National Aeronautics and Space Administration

MDAO Research on Performance Adaptive Aeroelastic Wing at NASA Ames

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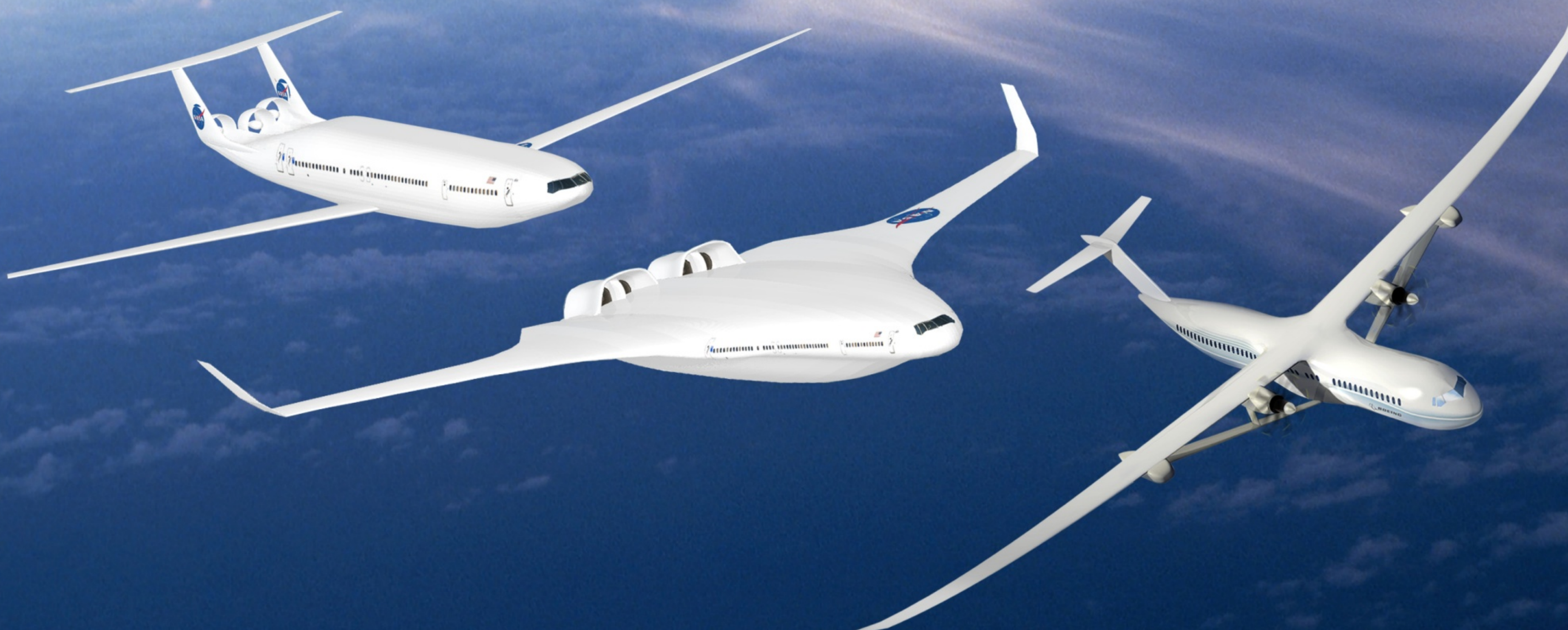
Boeing MDAO Technical Interchange Meeting

Mukilteo, WA

July 25, 2018



Outline

Introduction

Performance Adaptive Aeroelastic Wing Research

- Aero-Structural Drag Optimization Trade Study
- Real-Time Adaptive Drag Optimization
- Multi-Objective Flight Control

Collaboration with Boeing Research & Technology

- Integrated Adaptive Wing Technology Maturation (IAWTM) NRA
- SBIR Phase II-X / III on GLA Wind Tunnel Test
- Transonic Truss-Braced Wing (TTBW) NRA

Other Topic

- Aeroelastic Wing Shaping for Distributed Propulsion Aircraft

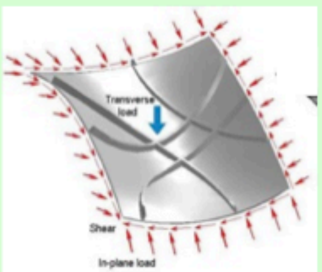
Summary

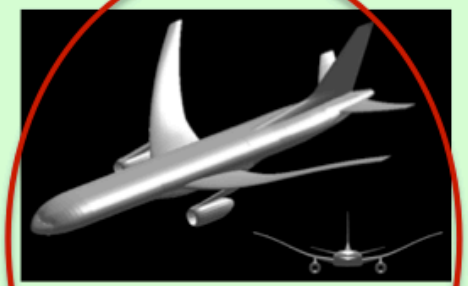
AATT Project Research Themes

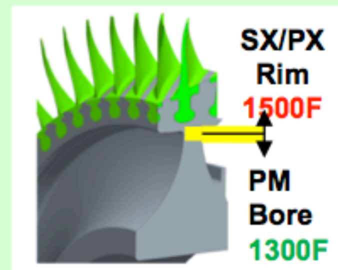
Based on Goal-Driven Advanced Concept Studies

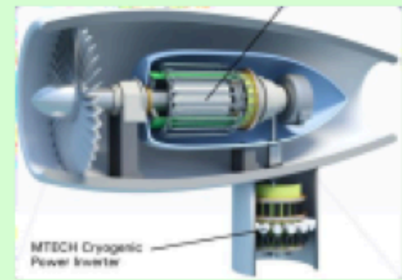
Goals Metrics (N+3)	Noise Stage 4 – 52 dB cum	Emissions (LTO) CAEP6 – 80%	Emissions (cruise) 2005 best – 80%	Energy Consumption 2005 best – 60%

Goal-Driven Advanced Concepts (N+3)









1. Lighter-Weight Lower Drag Fuselage

2. Higher Aspect Ratio Optimal Wing

3. Quieter Low-Speed Performance

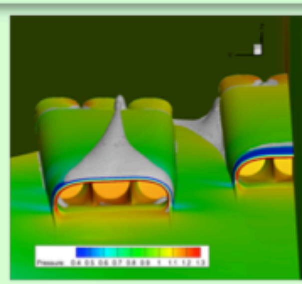
4. Cleaner, Compact Higher BPR Propulsion

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 (PAAW)

Adaptive aeroelastic wing shaping control can enable performance optimization of high aspect ratio wing transport

$$\alpha_c = \alpha - \gamma - \Theta \cos\Lambda - W_x \sin\Lambda + \frac{\partial\alpha}{\partial\delta}\delta + \left(\frac{\partial\Theta}{\partial\delta}\cos\Lambda + \frac{\partial W_x}{\partial\delta}\sin\Lambda\right)\delta$$

Aircraft AoA

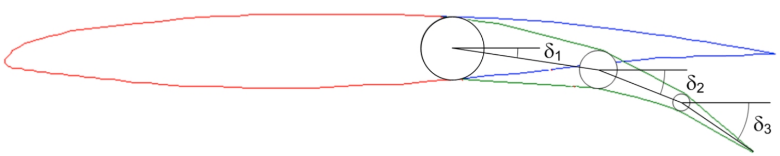
Jig Shape Twist

Wing Deflection (Twist and Bending)

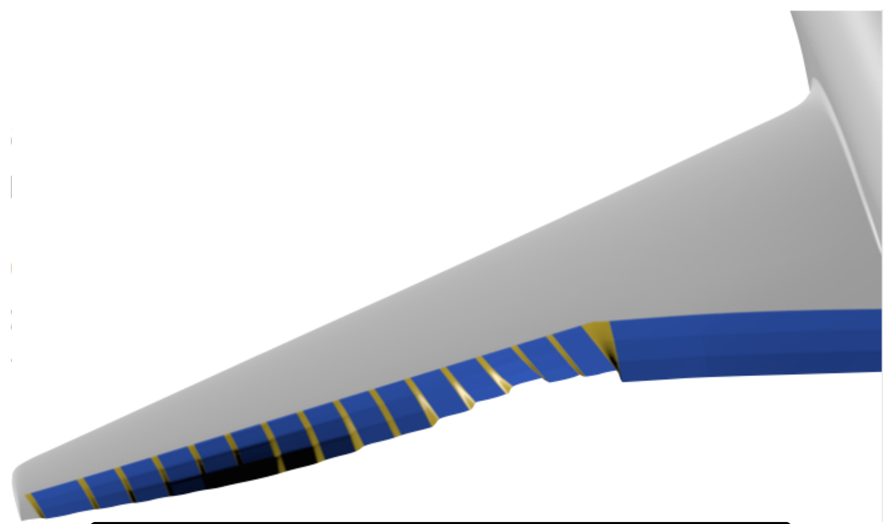
TE Camber Control

Wing Shaping Control

Variable Camber Continuous Trailing Edge Flap (VCCTEF) is an adaptive aeroelastic wing concept with both spanwise and chordwise shape changing features.



Chordwise Multi-Segment Variable Camber



Spanwise Continuous Trailing Edge Flap

Nguyen, N., "Elastically Shaped Future Air Vehicle Concept," NASA Innovation Fund Project 2010 Report, October 2010, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20110023698.pdf.

MDAO Research

MDAO research under NASA Advanced Air Transport Technologies (AATT) project investigates advanced adaptive aeroelastic wing technology concepts

Integrated Flight Dynamics
- Coupled ASE – Flight Dynamics
- Gust Modeling
- Actuator Dynamics of Control Surfaces

Aero-Structural Modeling
- Multi-Fidelity Aerodynamics
- Structural Dynamics
- Aeroelasticity
- Aeroservoelasticity (ASE)

Design Concepts
- VCCTEF / Continuous Leading Edge Slat
- Distributed Control Surfaces
- Distributed Propulsion

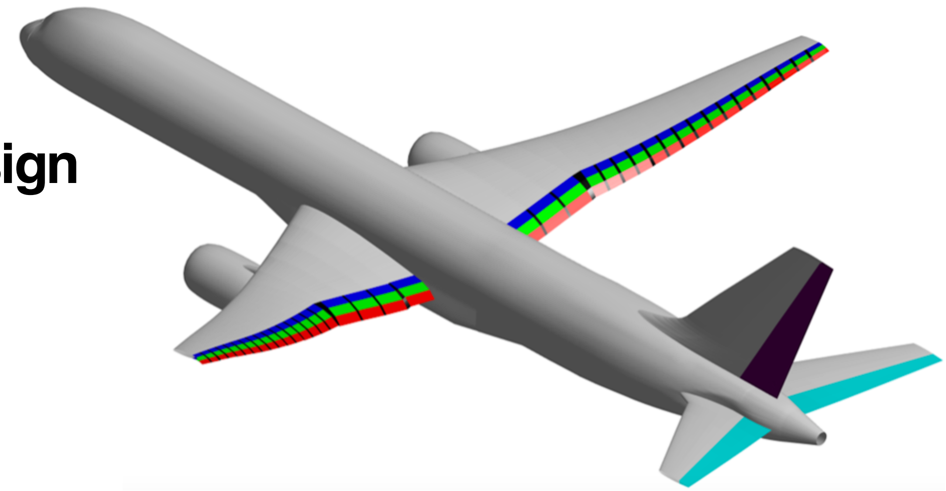
Aero-Structural Optimization
- Drag and Load Optimization of Elastic Structures
- Aeroelastic Constraints with Active Controls

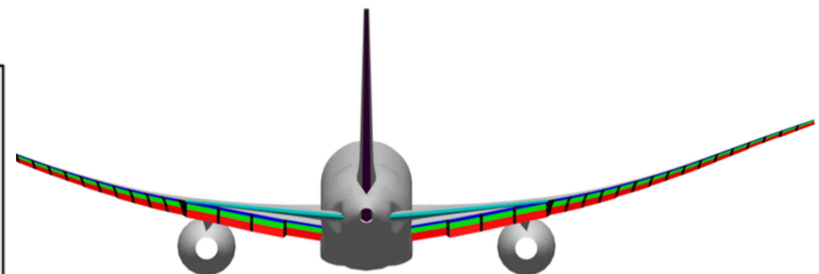
Performance Analysis
- Design Trade-Study
- Mission Analysis / Trajectory Optimization to Minimize Fuel Burn

