System Level Trade Study of Variable Camber Morphing Aircraft Design

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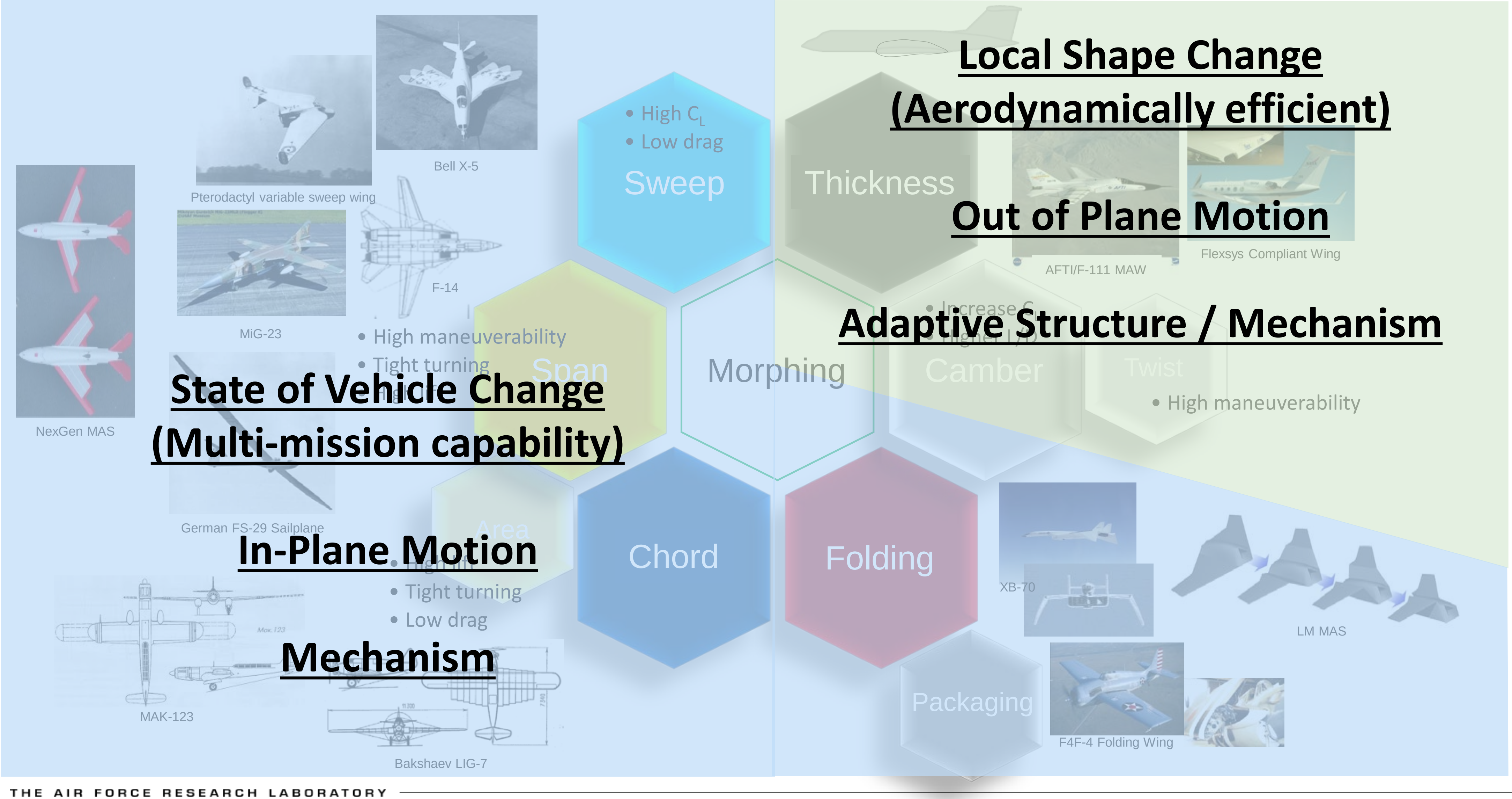
- Dr. Jay Tiley (AFOSR)

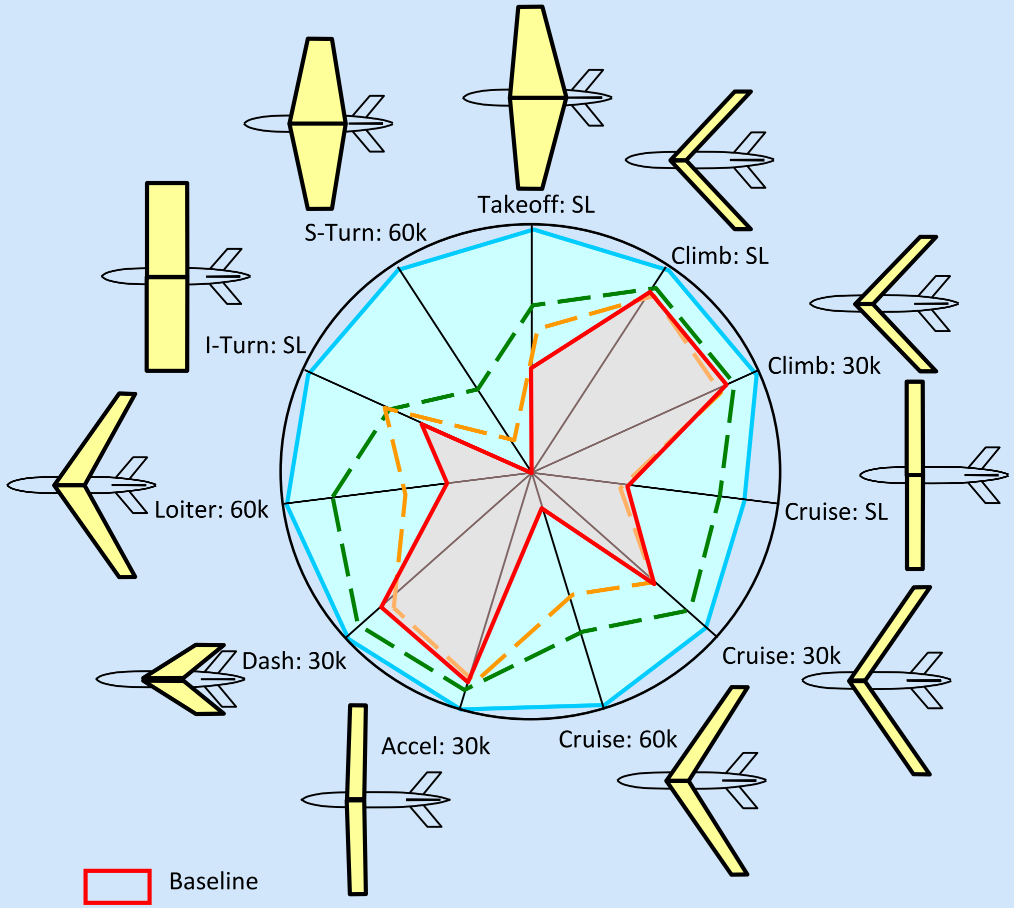
BLUF

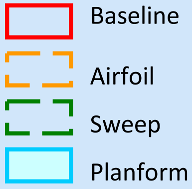
- This study was performed to understand the benefits and limitations of camber morphing technology and suggest right future investments and research direction
- Major benefits of camber morphing
  - Drag reduction of UAVs without active control capability (more than 10% drag reduction possible ONLY at high C_L condition)
  - Drag benefits can be accumulated at various flight conditions throughout entire mission
  - Span Increase without weight penalty possible
  - Pure/proverse yaw possible without vertical stabilizer – to be validated
  - low observable from lower control surface deflection and without vertical stabilizer
  - low noise without gaps and holes – to be validated
- Things to consider
  - Drag reduction of the conformal surface is < 2% when the conventional wing is also equipped with active control for minimum drag
  - Weight penalty of using morphing technology should be considered
  - Cost increase
  - Complicated shape change may not be required especially for drag reduction

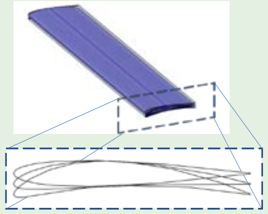
Morphing Aircraft

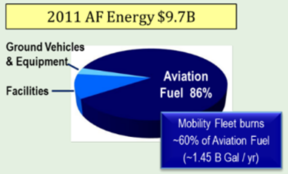


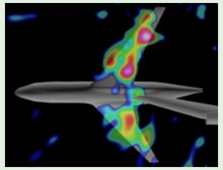
Why Morphing

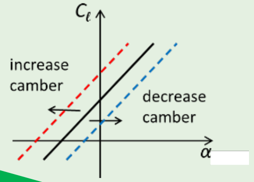












Eliminate:
- Gap & holes
- Split/clap ailerons
- Tail and rudders

Reduce:
- Fuel burn
- Airframe noise
- Radar signature

Increase:
- Endurance
- Range
- Survivability

Manipulate:
- Roll and yaw
- Lift distributions
- Wing performance over entire flight envelop

- Multi-role/multi-mission capability
- Provide wide range of aerodynamic performance and flight control
- Enable operational effectiveness

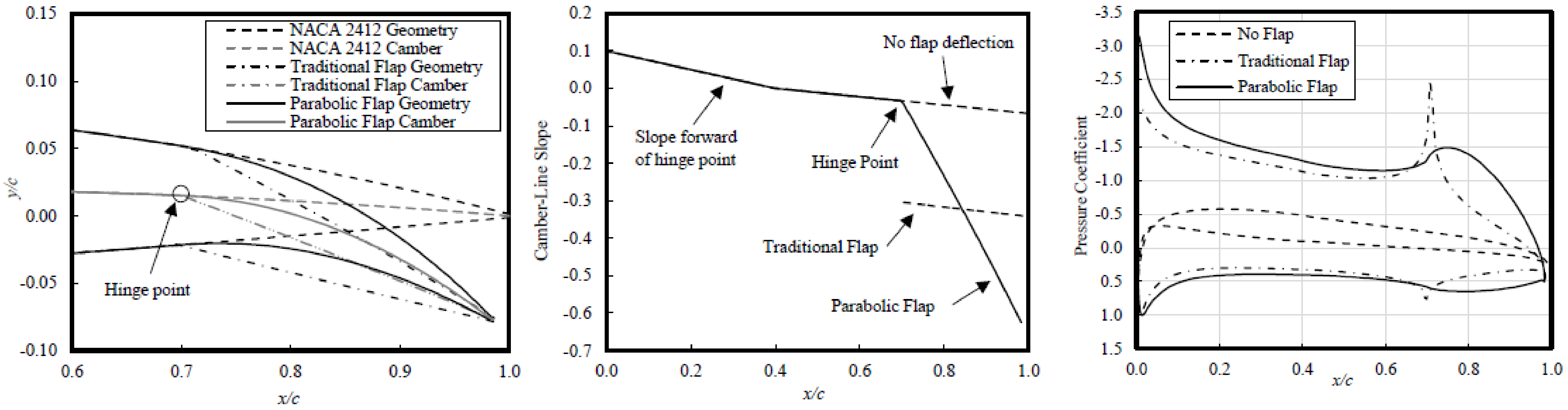
What People Expect from Conformal Surfaces?

