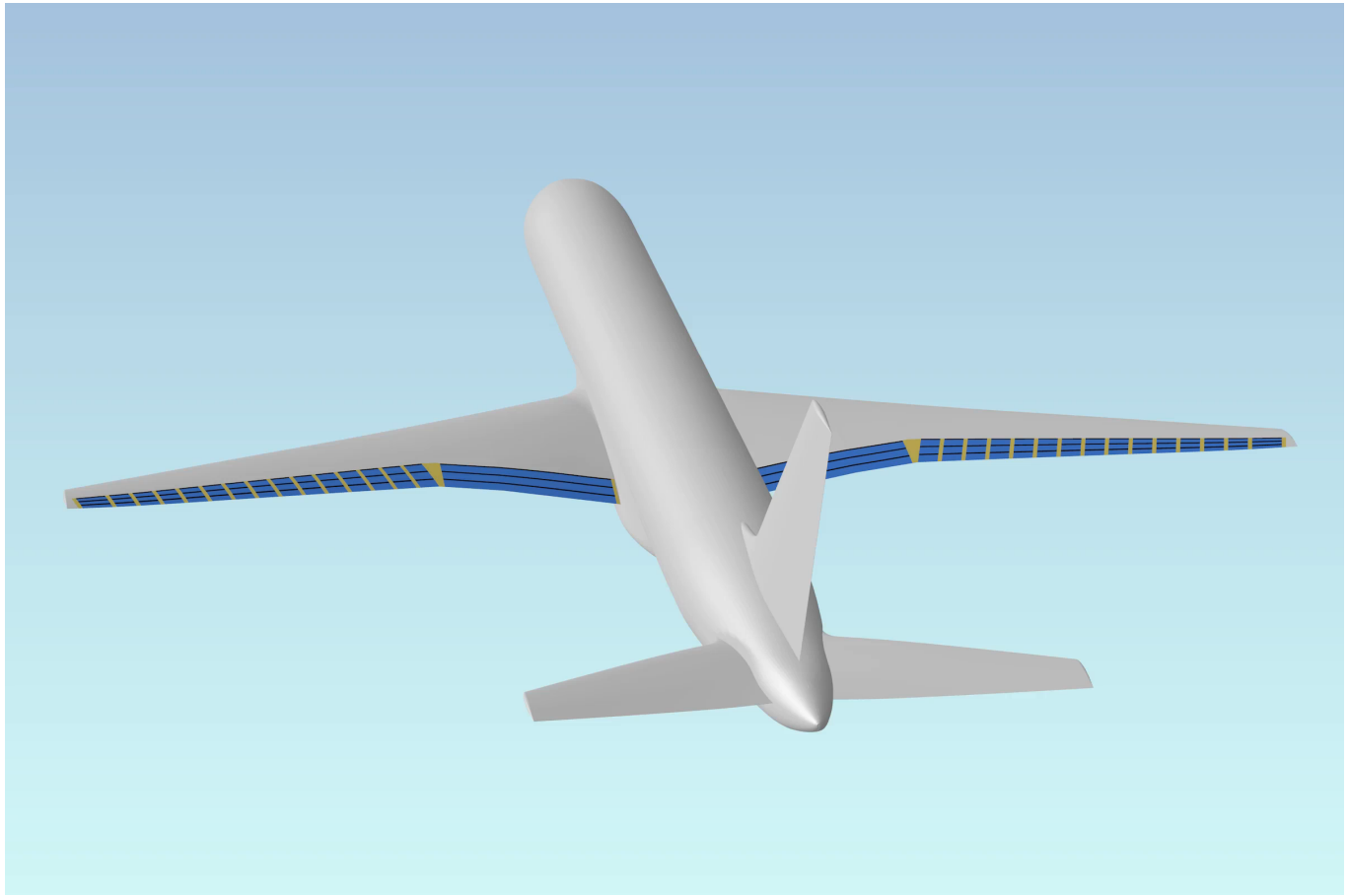




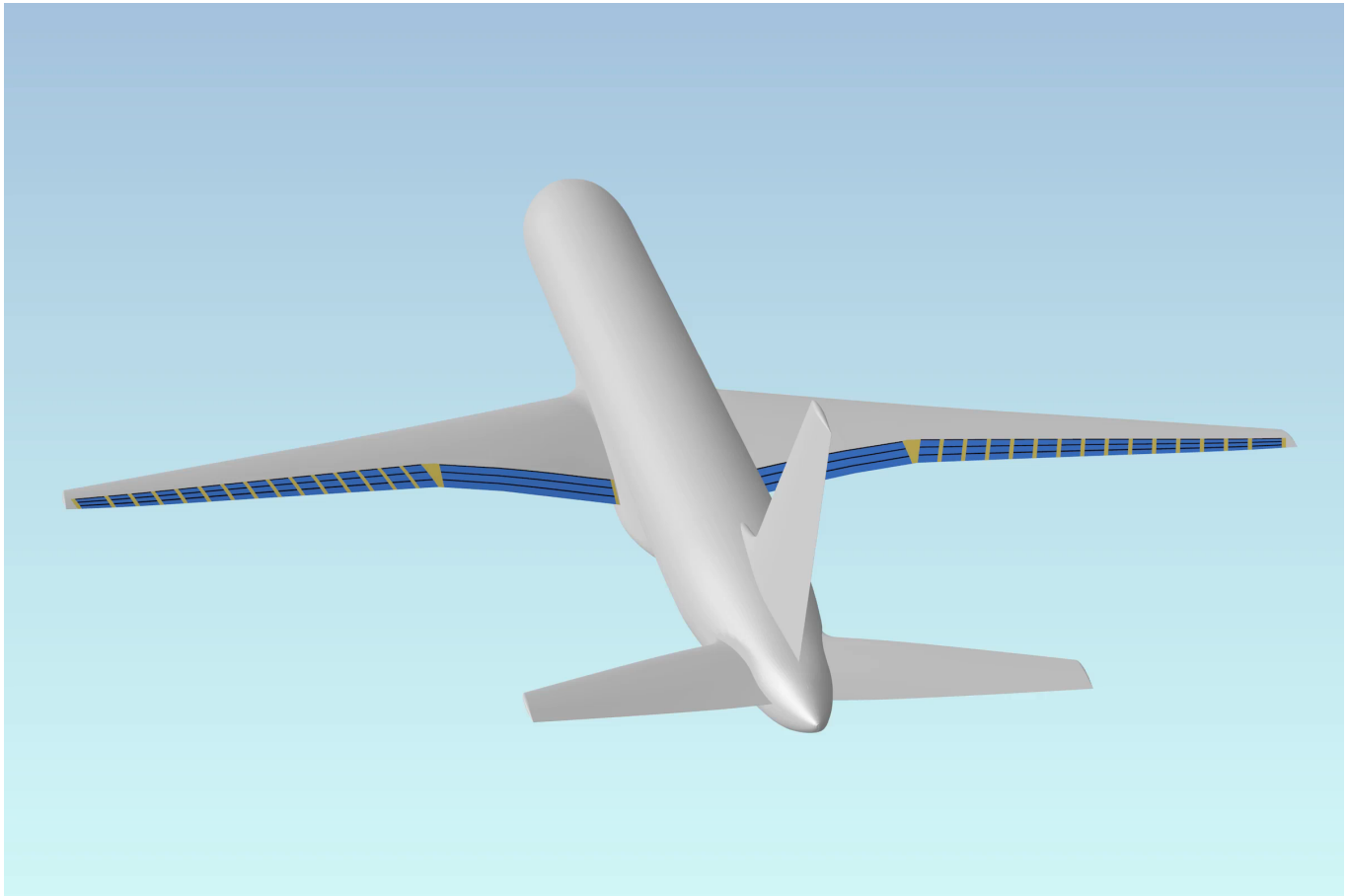




Flutter Animation



Flutter Suppression Animation



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Thank You