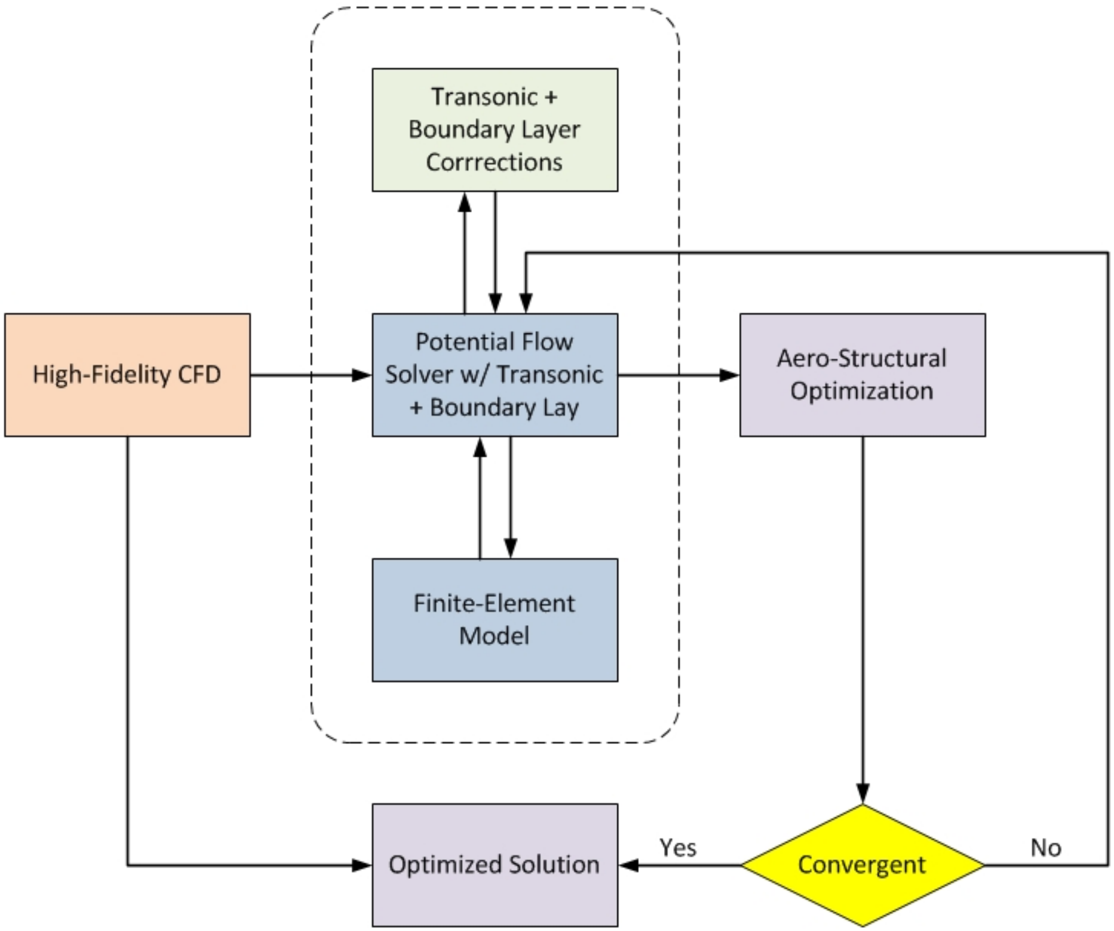
Aeroelastic Control
- Aeroelastic Control (Flutter Suppression, Load Alleviation)
- Real-Time Drag Optimization
- Multi-Objective Flight Control

Multi-Fidelity Aero-Structural Drag Optimization

Multi-fidelity aero-structural drag optimization framework developed to provide computational efficiency for design exploration of VCCTEF trade space

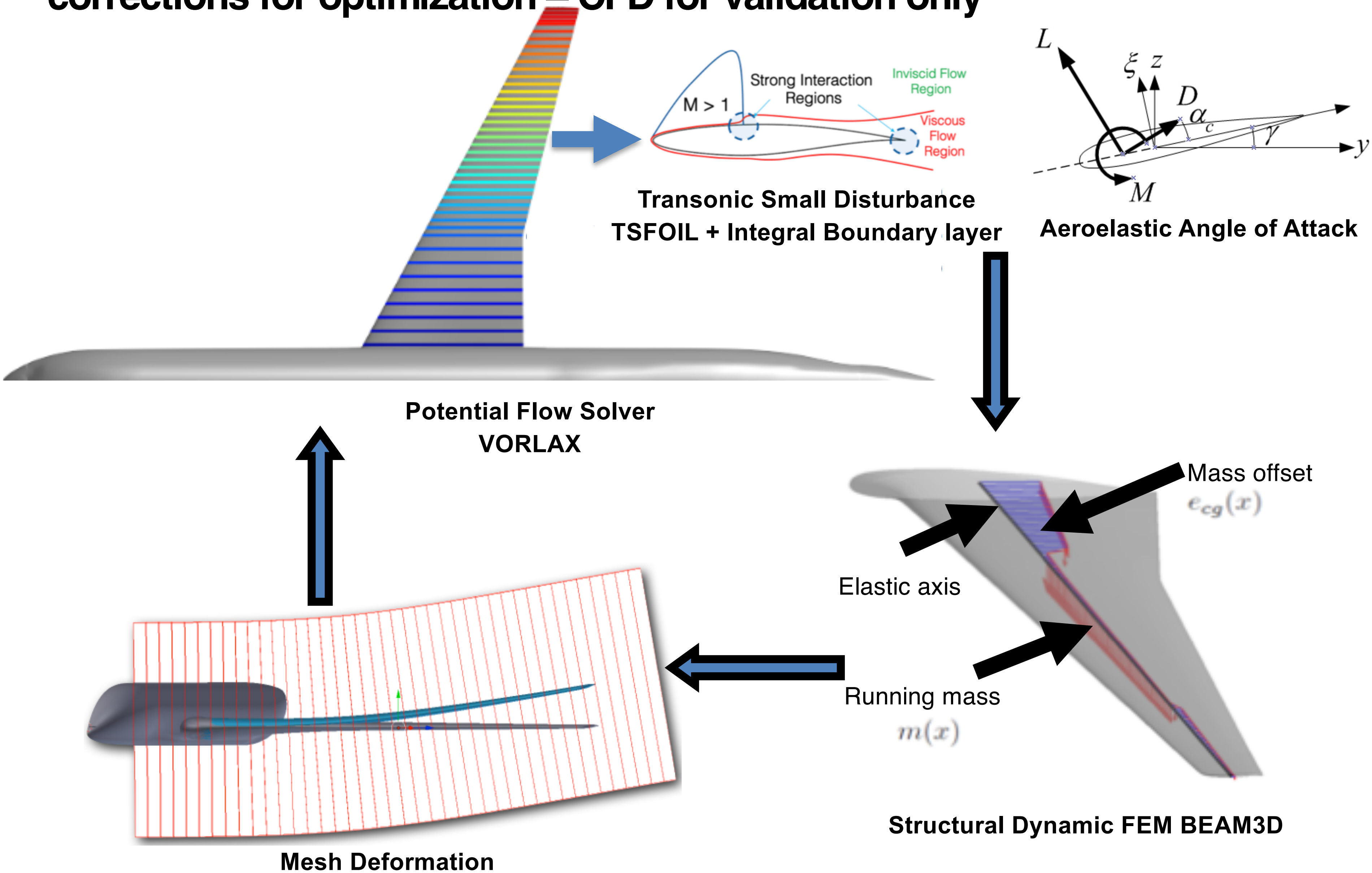






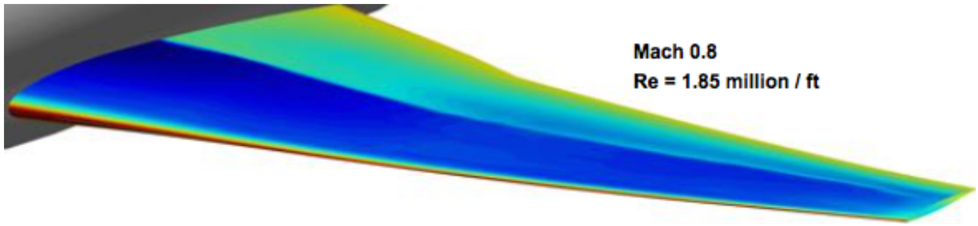
Aero-Structural Drag Optimization Framework

Computationally efficient aero-structural solver with transonic / viscous corrections for optimization – CFD for validation only



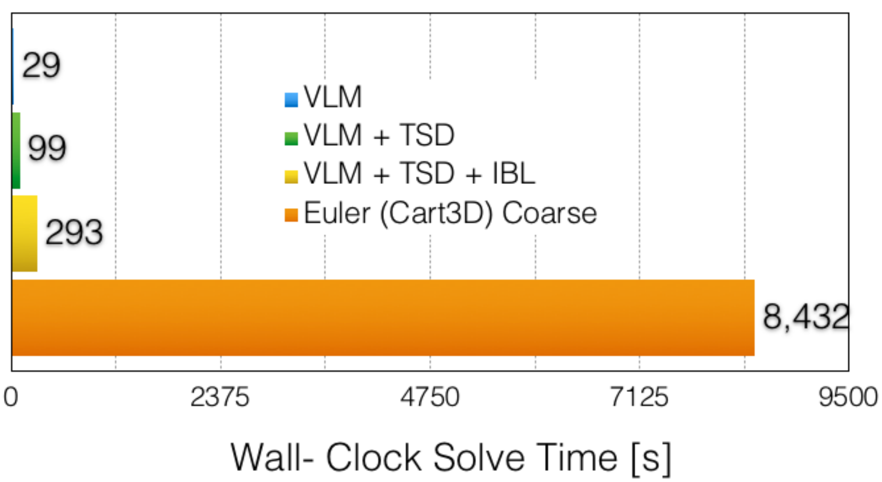
Aero-Structural Drag Optimization Framework

CFD validation

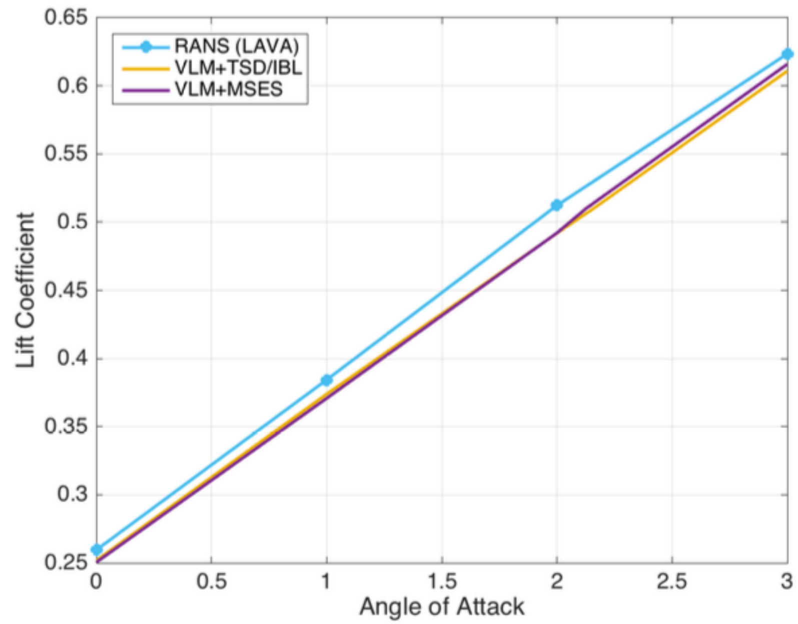


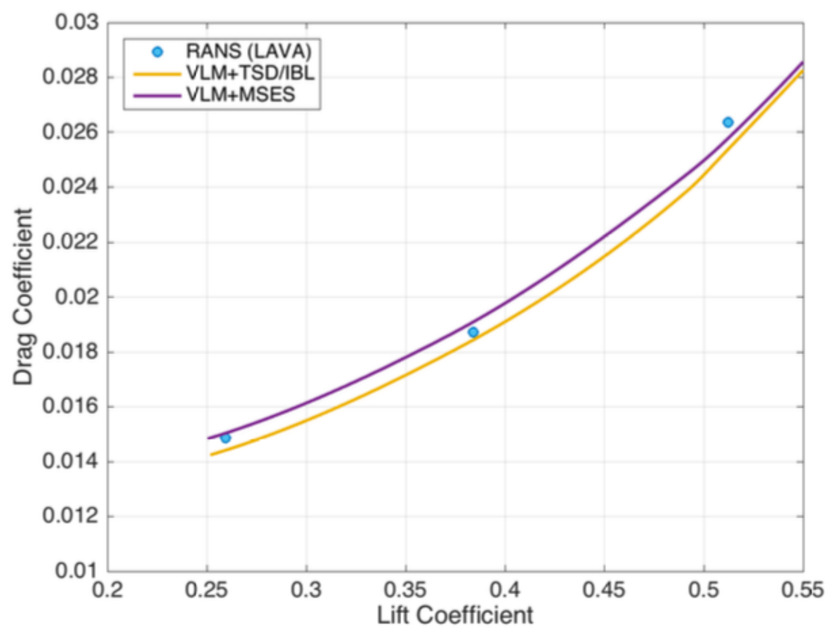
	Cruise L/D
VLM + TSD + IBL	20.9
RANS (LAVA)	19.5
Viscous Model Error	**7.4%**