Efficiency

Survivability

Myth I: Efficient – Less Drag

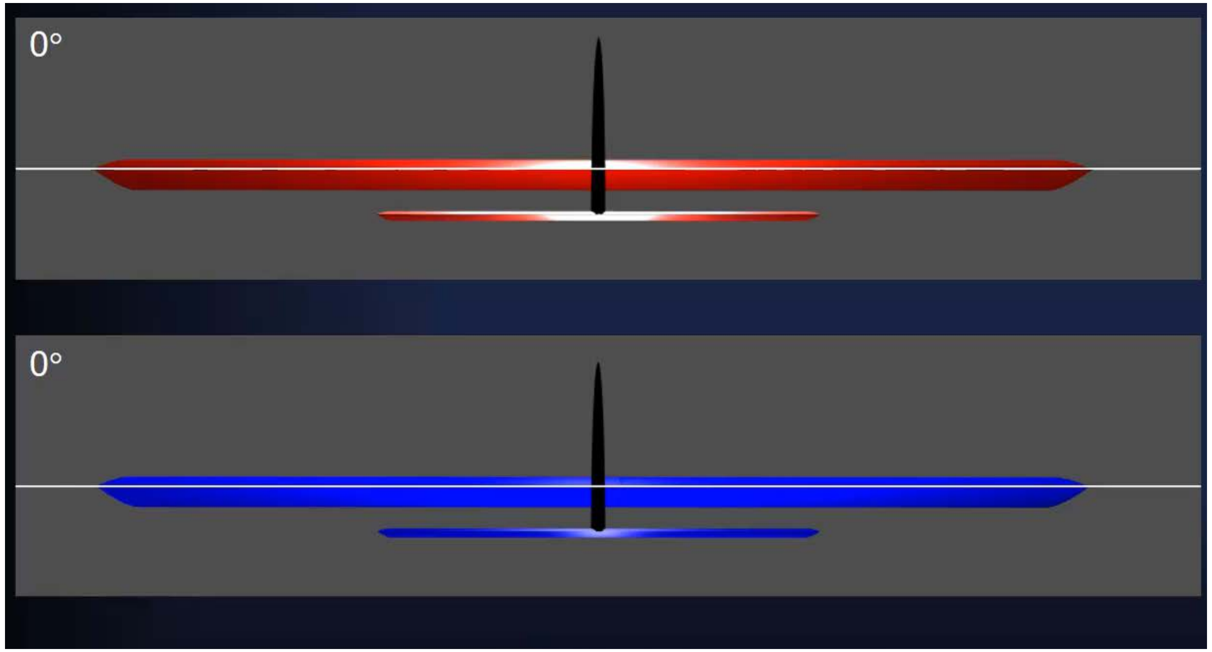
- Traditional flaps have a discontinuous camber line slope
- Pressure spike occurs at hinge location
- Conformal flap is to reduce the adverse pressure gradient, thus reducing drag
- The drag reduction depends on Cl and it is less than 4% up to Cl=0.6 (without active control and some assumptions)

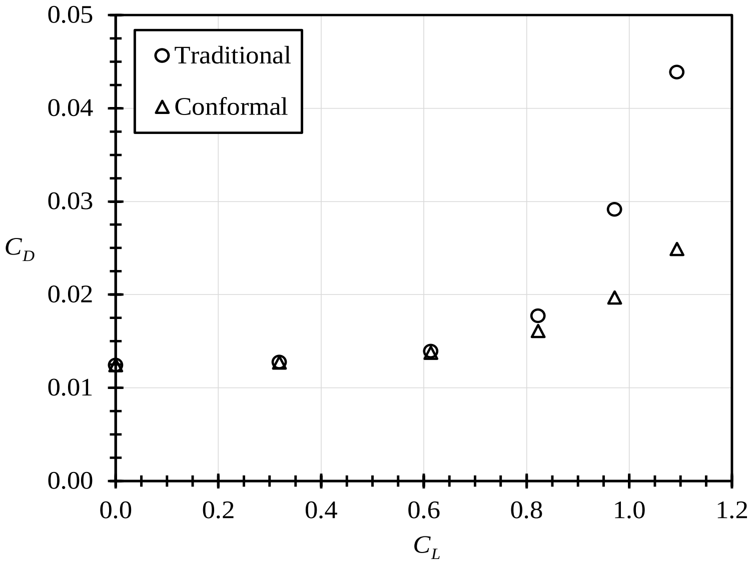


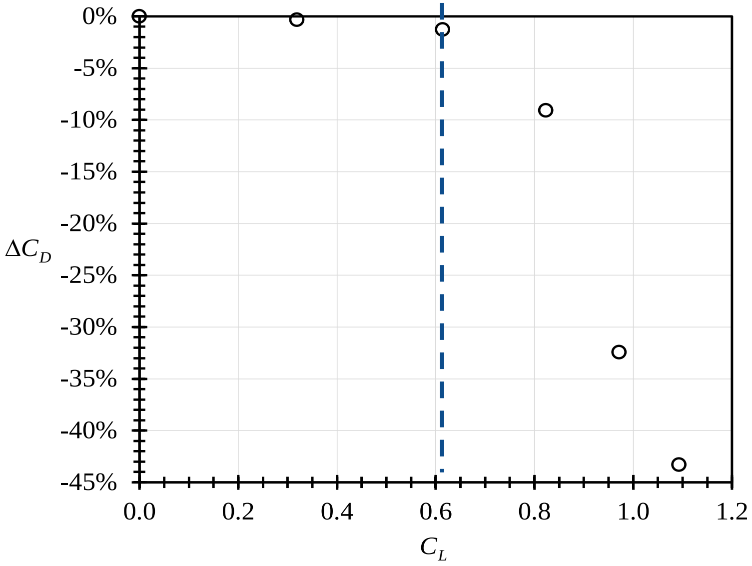
NACA 2412, x_f/c = 0.7 and $\delta_f = \delta_p$ = 15 deg

Drag Comparison for Equivalent Lift (Untrimmed)

Constant deflection along the entire wing

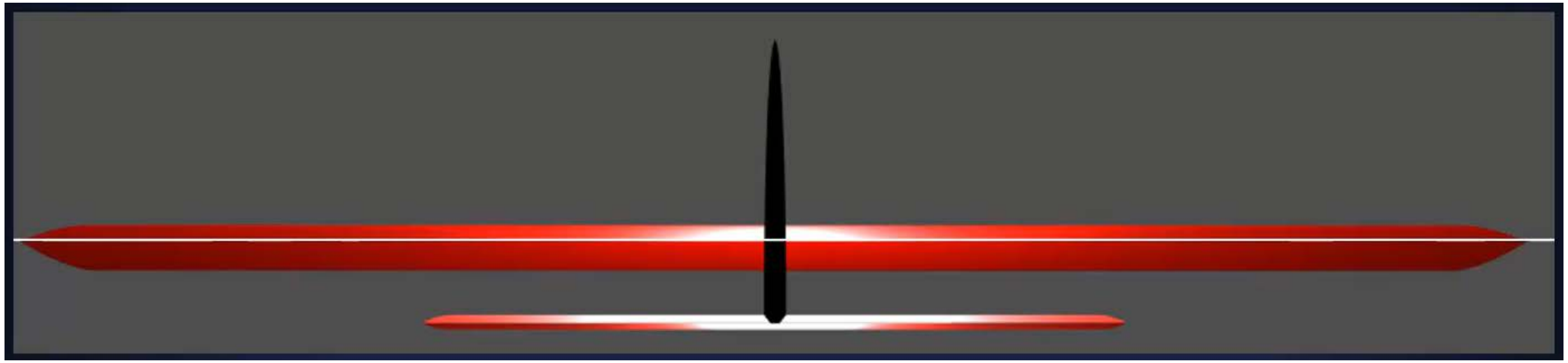


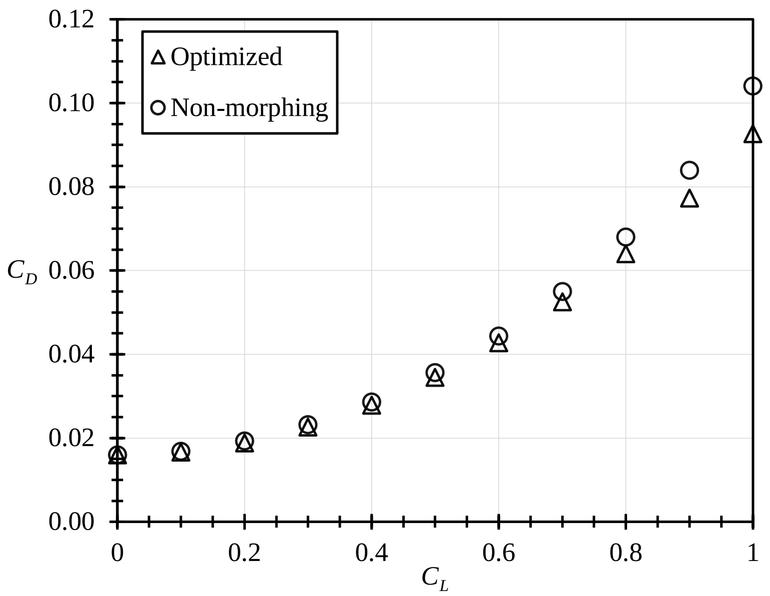


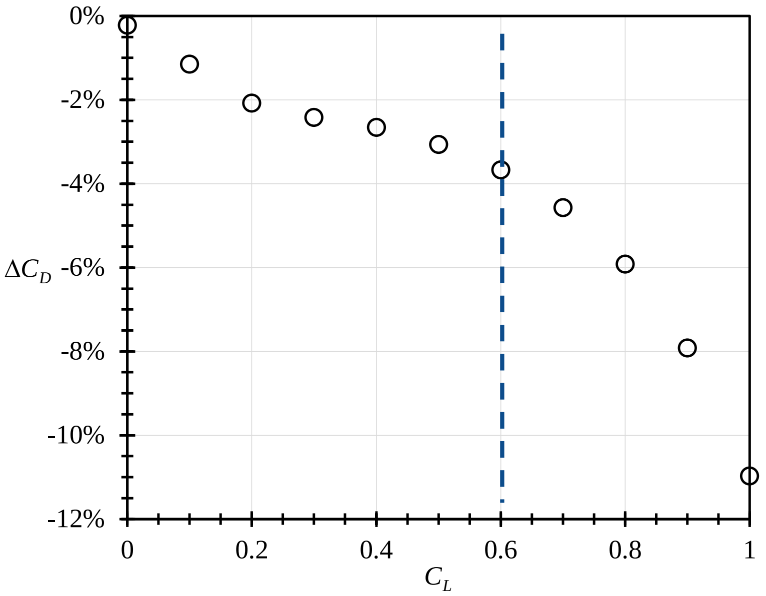


Drag reduction is less than 2% up to C_L= 0.6

Optimal Morphing Configurations for Any Flight Condition (Trimmed)