Computational time comparison



All models run on quad-core macbook pro

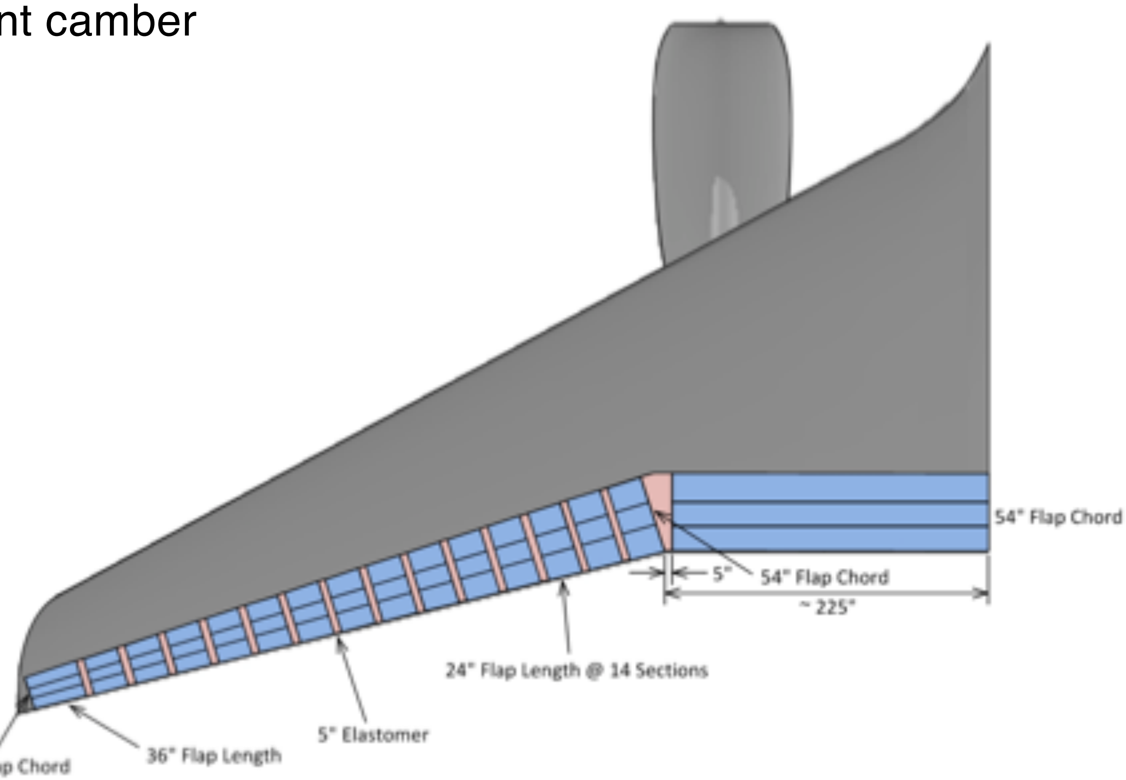




Aero-Structural Drag Optimization Trade Study

Conduct drag optimization trade study on NASA Generic Transport Model (B757-derived geometry) with flexible wings

- Number of inboard vs. outboard spanwise variable camber flap sections
- Two-segment camber vs. three-segment camber
- Camber shapes
  - Conventional plain flap
  - Circular arc camber
  - Parabolic arc camber
  - Unconstrained flap

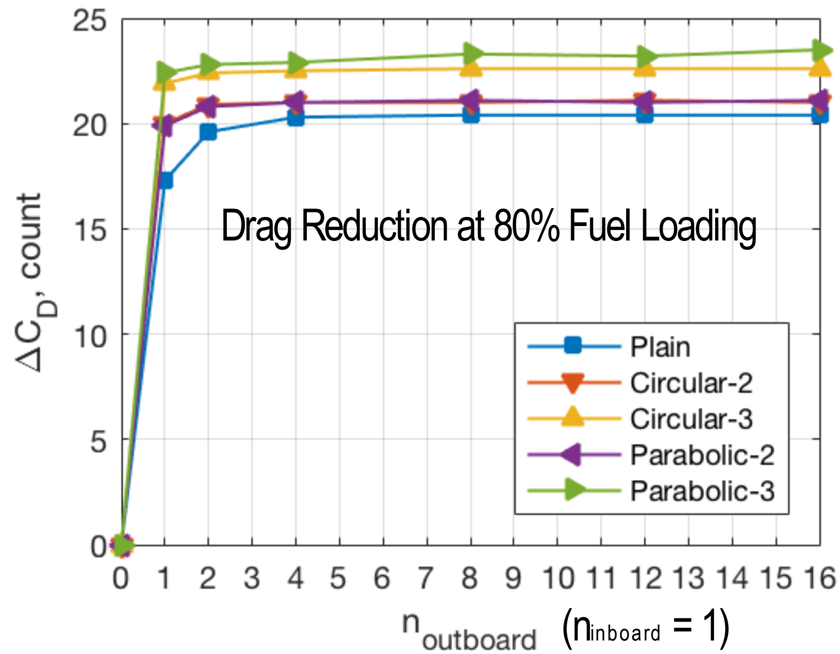


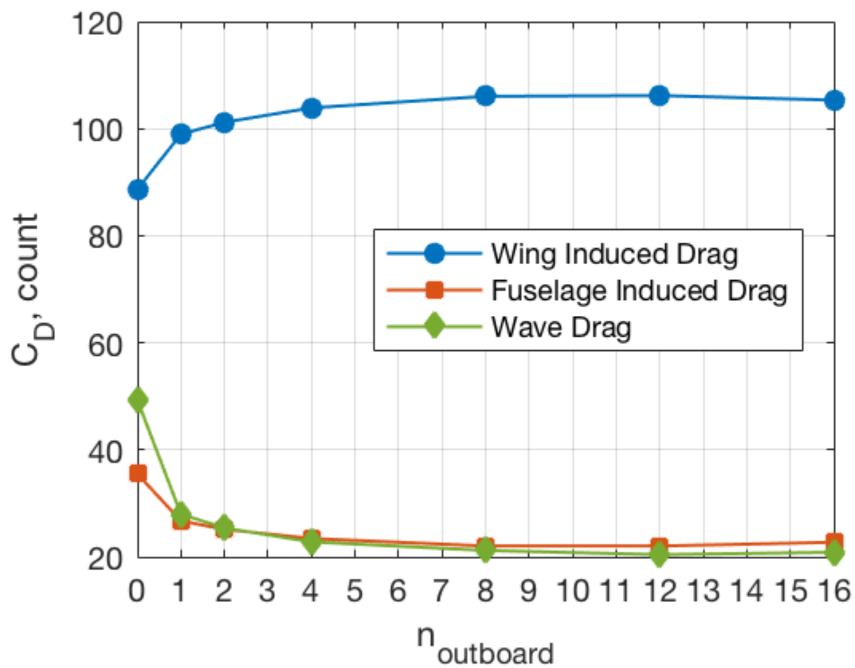
- Flap system weight and power (to be considered in the future)

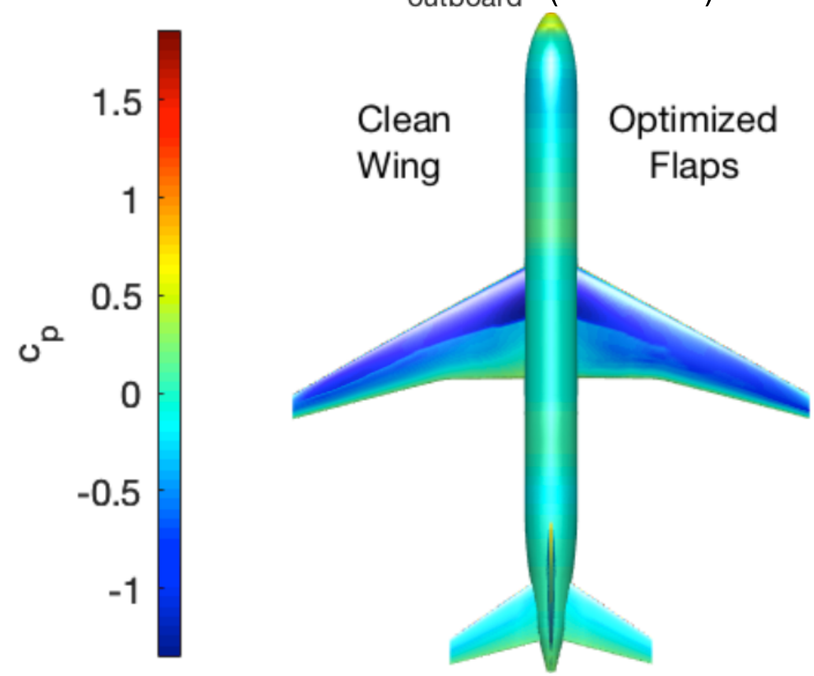
Aero-Structural Drag Optimization Trade Study

Trend

- Drag reduction can be achieved with as few as four outboard flaps and one inboard flap
- Increasing number of cambered segments improves drag reduction
- Parabolic arc camber performs better than circular arc camber
- Primary contribution is due to wave drag reduction







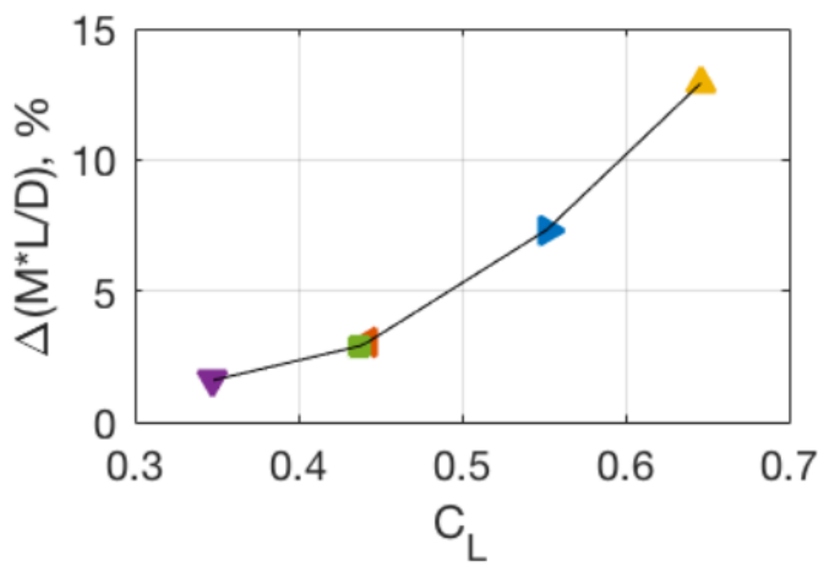
Aero-Structural Drag Optimization Trade Study

Summary results

Flight Condition	L/D Clean	L/D with Flaps	% L/D Increase
80% Begin Cruise	19.5	21.3	9.2
20% End Cruise	20.9	21.7	3.8
+30% Gross Weight Mid-Cruise	17.3	20.1	16.2
-30% Gross Weight Mid-Cruise	20.4	20.8	2.0
Mach 0.85 Overspeed Dash-Cruise	14.8	15.3	3.4

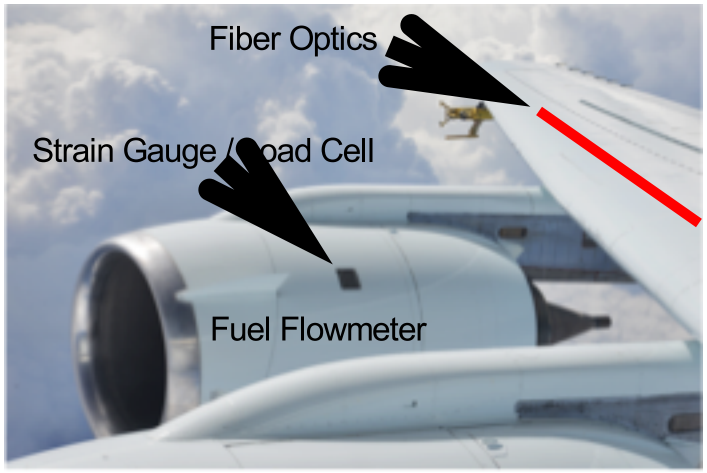
Three-Segment Parabolic Arc Camber $n_{inboard} = 4 + n_{inboard} = 16$

- Drag reduction can be presented as figure-of-merit M*L/D improvement

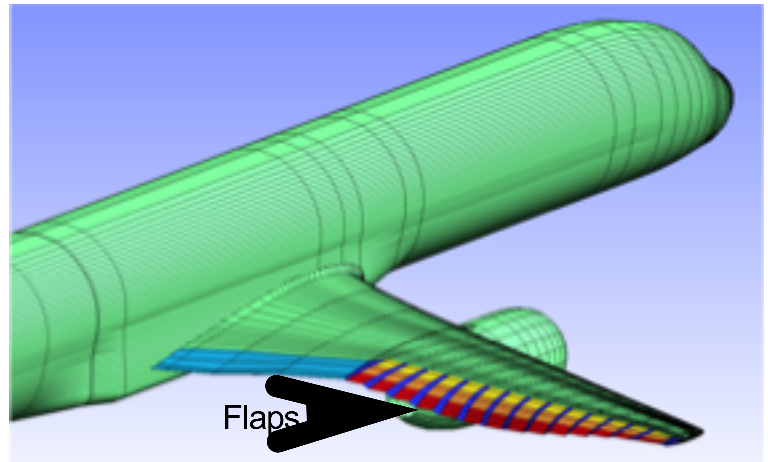


Real-Time Adaptive Drag Optimization Control

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



Sensor System

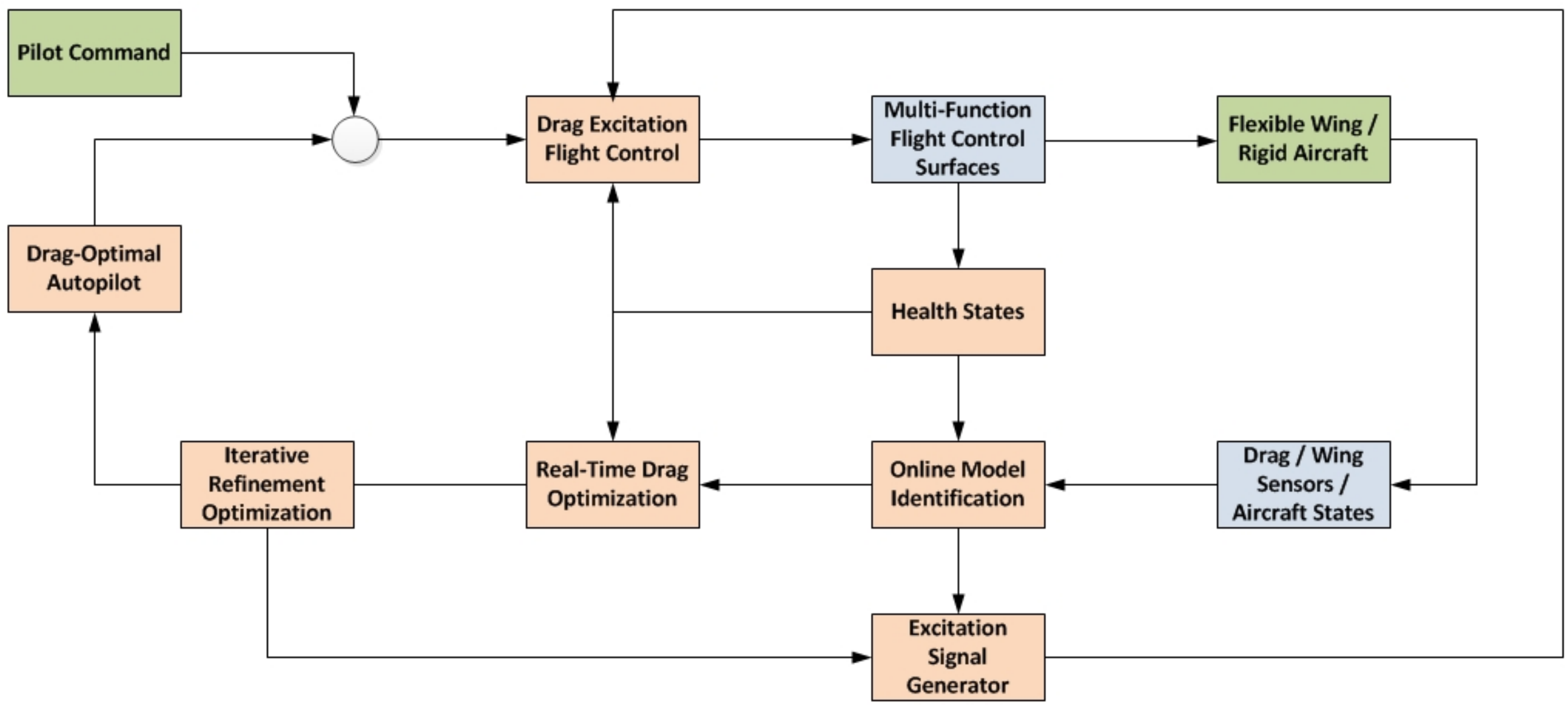


Actuator System

Mission-adaptive wing reconfiguration by sensor-driven onboard aerodynamic model identification and real-time optimization

- Could eliminate off-line optimization and in-flight table look-up
- More effective strategy drag reduction to account for aircraft production variances and wide range of operating conditions due to gross weight, mach, and altitude

Real-Time Adaptive Drag Optimization Control



Adaptive drag optimization framework integrates aircraft flight control system with adaptive estimation and real-time drag optimization control

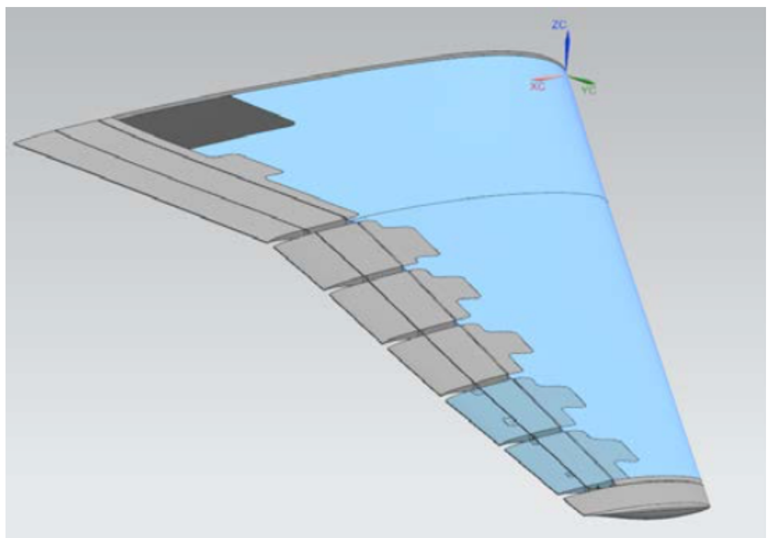
- Lift and drag estimation from sensors and adaptive estimation algorithms
- Aerodynamic surrogate model identification by least-squares
- Gradient-based optimization

Real-Time Drag Optimization Wind Tunnel Test

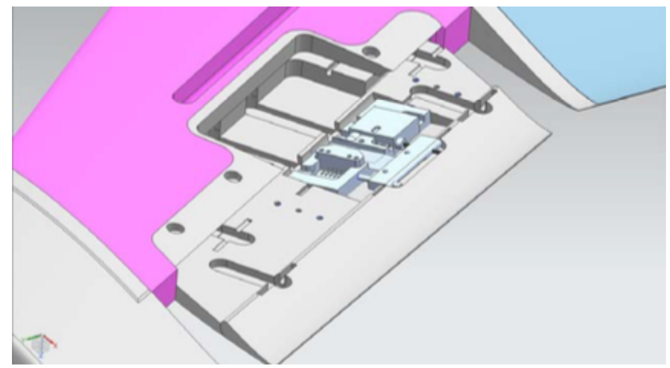
Real-time drag optimization wind tunnel has recently been completed at University of Washington in June 2018

- NASA SBIR Phase II contract with SSCI (Scientific Systems Company, Inc) and UW
- Demonstrate successfully real-time drag optimization algorithms

CRM aspect ratio 9 flexible wing model with 12 actuated VCCTEF



CRM Wing Model with Actuated VCCTEF



Flap Servo-Actuator

- Complex model design with 12 actuated flaps
- Consumer-grade servos with low bandwidth
- Continuous and discrete trailing edges tested

Real-Time Drag Optimization Wind Tunnel Test

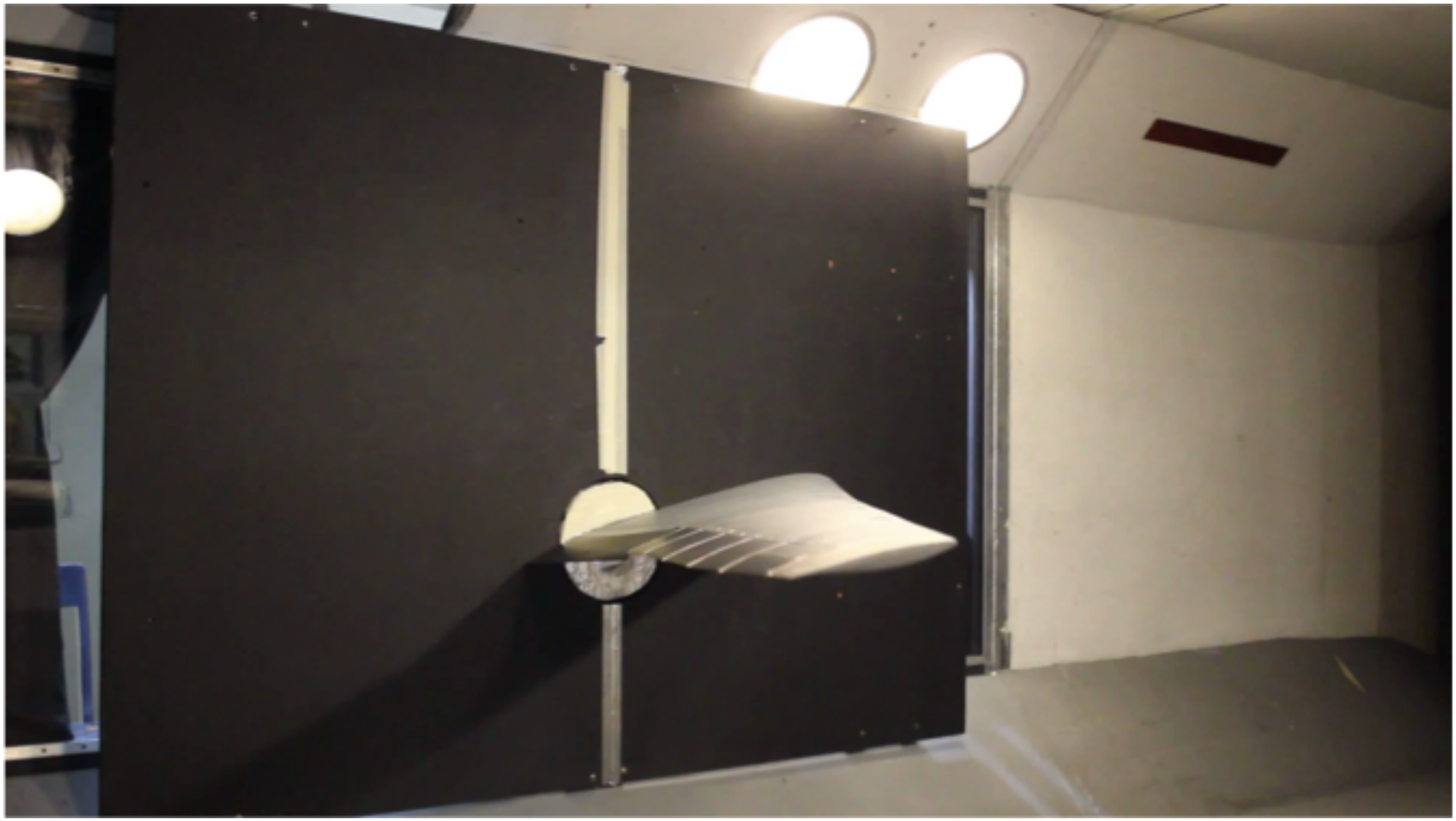
Significant challenges with hardware issues

- Frequent failures of servos which are unreliable
- Mechanical slobs in actuator system causes poor accuracy in position measurement

Three test entries

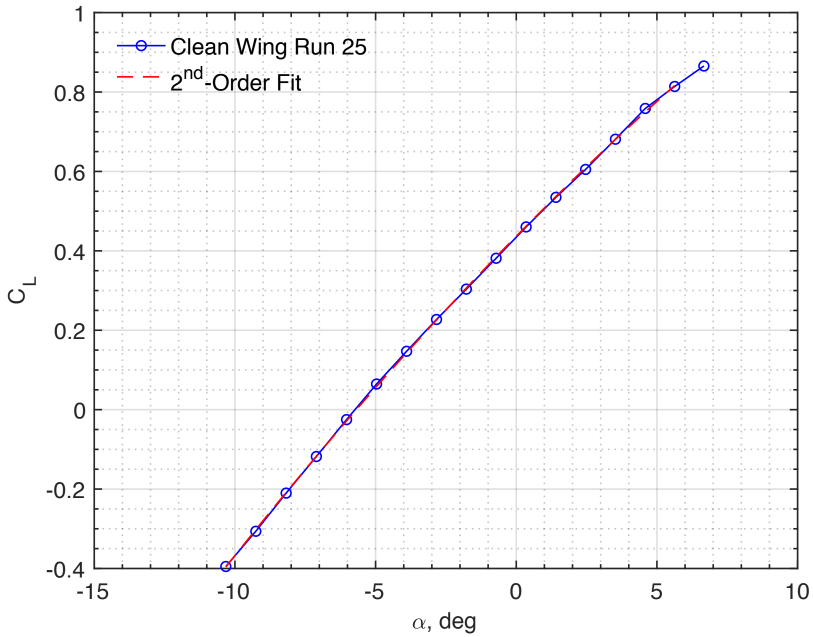
- September 2017 – system shakedown with no test data
- April 2018 – model identification produced incorrect parameters, no useful optimization results
- June 2018 – NASA algorithms were successfully demonstrated