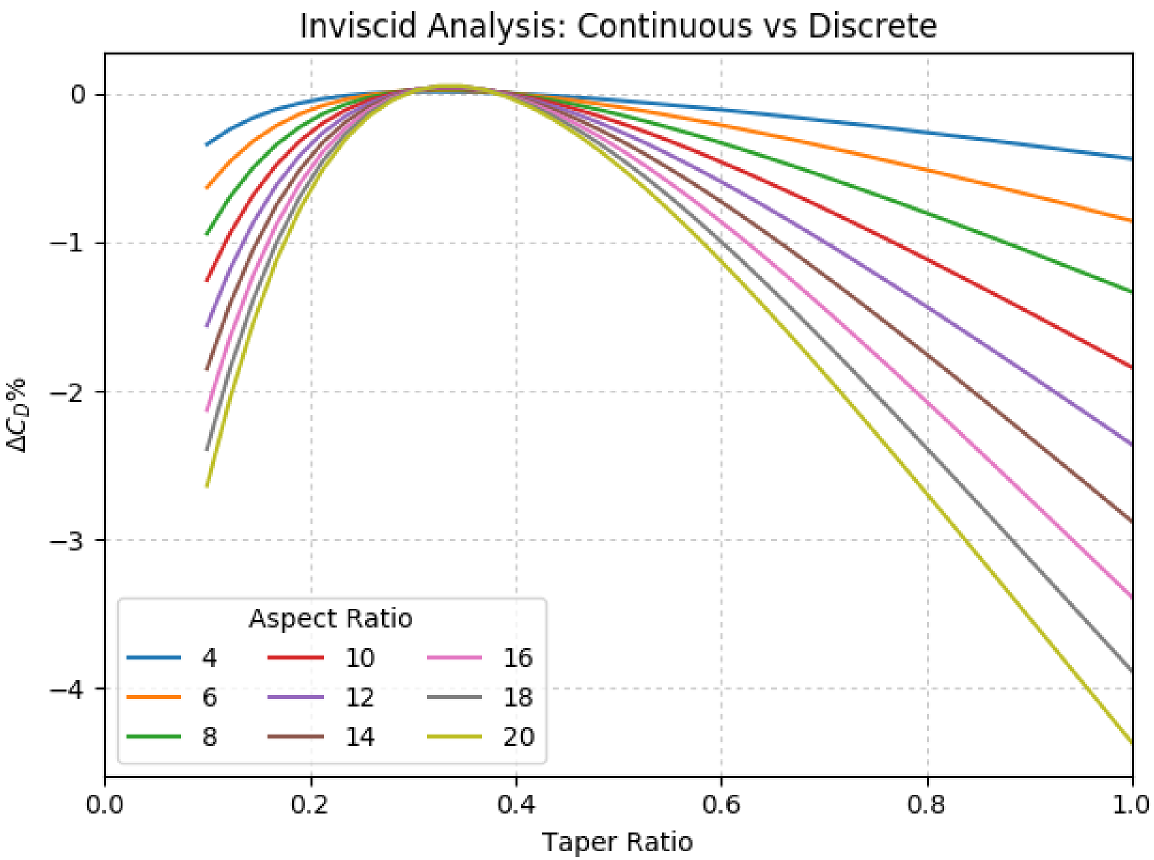




Drag Comparison of Spanwise Discrete vs Continuous Wing

Discrete

Continuous



NACA 0015, R_E= 6.28E5, c_f/c =0.4
2 actuators

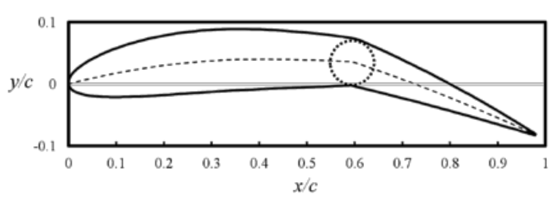
VCCW Terminology

Control Surface Cross Section

Control Surface Distribution

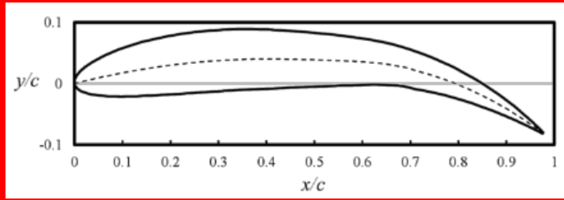
3D Effects

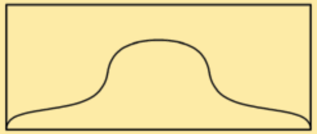
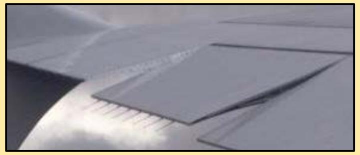
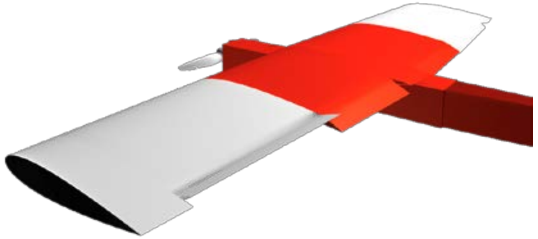
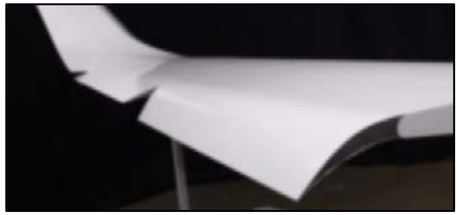
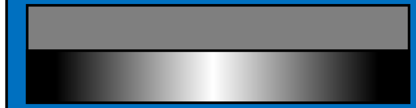
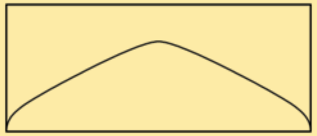
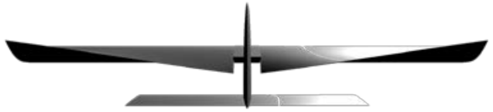
Articulated



0-40%
Depends on c_f/c, α, δ

Conformal



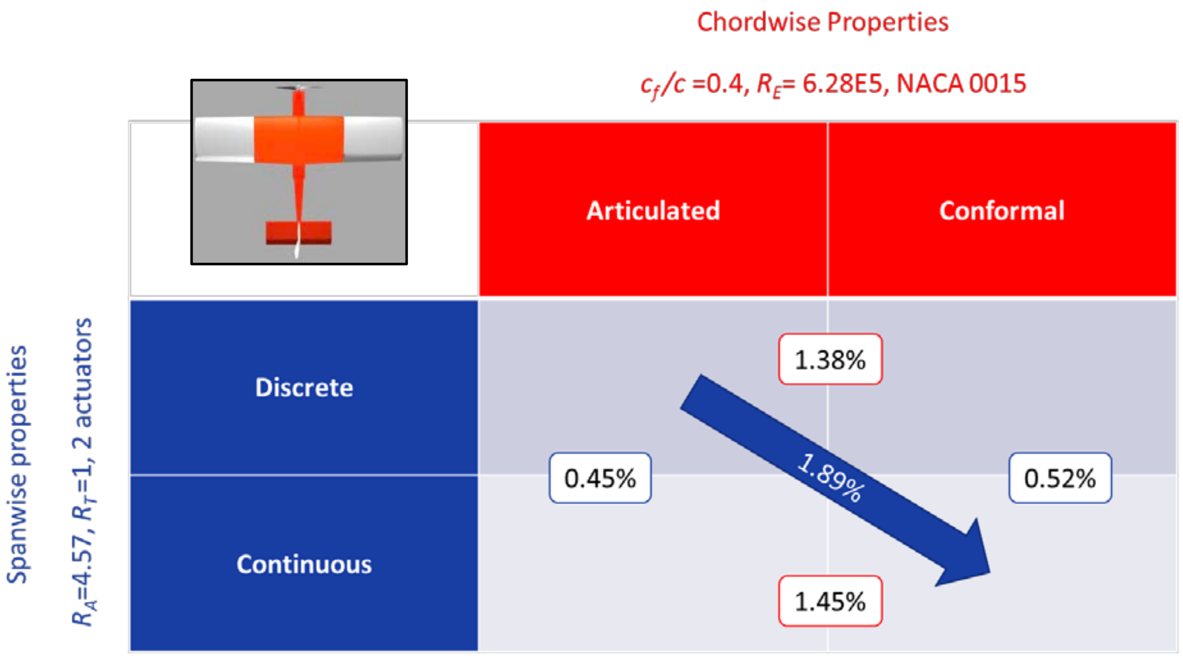
Control Surface Distribution	Spanwise Lift Distribution (Induced Drag)	Spanwise Gap Between Flaps	Articulated	Conformal
Discrete 			Type 1: Traditional 	Type 2 
Continuous 			Type 3	Type 4: Fully Morphing 