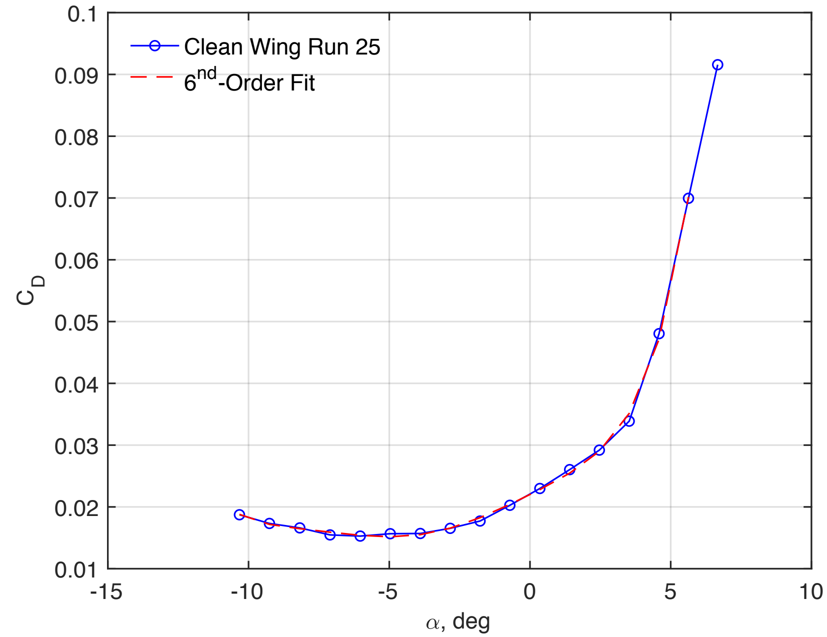
Real-Time Drag Optimization Wind Tunnel Test



Real-Time Drag Optimization Wind Tunnel Test

Surrogate model identification least-squares technique developed by NASA





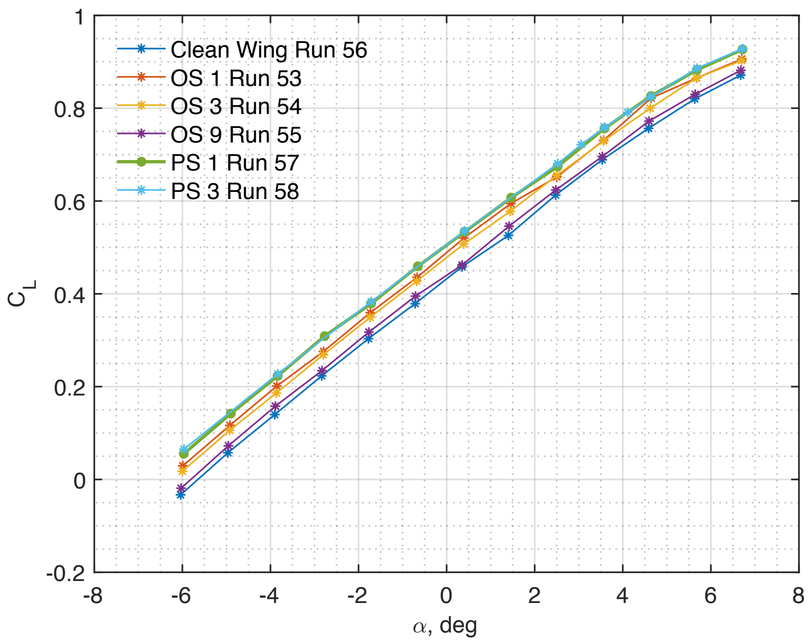
- Second-order C_L and six-order C_D surrogate models
- Random and scheduled excitation of flap commands

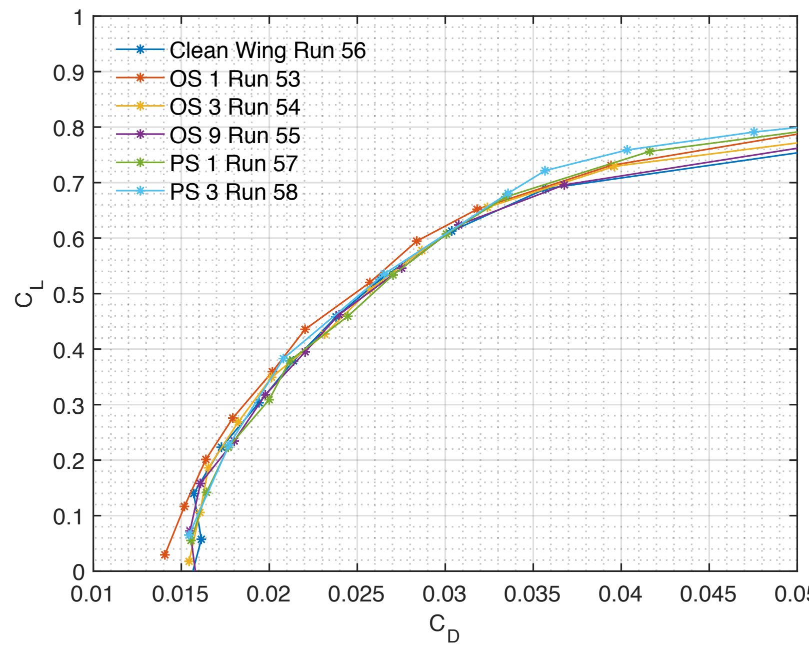
Real-time optimization algorithms developed by SSCI and NASA

- Generic algorithm (black box) by SSCI
- Four methods by NASA: 1) analytical method, 2) gradient-based, 3) iterative, and 4) pseudo-inverse

Real-Time Drag Optimization Wind Tunnel Test

Real-time drag optimization results



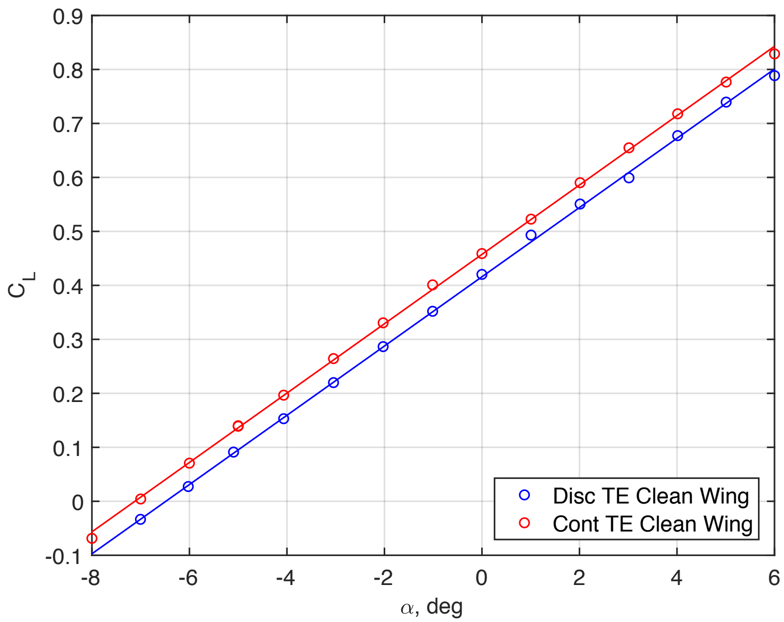


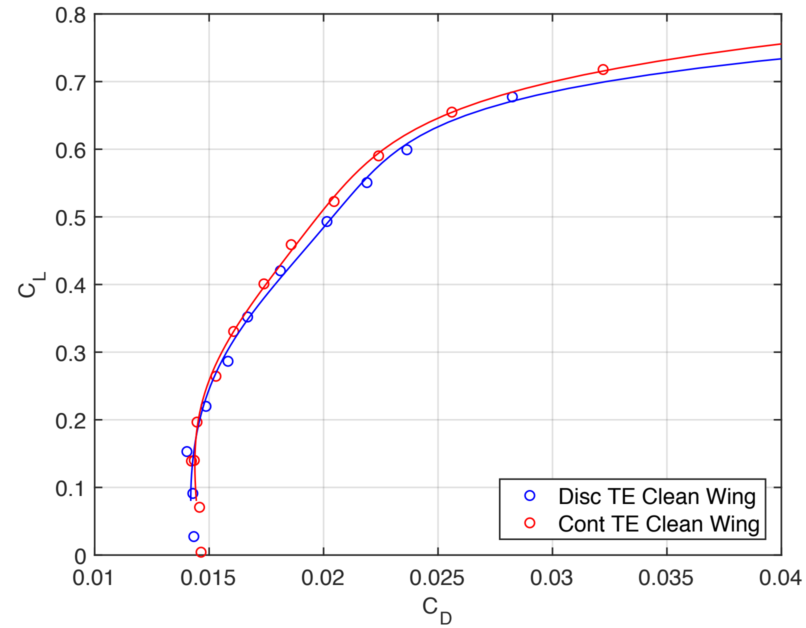
- Wing re-twisted for design C_L of 0.5
- Target off-design C_L of 0.65 and 0.7
- Optimized wing achieves 13 count 3.9% drag reduction at C_L of 0.65
- Pseudo-inverse optimization gives 36 count or 9.4% drag reduction at C_L of 0.7

	$C_L^* = 0.5$		$C_L^* = 0.65$		$C_L^* = 0.7$	
Run	C_D	ΔC_D	C_D	ΔC_D	C_D	ΔC_D
Clean Wing Run 56	253	0	330	0	382	0
Optimal Solution 1 Run 53	248	5	317	13	364	18
Optimal Solution 3 Run 54	255	-2	321	9	367	15
Optimal Solution 9 Run 55	256	-3	329	1	376	6
Pseudo-Inverse Solution 1 Run 57	259	-6	322	8	360	22
Pseudo-Inverse Solution 3 Run 58	252	1	321	9	346	36

Real-Time Drag Optimization Wind Tunnel Test

Comparison of continuous and discrete trailing edge designs



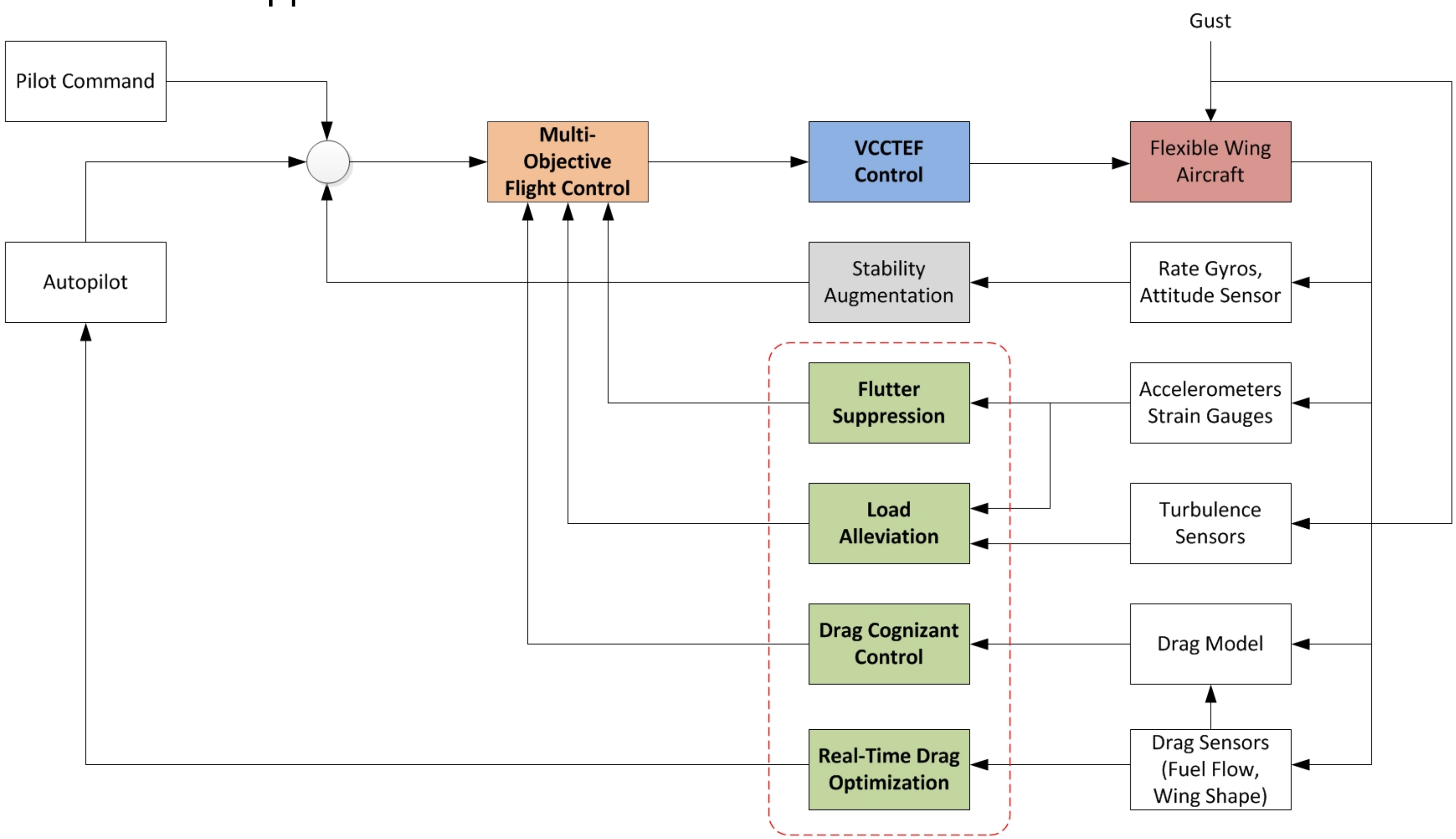


- Continuous trailing edge is sealed with elastomers
- Discrete trailing edge has small 1/16-inch flap gaps
- Continuous trailing edge produces higher lift and lower drag than discrete trailing edge – 13 count or 6.7% drag reduction at C_L of 0.5

Multi-Objective Flight Control

Multi-objective flight control leverages multi-functional flight control surfaces such as VCCTEF to achieve multiple objectives simultaneously

- Roll control and high lift requirements
- Drag reduction during cruise and maneuvers
- Gust and maneuver load alleviation
- Flutter or modal suppression



Multi-Objective Optimal Control

Multi-objective cost function

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

Pilot Command Tracking

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

ASE Mode Suppression | Drag Minimization | Load Alleviation

GLA (Gust Load Alleviation) with adaptive gust estimation

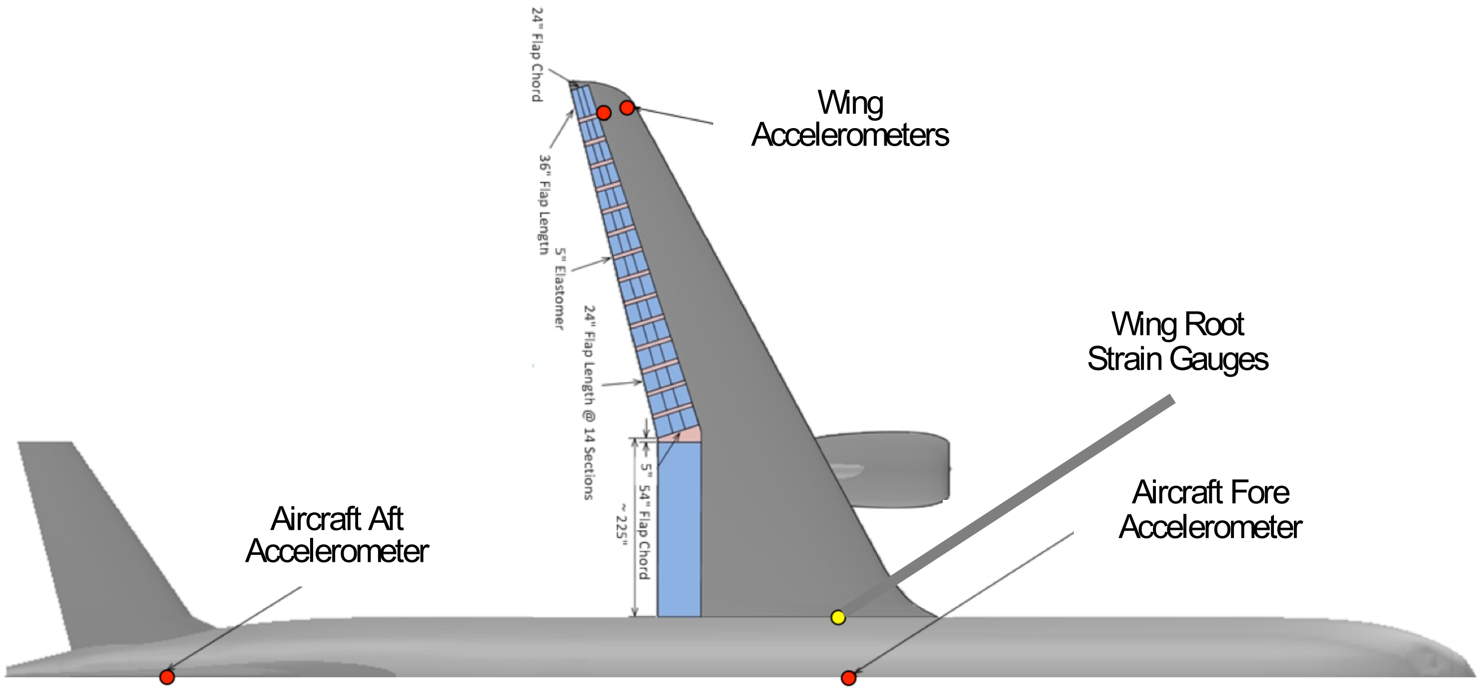
$$I_{\alpha q} \dot{\hat{w}}_r = \begin{bmatrix} \dot{\hat{w}}_{r_\alpha} \\ \dot{\hat{w}}_{r_q} \end{bmatrix} = -\Gamma_{w_r} \left(a_{z_{\dot{x}_r}}^{-1} \varepsilon_r + \nu_{w_r} I_{\alpha q} \hat{w}_r \right)$$

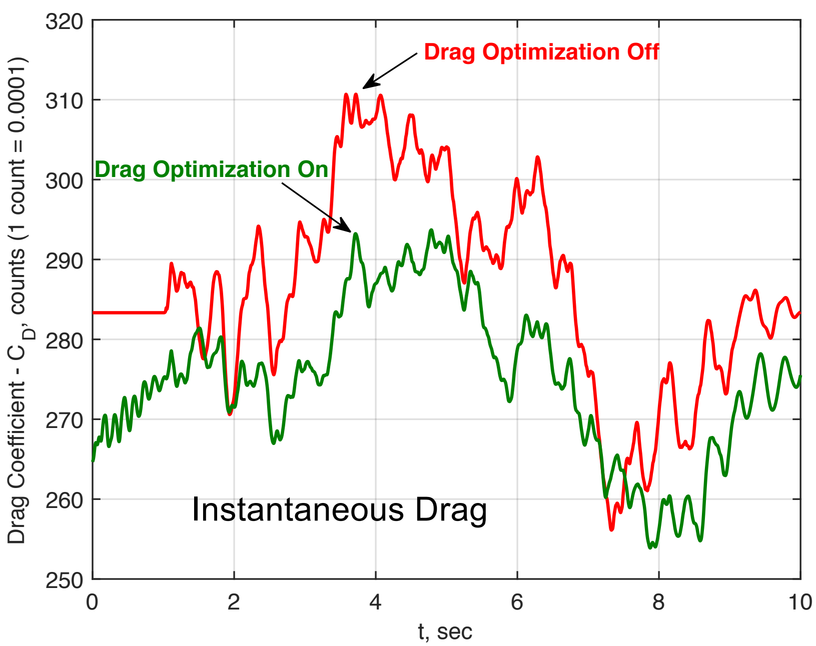
(rigid-component gust)

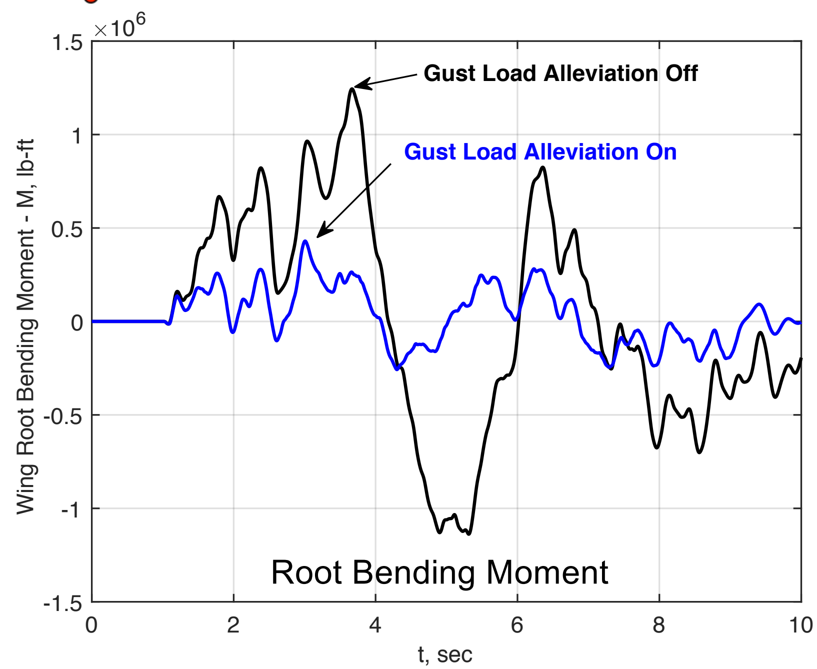
$$\dot{\hat{w}}_e = -\Gamma_{w_e} \left[a_{w_{w_e}}^\top \left(a_{w_{w_e}} a_{w_{w_e}}^\top \right)^{-1} \varepsilon_e + \nu_{w_e} \hat{w}_e \right]$$

(elastic-component gust)

Multi-Objective Gust Load Alleviation / Drag Minimization



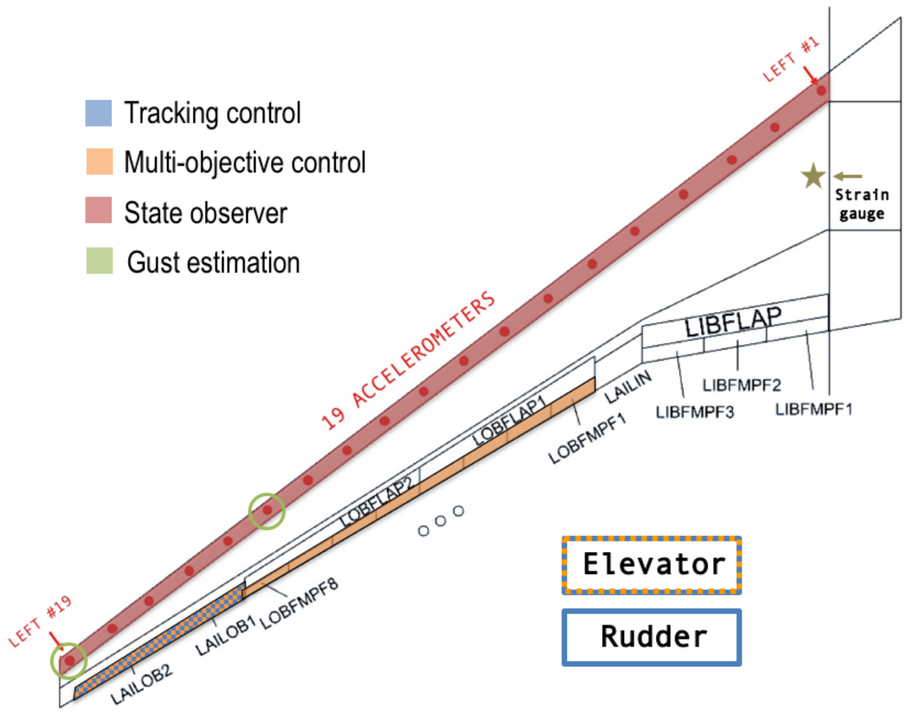




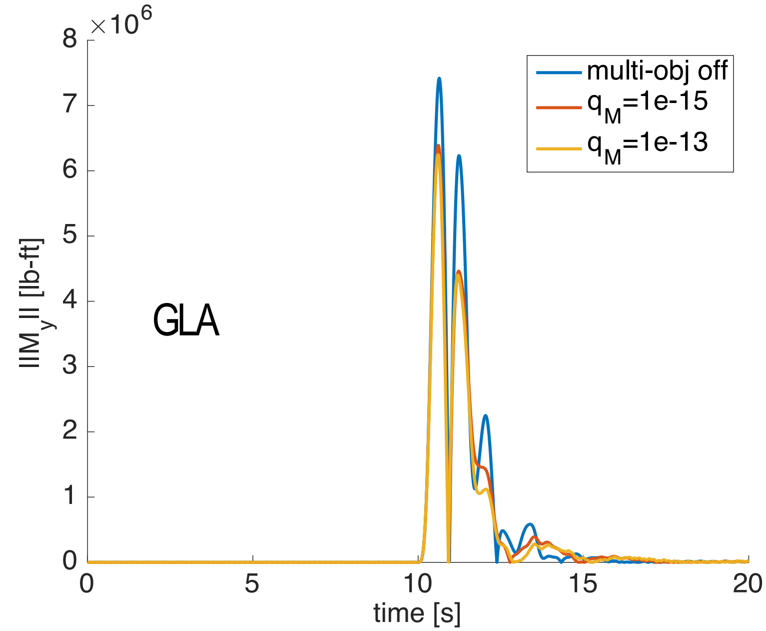
Collaboration on IAWTM NRA

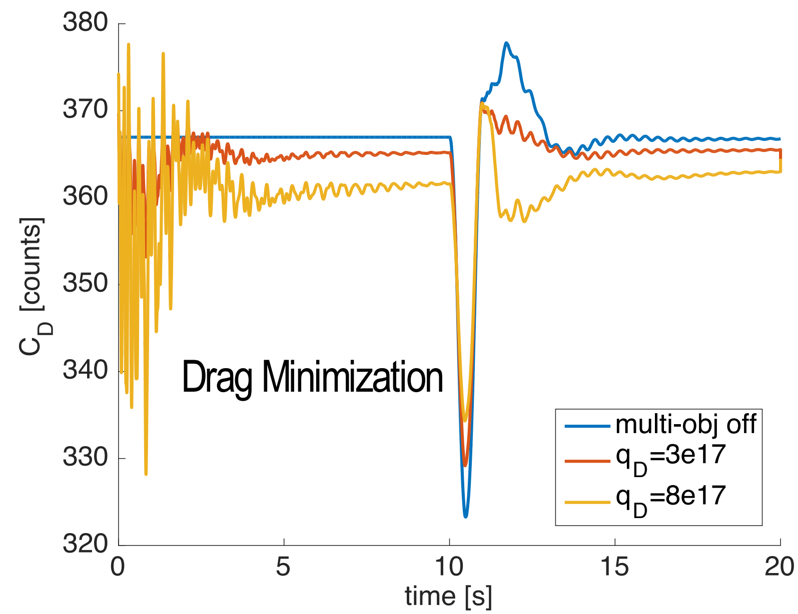
Multi-objective flight control design for ASE model of CRM aspect ratio of 13.5