1-2% for optimal configurations

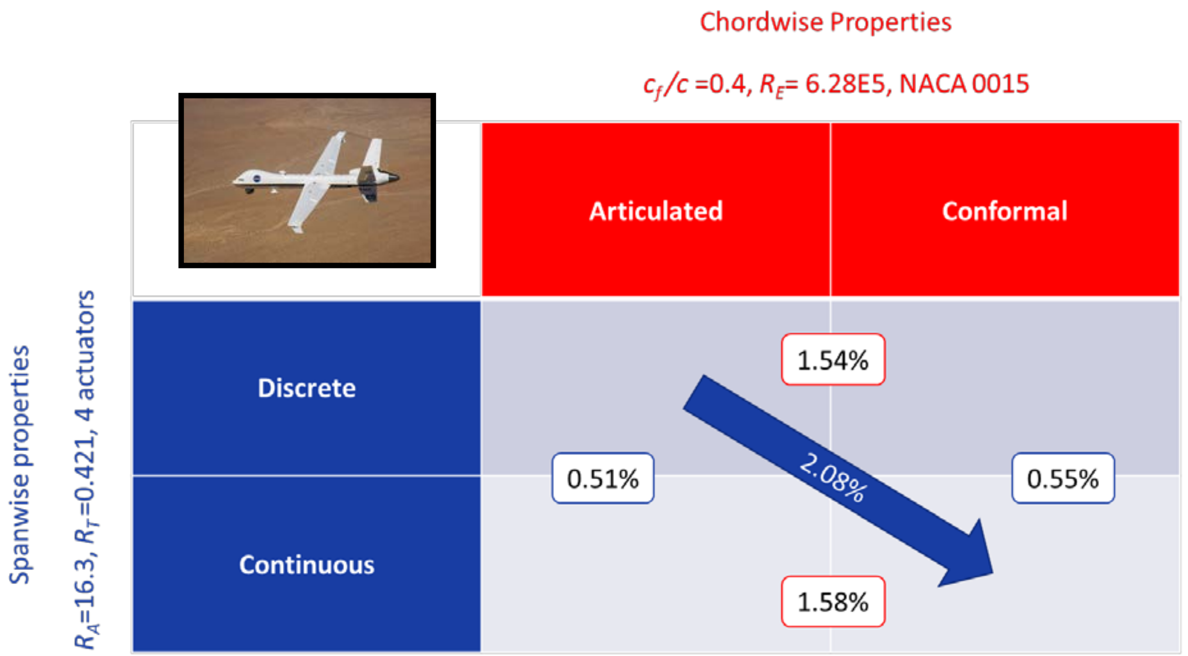
???

Drag Reduction Benefit of Conventional Wing Versus Morphing Wing with *Active Control for Minimum Drag*

Example from GBS



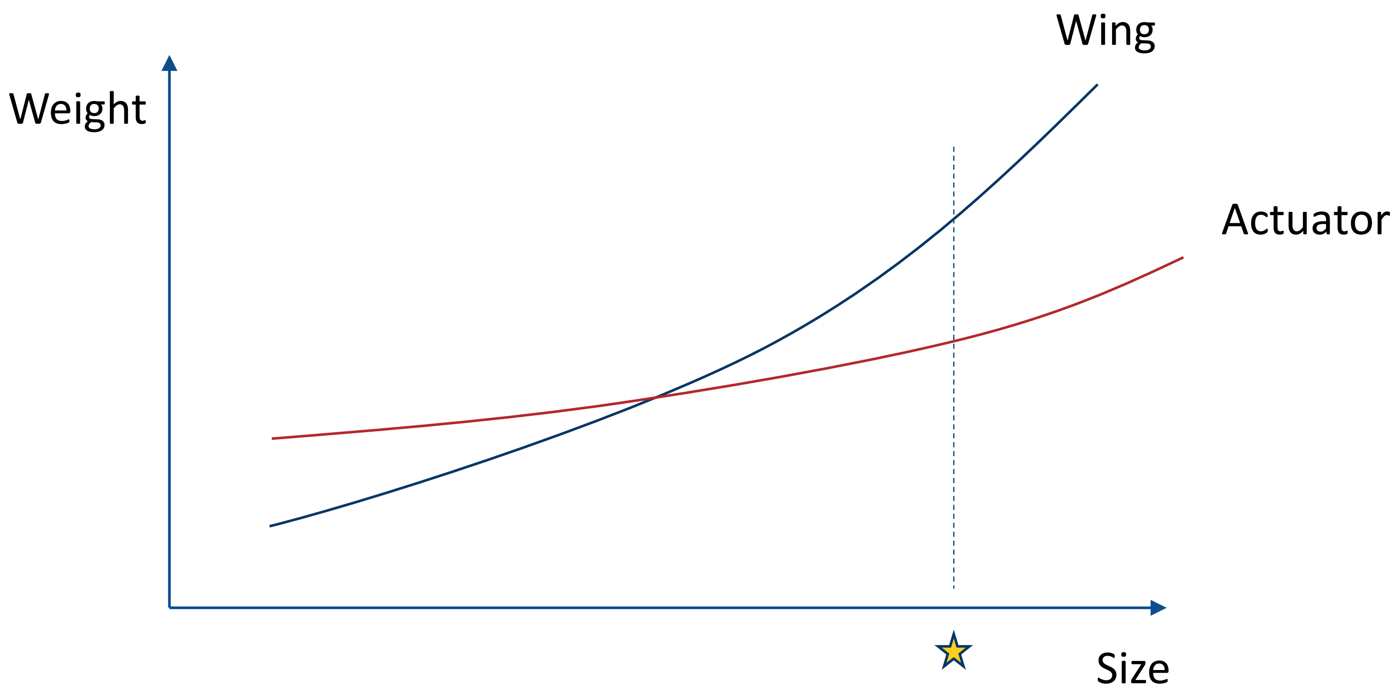
Example from Ikhana



Ran 4 cases, 1 in each quadrant. Compared the total drag for each case. Found the results are additive and nearly independent.

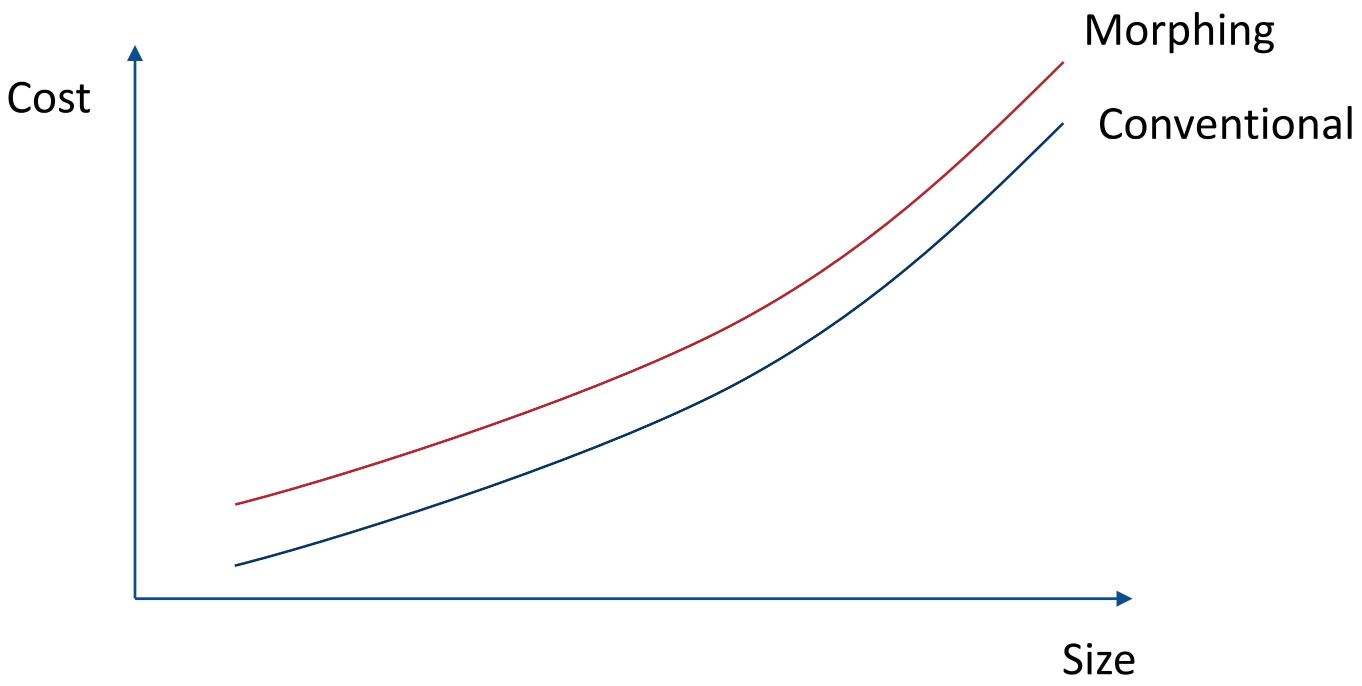
Myth II: Lighter

- Morphing requires more than two actuators
- Requires bigger actuator because compliant mechanism requires more actuation power
- May require an special engineered skin material and compliant mechanism



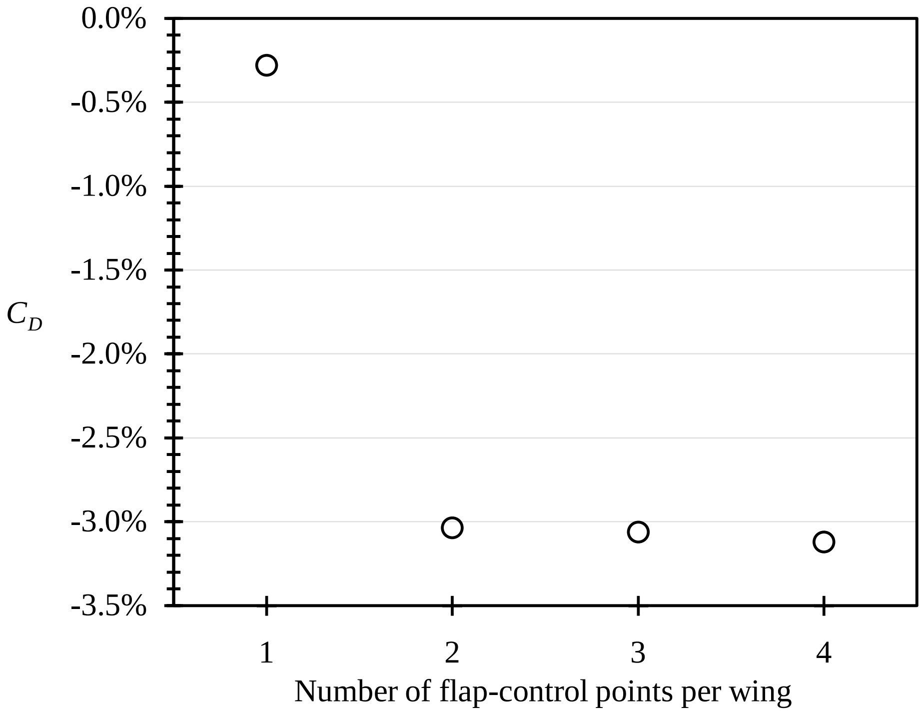
Myth III: Low Cost and Simple

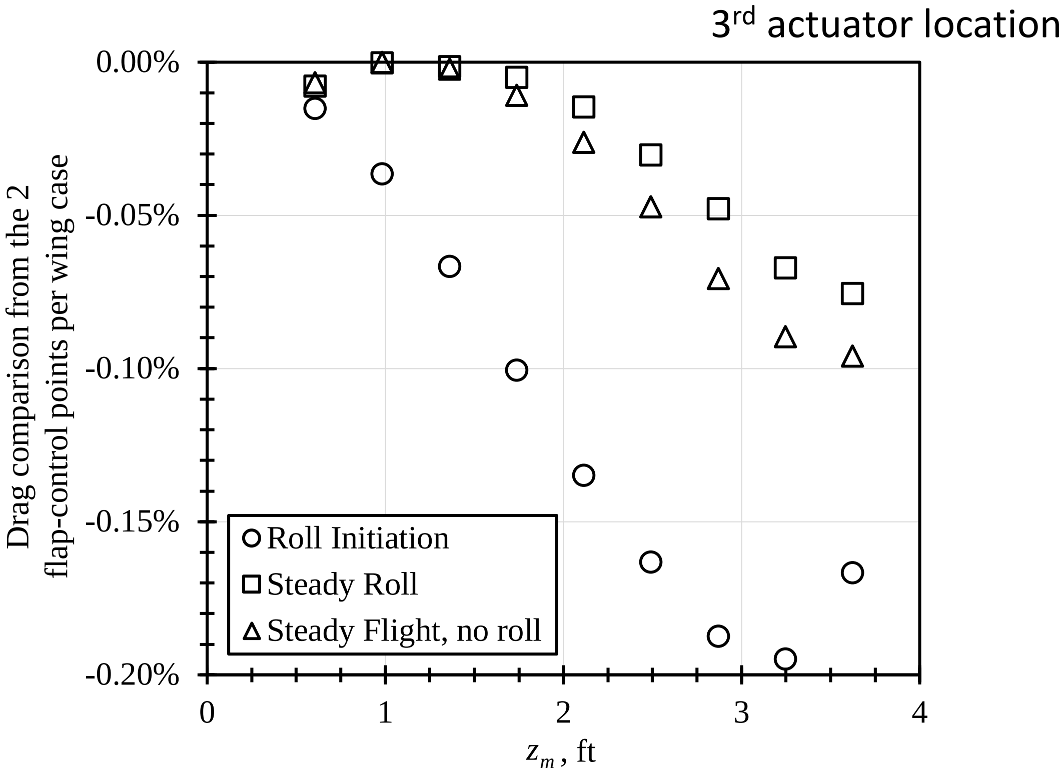
- Higher cost than conventional control surface due to
  - May require an special engineered skin material
  - Compliant mechanism construction
  - May require more actuators



Myth IV: More Actuators to Create Higher Order Curve is Better

- Full model analysis incorporating Viscosity with wings and empennage.
- The drag reduction from the baseline pitch trimmed case shows there isn't much drag benefit for having more that 2 flap-control points per semi span.
- Drag reduction benefits of adding the 3rd actuator are very small



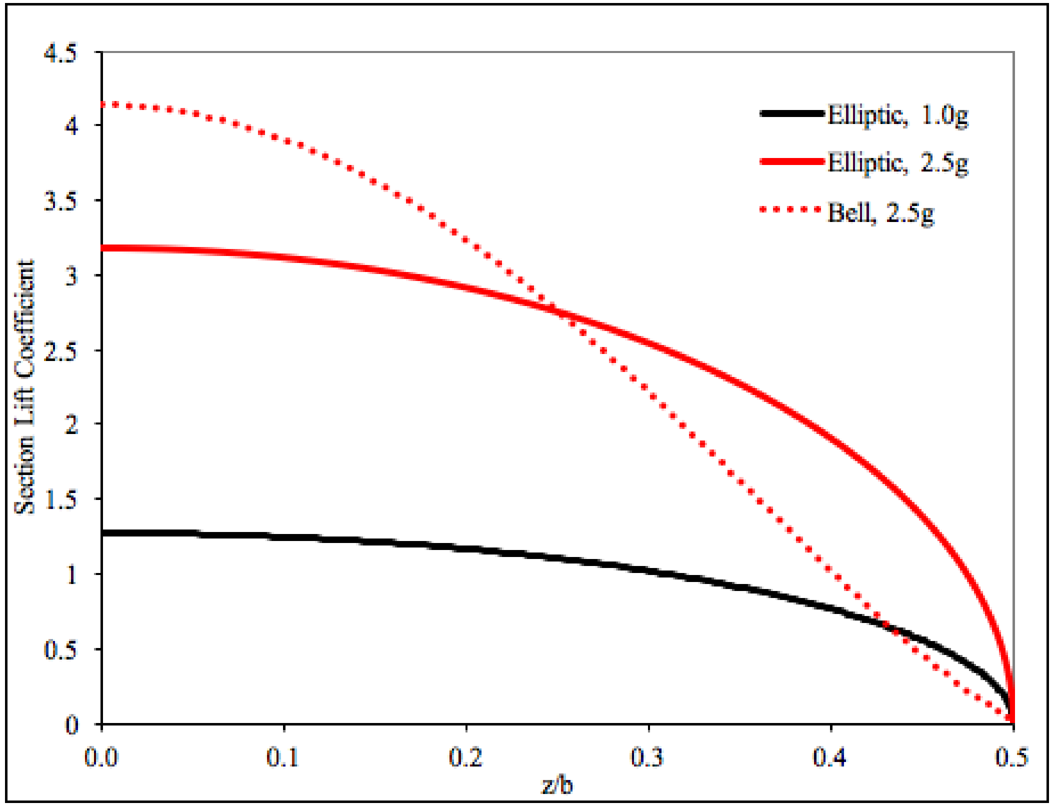


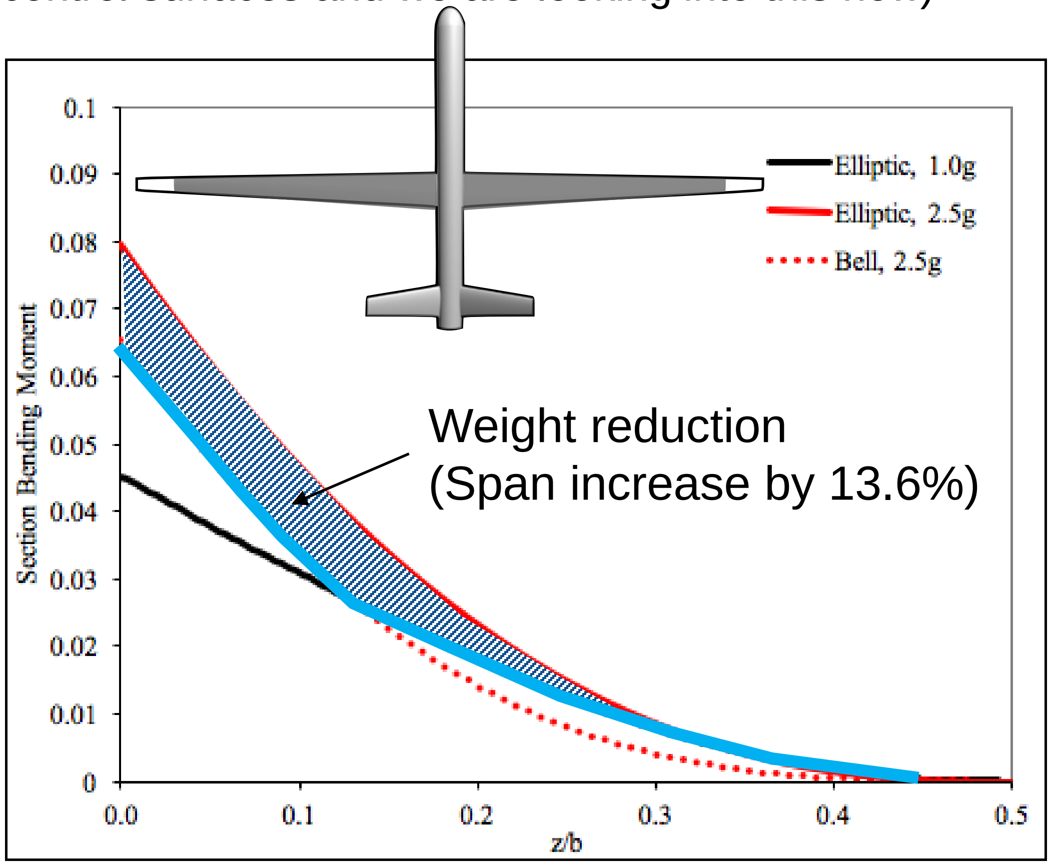
Then Why Morphing?

Benefit I: Span Increase W/O Weight Penalty

- Increase span by 13.6% or use less material for drag reduction (10% endurance increase)

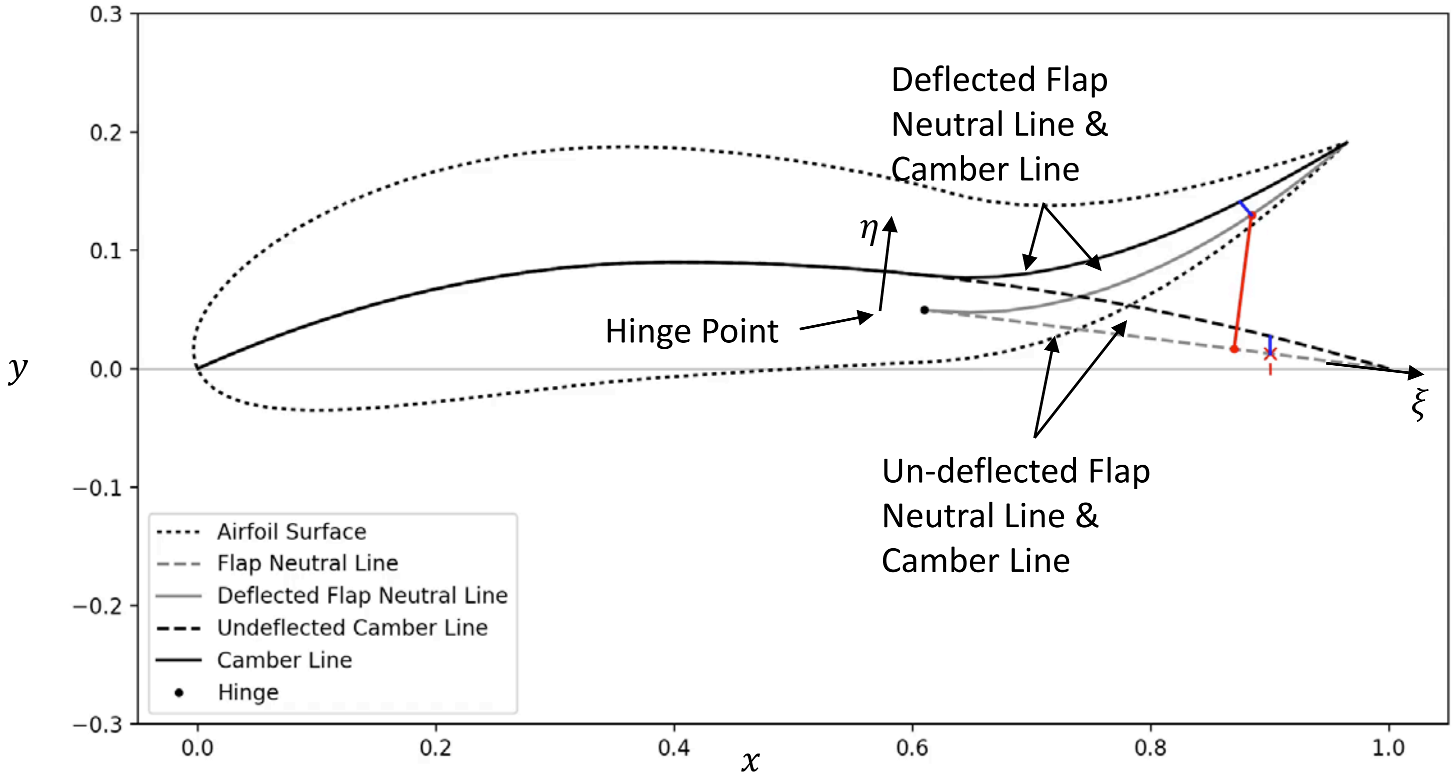
  (It may possible to do the same thing with multiple discrete control surfaces and we are looking into this now)