- ASE model with sensors and actuators provided by BR&T
- Conduct control design and simulations



- Investigate predictive GLA with forward-looking sensors, e.g., LIDAR





Gust Load Alleviation Wind Tunnel Test

Funded by NASA SBIR Phase II-X / III and AATT project

- Prime contractor SSCI
- Subcontractors UW and BR&T

Develop a GLA experiment at UW to evaluate multi-objective optimal control for GLA and drag optimization

- Evaluate in simulations predictive GLA using LIDAR model provided by BR&T

Current test schedule is planned for January 2019

Coordination with IAWTM wind tunnel in NASA LaRC TDT scheduled in April 2019

- Provide lessons learned and potential insight for control implementation

Collaboration on IAWTM NRA

Aero-structural optimization of CRM aspect ratio 13.5 with mini-trailing edge flap

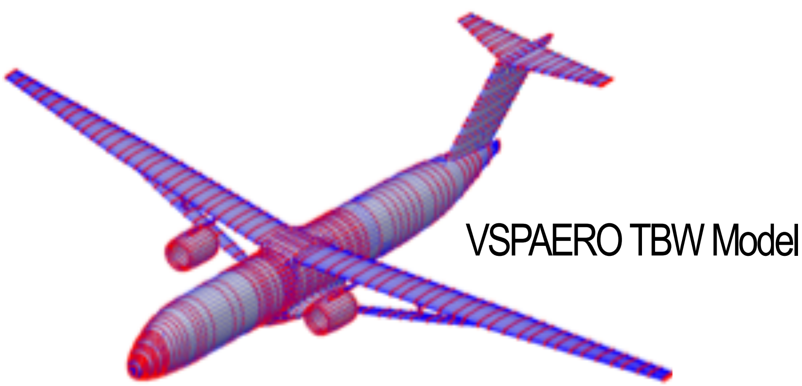
- Apply aero-structural framework for drag optimization
- Provide drag derivatives for ASE model for multi-objective flight control design

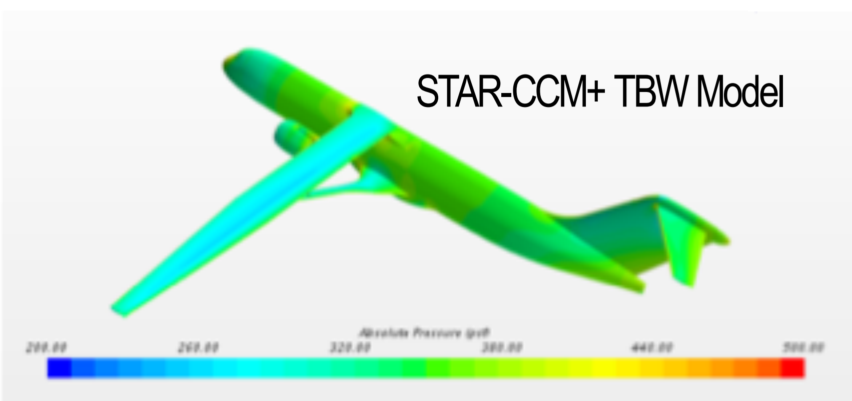
Collaboration on TTBW NRA

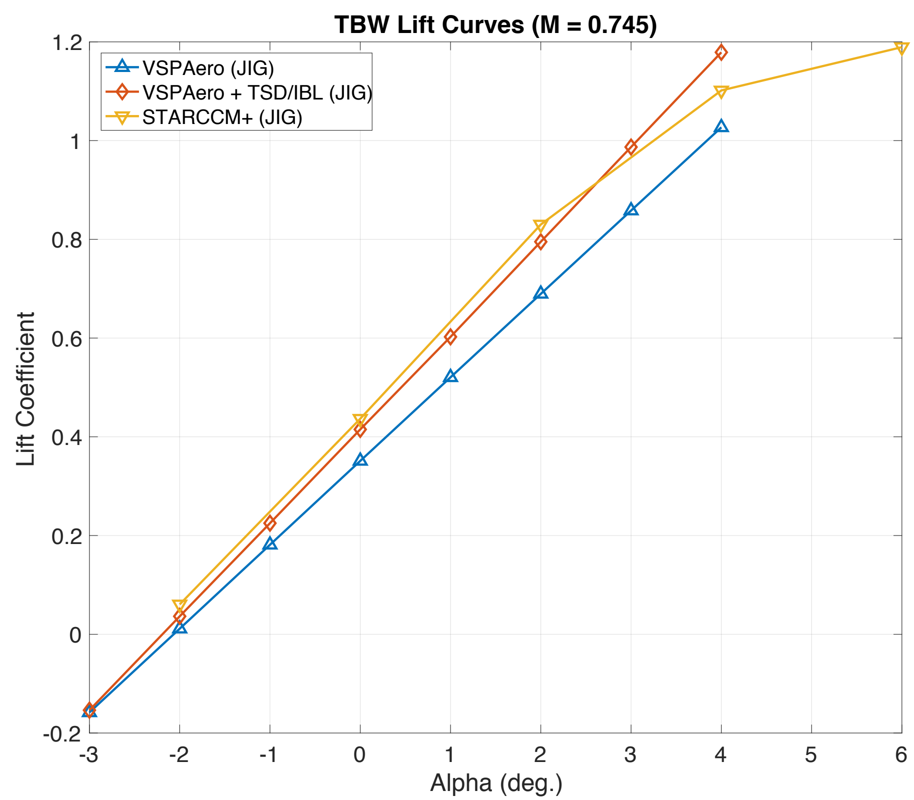
Develop aero-structural capability for enabling low-order transonic flutter analysis and optimization

Develop coupled ASE flight dynamic model of transonic TBW

Multi-fidelity modeling using VSPAERO with transonic and boundary layer correction and STAR-CCM+ for validation

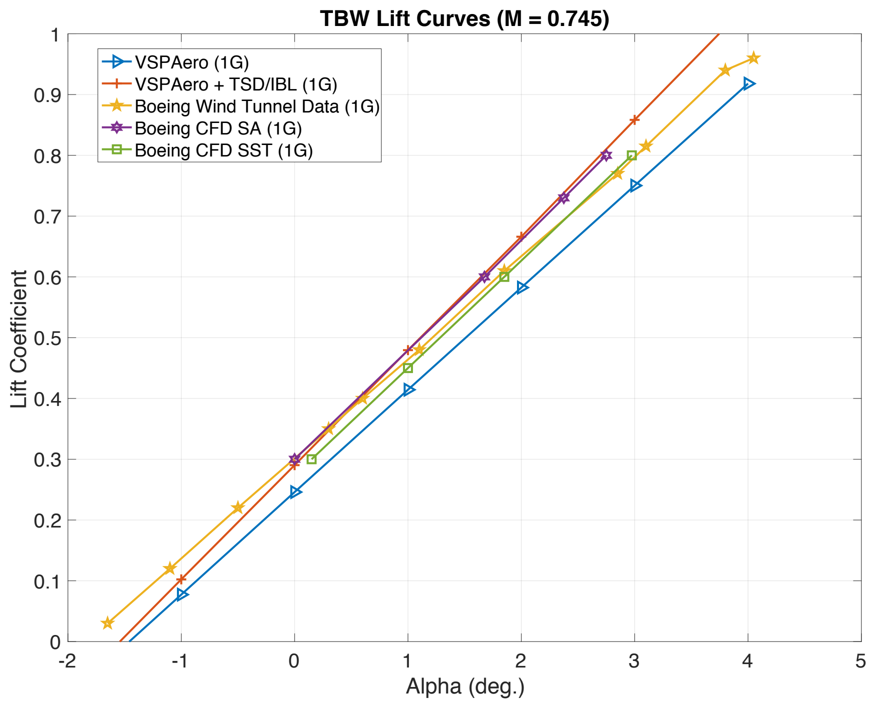


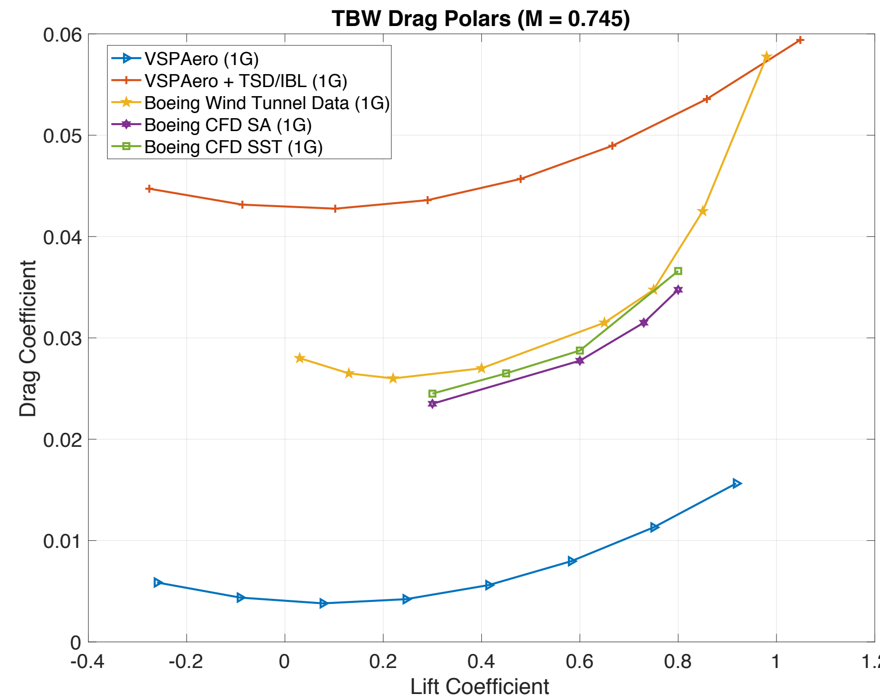




Collaboration on TTBW NRA

Aero-structural model is able to match C_L reasonably well with Boeing CFD and wind tunnel data