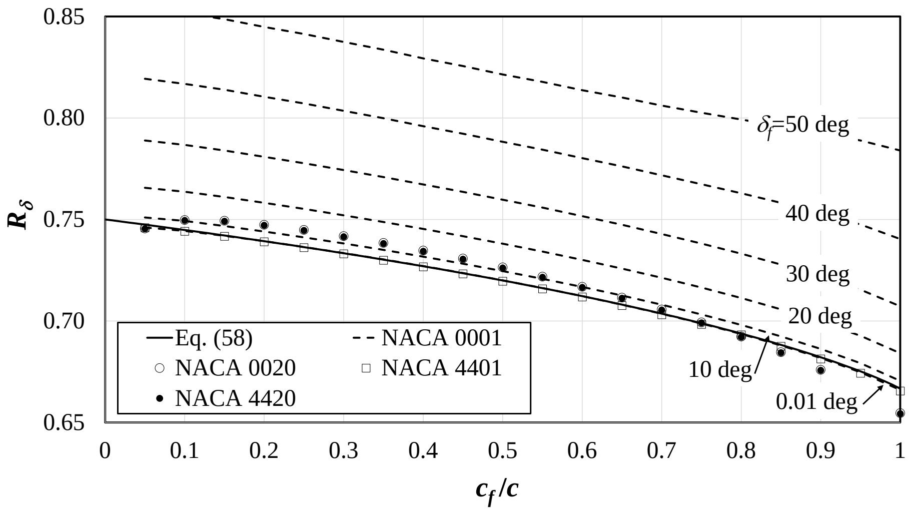


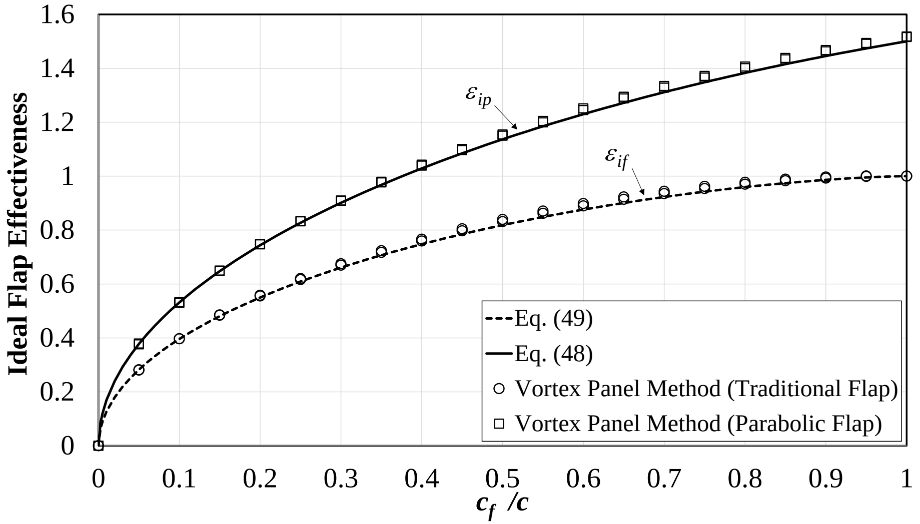


AFRL

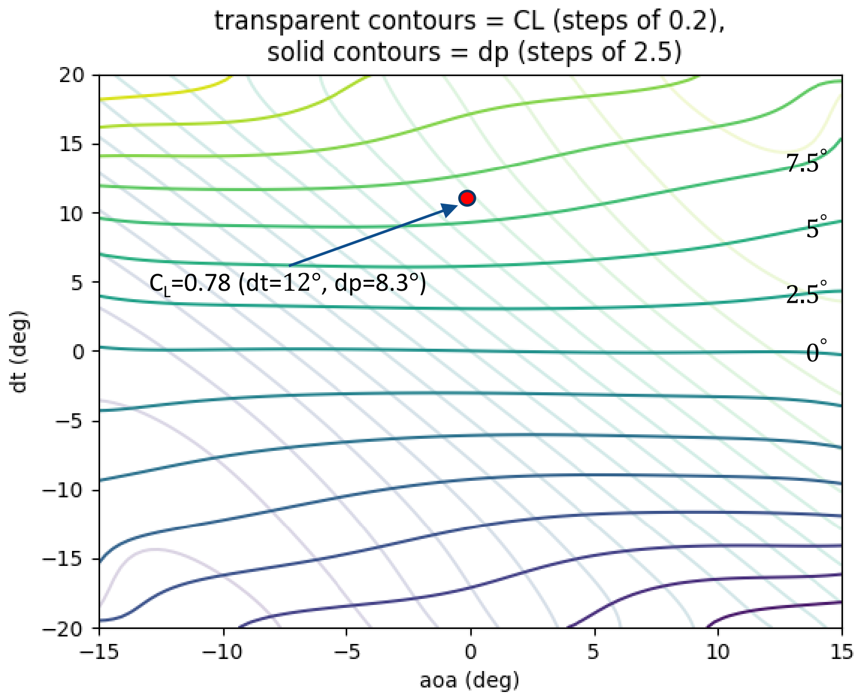
Benefit II: Requires Less Deflection for the Same Lift Generation (Less Observable)