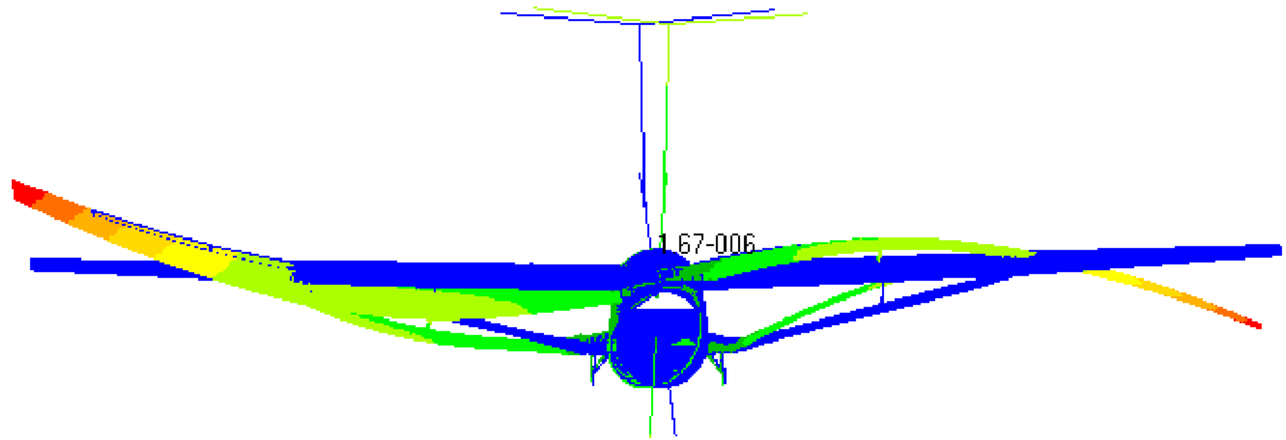


FEM captures geometric nonlinearity due to tension stiffening by the strut

Collaboration on TTBW NRA

Boeing NASTRAN FEM

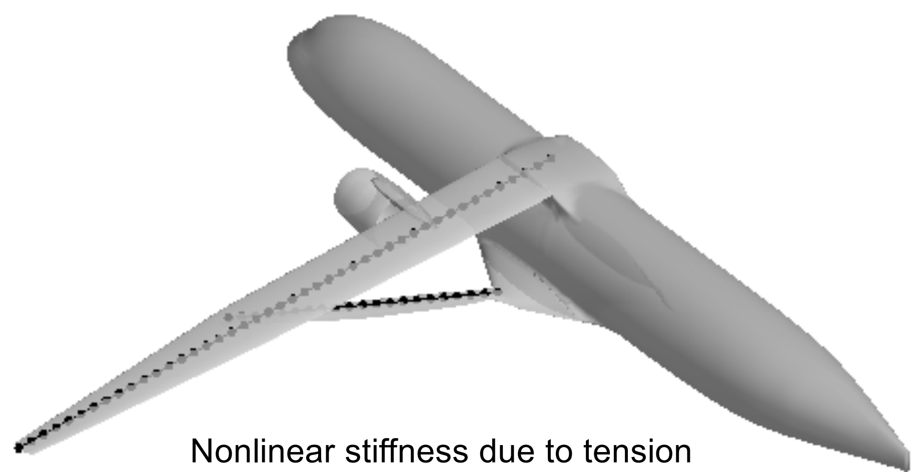
Mode Number	Frequency (rad/s)
1	11.9137
2	12.5876
3	13.2941
4	15.2499
5	18.2112
6	18.7219
7	22.3561
8	23.2483
9	30.4026



Equivalent beam nonlinear FEM

Mode	MATLAB FEA (rad/s)	NASTRAN (rad/s)	Percent Difference
1st Symmetric	12.246	12.273	0.220
1st Antisymmetric	12.927	12.842	0.658
2nd Symmetric	15.558	15.250	1.980
2nd Antisymmetric	18.925	18.271	3.456
3rd Symmetric	20.232	20.359	0.628
3rd Antisymmetric	20.734	20.795	0.294
4th Symmetric	29.113	28.998	0.395
4th Antisymmetric	35.758	35.574	0.515
5th Symmetric	43.872	43.830	0.096
5th Antisymmetric	48.282	48.818	1.110
6th Symmetric	60.506	60.102	0.668
6th Antisymmetric	69.378	66.178	4.612

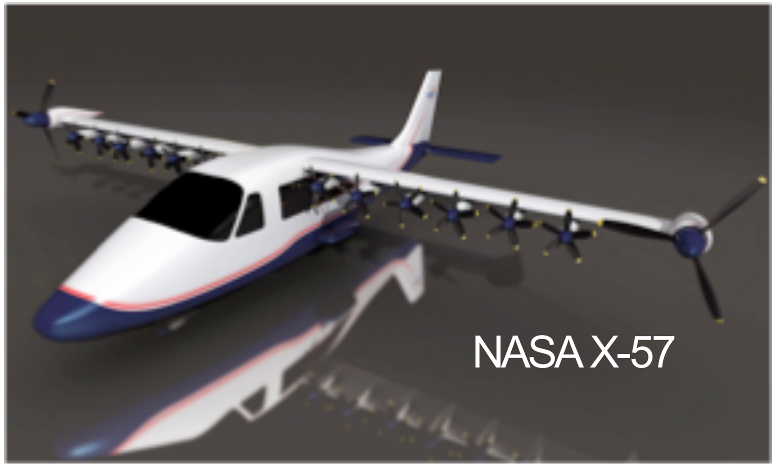
- Stiffness and mass properties still need to be updated from Phase II to Phase IV NRA

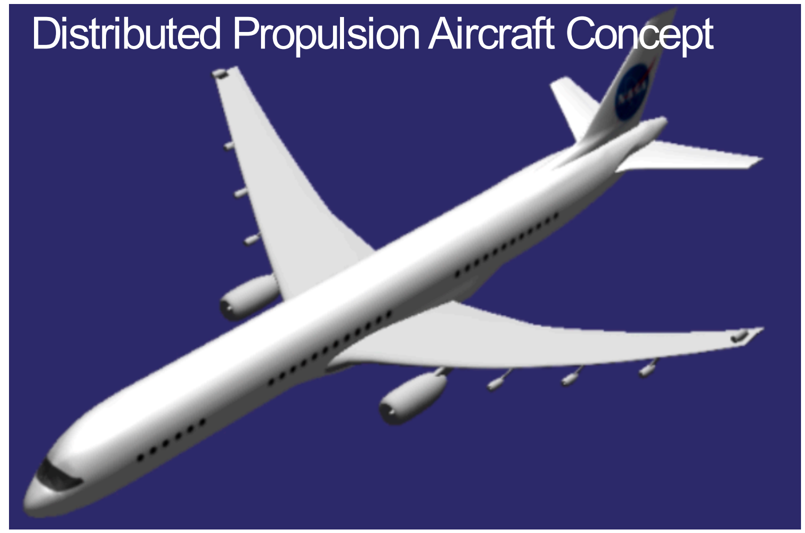


Nonlinear stiffness due to tension stiffening effect of main strut

Other Topic - Aeroelastic Wing Shaping for Distributed Propulsion Aircraft

Leverage wing flexibility using distributed propulsion to change wing shape for improved aerodynamic efficiency

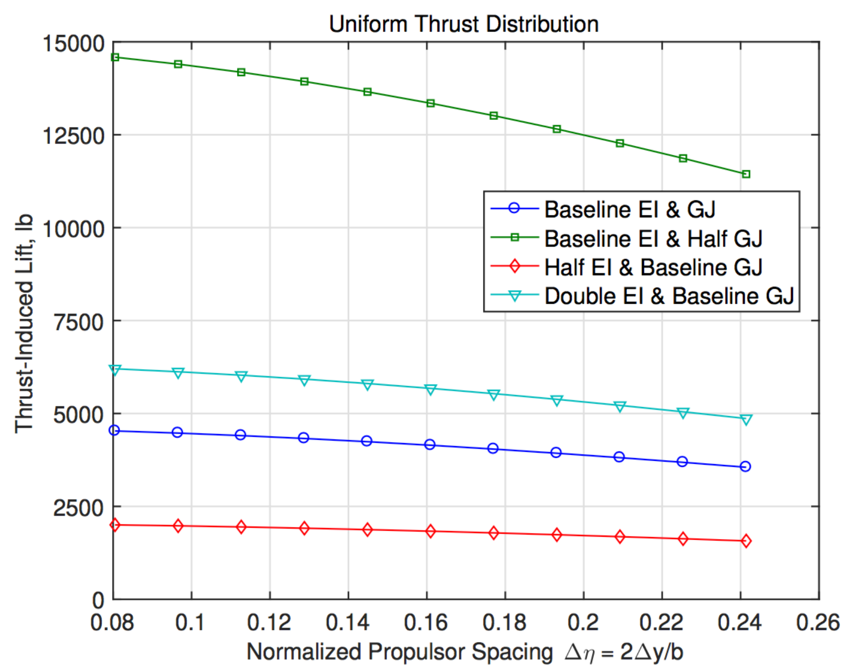




Thrust-induced lift and stiffness

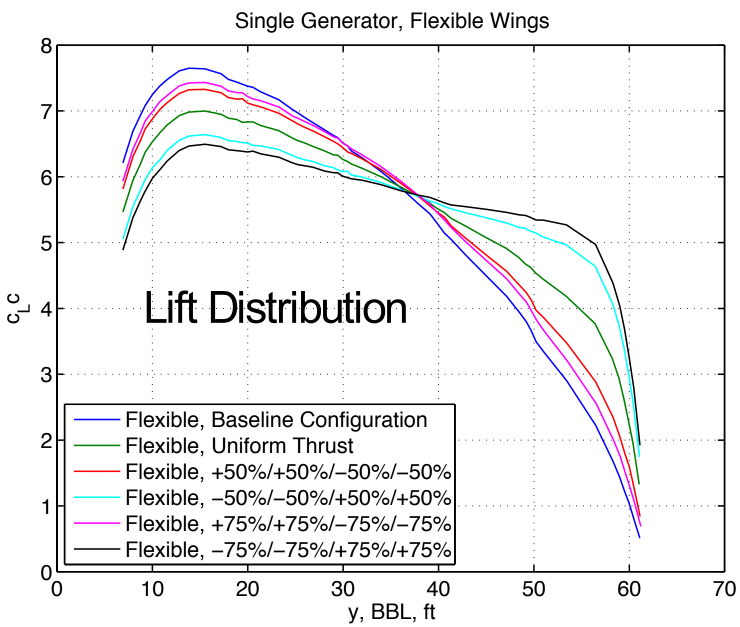
$$C_L = C_{L_0} + C_{L_\alpha}\alpha + \sum_{i}^{N} C_{L_{T_i}} T_i$$

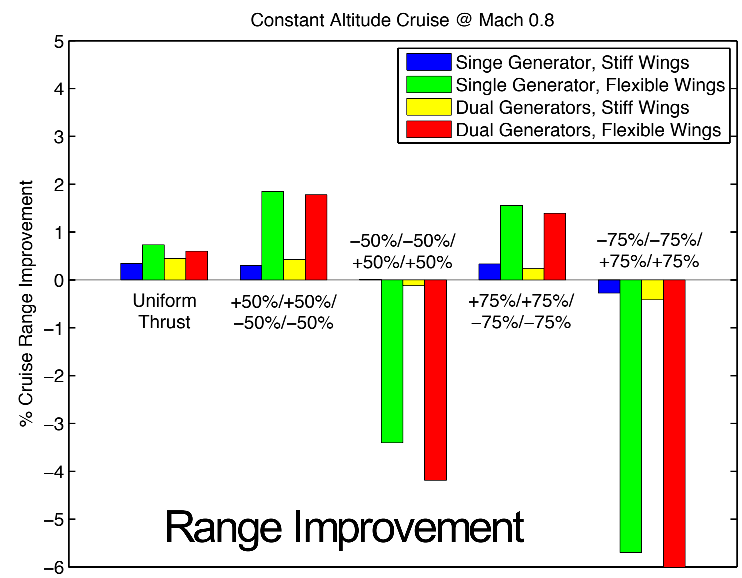
$$\Delta f_z^p = \sum_{i=1}^{n} \delta\left(x - x_i\right) T_i \left(-W_x \sin\Lambda - \Theta \cos\Lambda\right)$$



Other Topic - Aeroelastic Wing Shaping for Distributed Propulsion Aircraft

Span load can be optimized to reduce induced drag





Flutter can be addressed with propulsor placement and is shown not to be a problem.

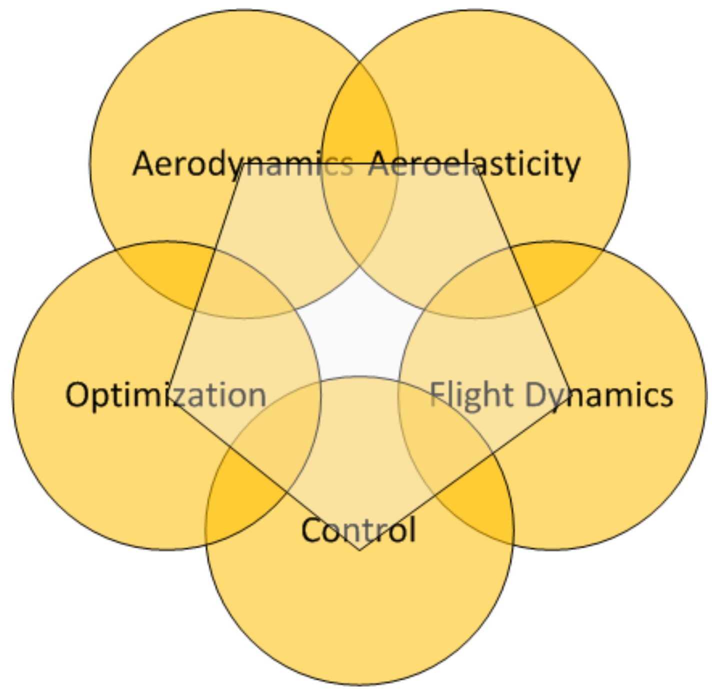
Summary

Performance adaptive aeroelastic wing technology can change future aircraft design.

Aeroelastic control of adaptive wing can improve fuel efficiency by real-time drag optimization and reduce structural weight by load alleviation and modal suppression.

Adaptive wing technologies can only be achieved through a fully integrated multidisciplinary design process in order to realize its full potential.

Collaboration with Boeing can further advance adaptive wing technologies for potential future transition into aircraft development programs.



Thank You