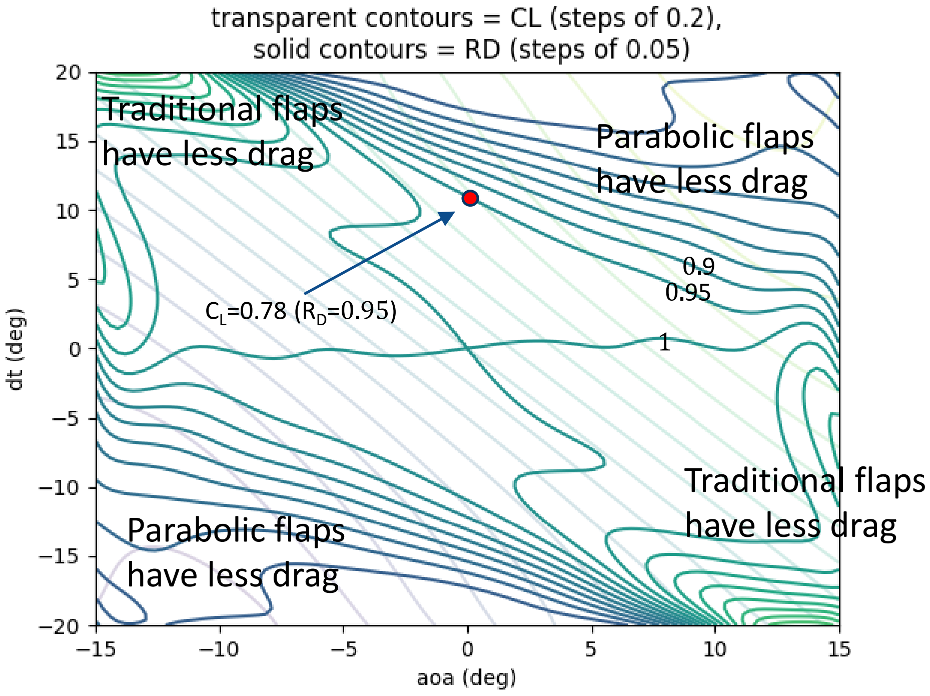






2D Comparison of the NACA 0015 Airfoil

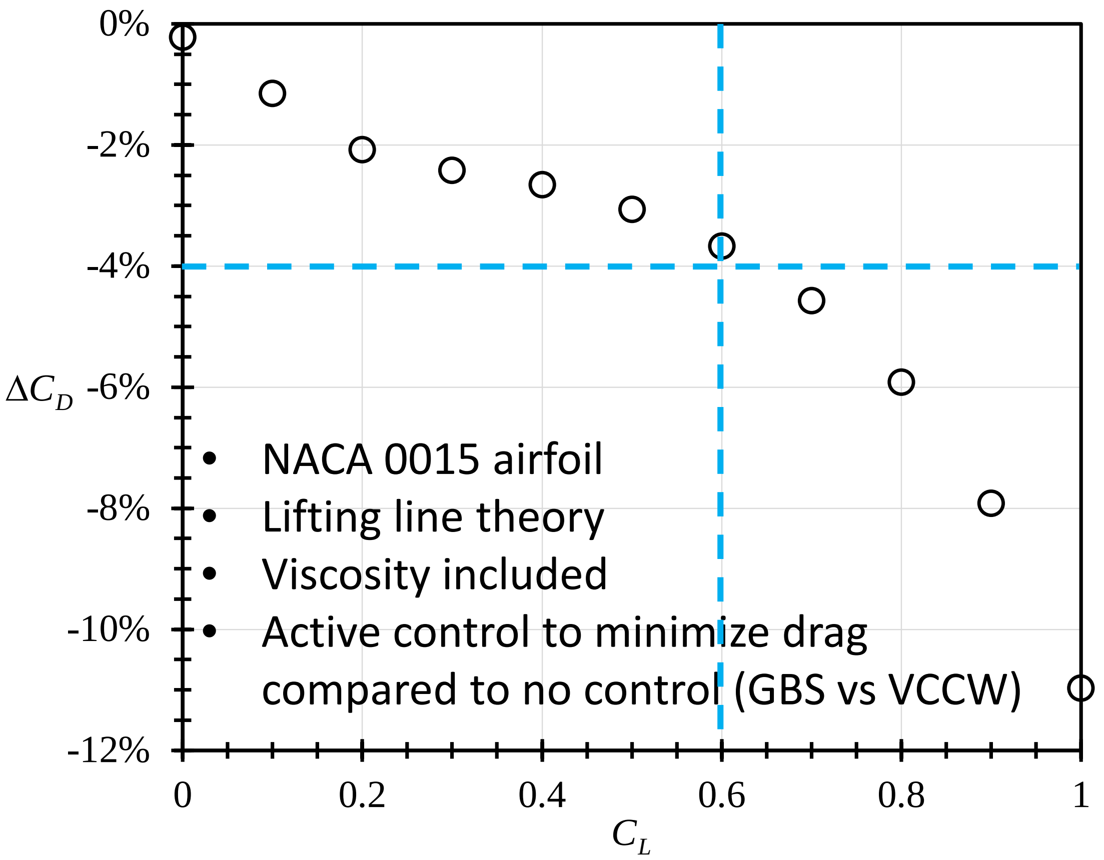


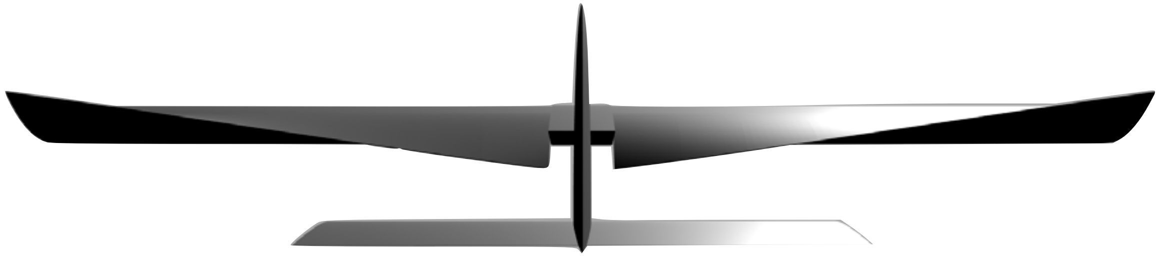


Traditional flap (dt)
Parabolic flap (dp)

$$R_D = \frac{C_{D_{p\_parabolic}}}{C_{D_{p\_traditional}}}$$

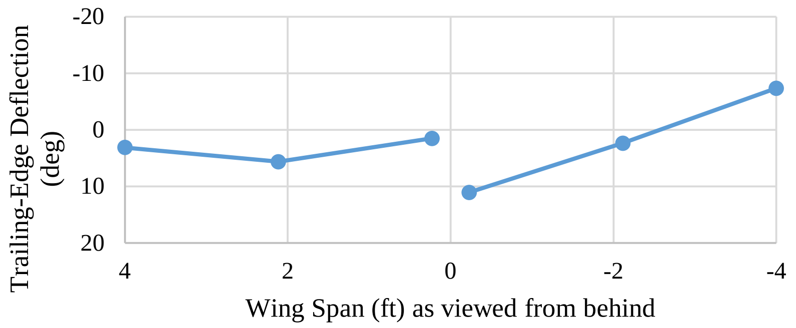
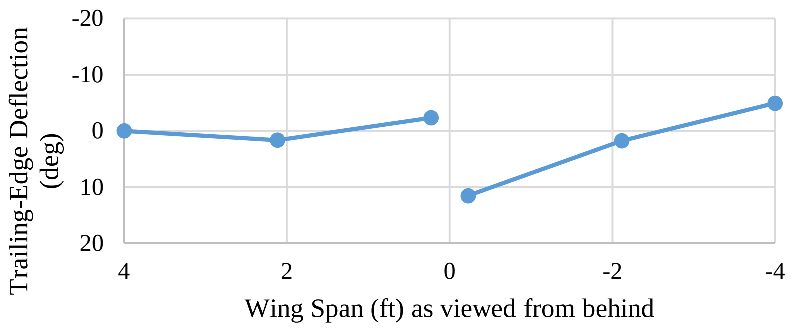
Benefit III: Higher Drag Reduction Benefit as C_L Increases and Active Control for a Minimum Drag





- Drag reduction is less than 4% up to C_L= 0.6
- Higher drag reduction benefit as C_L increases comparing to non-morphing aircraft (when L is constant)
  - **Low speed**
  - **High lift**
  - **(Large range of speed and weight)**
- Actively optimize shapes for various speed for entire mission to maximize the benefit
  - Traditional wing usually designed for a single cruise speed with a large weight

Benefit IV: Pure Roll or Yaw W/O (or Smaller) Vertical Stabilizer

<table>
<tr><th></th><th>Pure Roll @ Zero Yaw</th><th>Pure Yaw @ Zero Roll</th></tr>
<tr><td>Cruise speed 65 ft/s</td><td>
</td><td>
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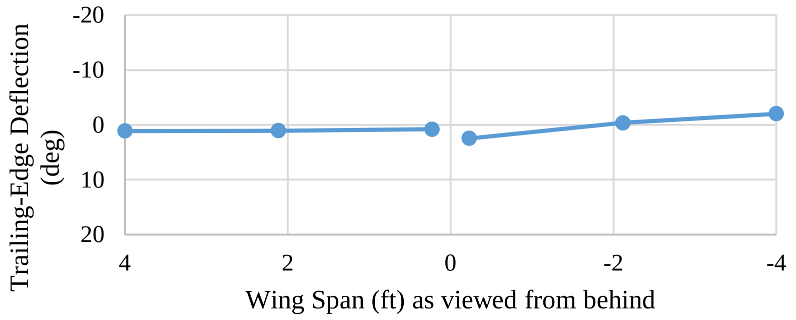
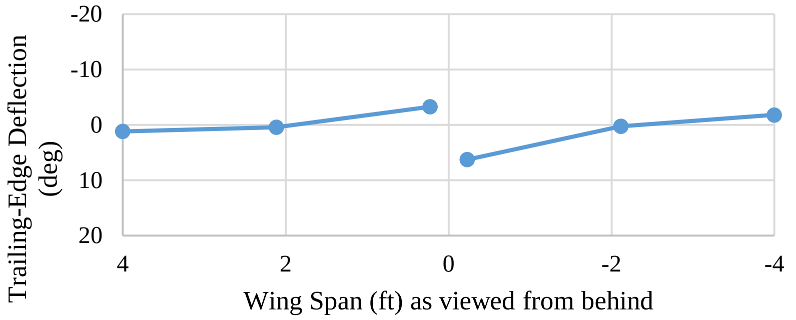
<tr><td>Fast speed 140 ft/s</td><td>
</td><td>
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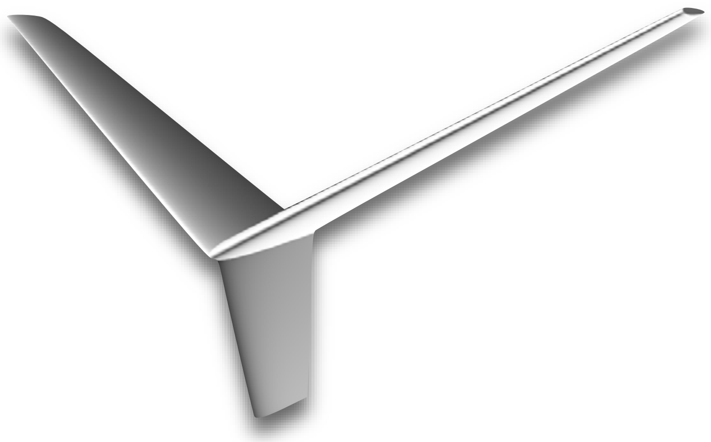
- Adverse-yaw is usually solved or mitigated by using an aileron to rudder interconnect gain
- Resolve the issue by using wing actuators alone

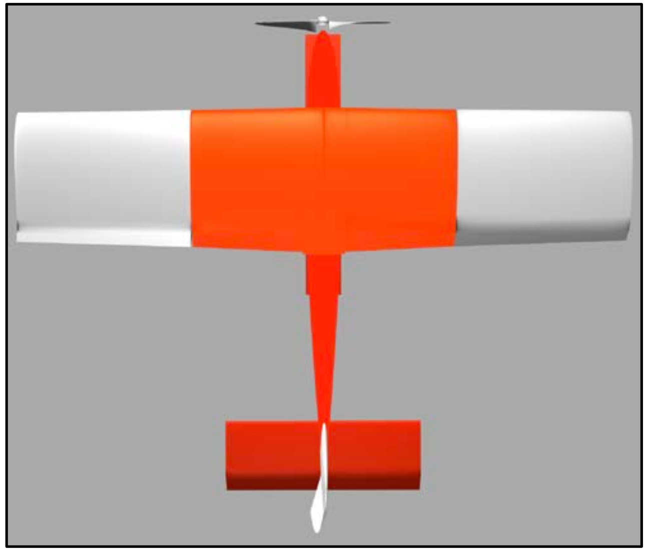
Benefit V: Increase Survivability

- Low observable
  - Reduce radar cross section by eliminate vertical stabilizer
  - Eliminate clap aileron or spoilers for yaw control
  - Eliminate gaps and holes
- Reduce airframe noise
  - Eliminate gaps and holes
- Increase efficiency
  - Eliminate gaps and holes
  - Reduce weight by eliminating vertical stabilizer
  - Empennage responsible 4-7% total drag

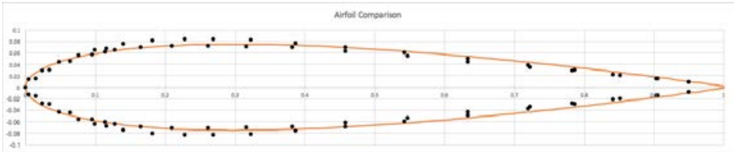


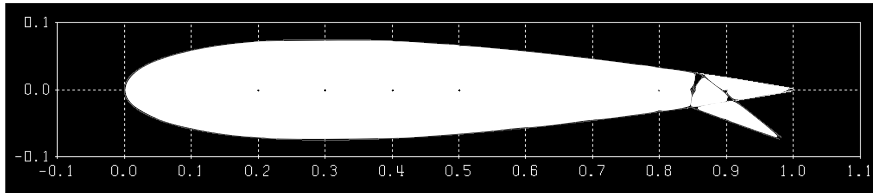
Flight Vehicle Selection, Design, Build, & Test

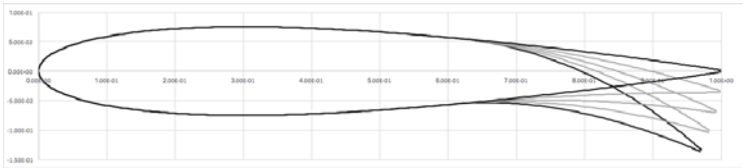
Baseline and Morphing Vehicle

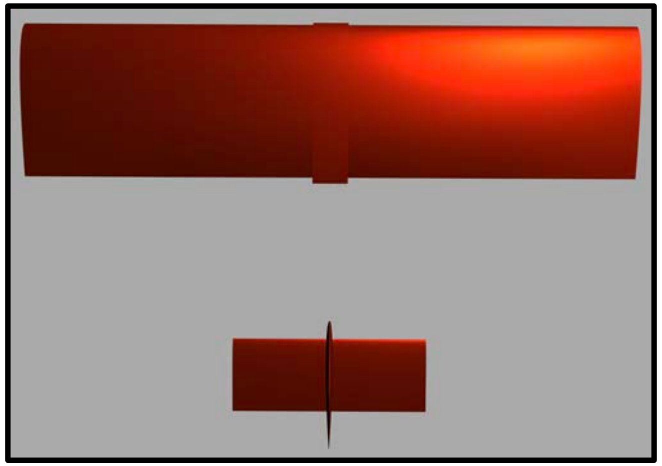


- Giant Big Stik
- Airfoil = NACA0015, NACA0006
- Aileron C_f/C = 0.12 (tip) ~ 0.16 (root)
- Weight: 21 lbs
- Span = 8 ft
- Wing area = 14.5 ft^2
- Control Throws: Aileron ± 21-29°







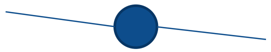


- Airfoil = NACA0015, NACA0006
- Aileron C_f/C = 0.4 (~10° along entire span is equivalent to 30° deflection of original aileron)
- Chord = 21 inches (Aspect Ratio = 4.57)
- Span = 8 ft
- Deflection ± 20° (± 2.85 inch trailing-edge deflection)

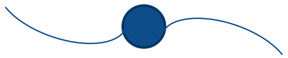
Control Law Applied to GBS

- Animation showing the control law
- pbar represent the pilots roll command
- CL represents the flight condition
- Includes the different modes to be used in the flight test and the flaps capability
  - Mode 1 (aileron) is a constant deflection per wing

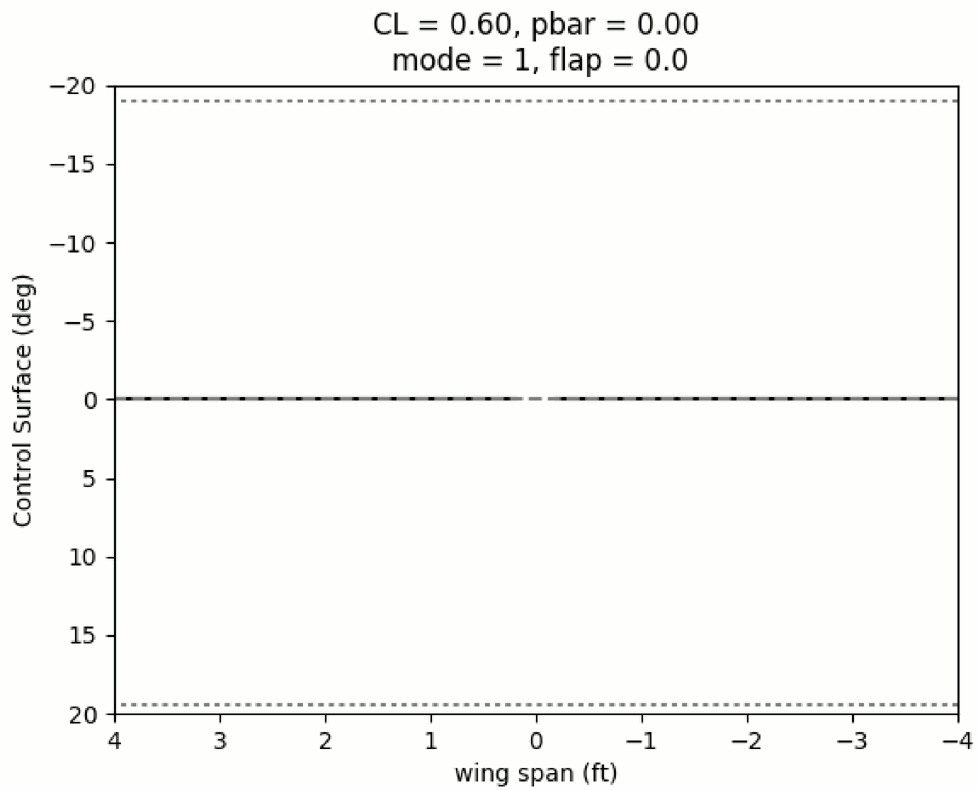
  - Mode 2 (roll) incorporates the asymmetric portion of the control law (only pbar)



  - Mode 3 (roll and lift) incorporates the total control law



- Incorporates saturation limits from the morphing-wing mechanism
  - Shown as the finely dashed lines



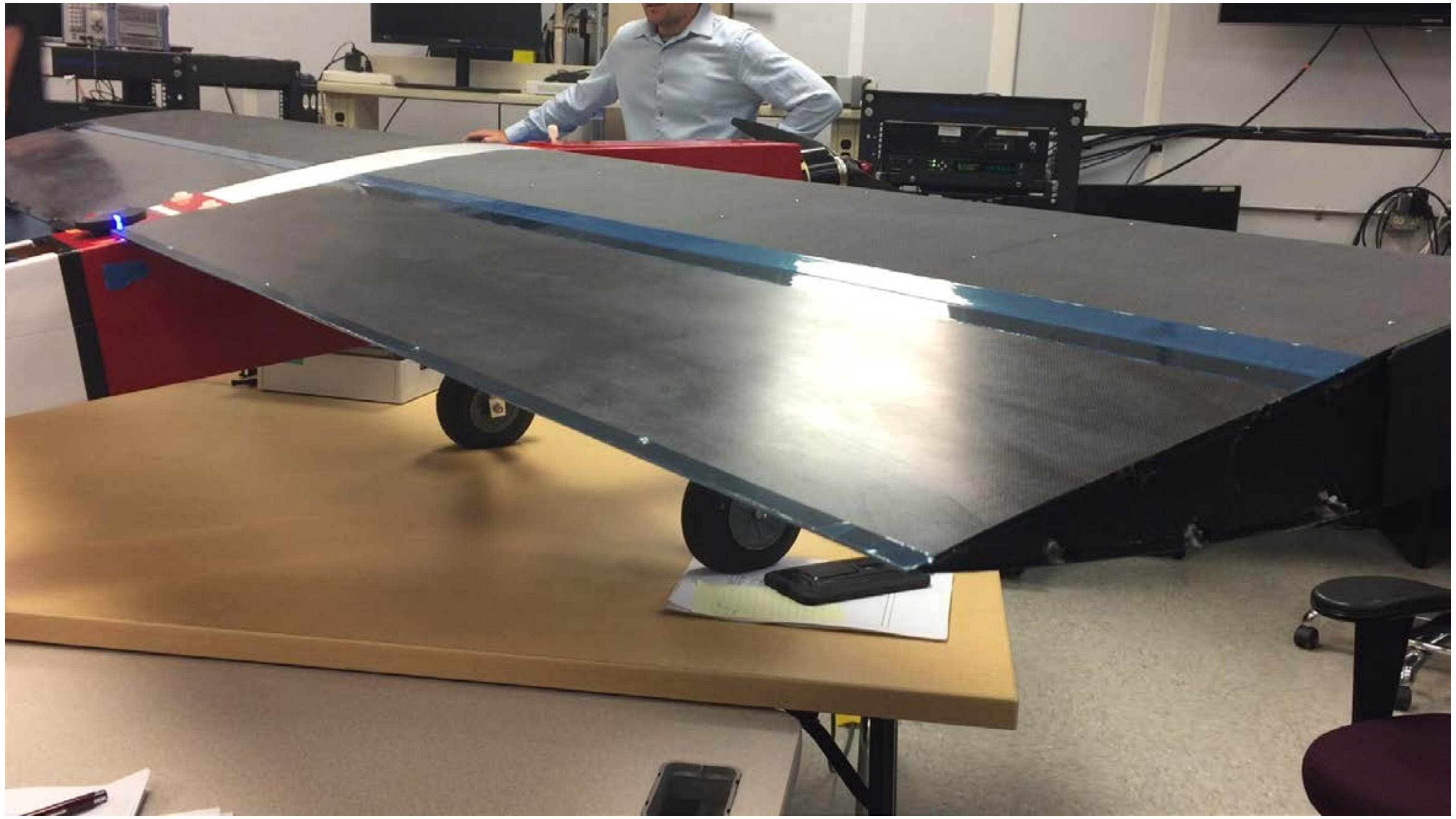
(Wing Span (ft) as viewed from behind)

Truck Test

- A half span wing (4’ X1.75’) to confirm its structural integrity
- The wing structure was tested up to about 40% higher than the expected cruise airspeed and 4G loading at various angles of attack (±20 degrees), spanwise shape variation, and trailing edge flap deflections (±2.5 inches).

Morphing Vehicle with VCCW

- Servo actuator
- 70º/sec slew rate
- ± 25º maximum deflection
- Various shapes possible
    - Linear Variation
    - Bathtub Shape



Summary and Accomplishments

- This study was performed to understand the benefits and limits of camber morphing technology and suggest right future investments and research direction
- Low drag – Increase endurance
  - Smooth control surface (up to 11% drag reduction at trimmed condition)
  - Increase span without weight penalty
  - Weight reduction by eliminating vertical stabilizer (Empennage is responsible for 4-7% total drag)
- Increase survivability – Low observable
  - Reduce radar cross section
    - Eliminate clap aileron, spoilers, or vertical stabilizer for yaw control
    - Smaller control surface deflection (requires 65-75% of conventional control surface deflection to generate the same amount of lift)
    - Eliminate gaps and holes
  - Reduce airframe noise
- Suggested applications of the camber morphing technology
  - Small to mid size UAVs without active control capability (Drag reduction of the conformal surface is < 2% when the conventional wing is also equipped with active control for minimum drag)
  - Yaw control of Tailless aircrafts (no vertical stabilizer)
  - High endurance and low observable vehicle
- Publications (2017-2019 including SFFP)
  - Conference papers and presentations
    - Published (13), Submitted (3-SCITECH 2020)
  - Journal publications
    - Published(3), In-review (1), Preparing (2)

Questions?