

Membrane Wing Aerodynamics for μ AV

Applications

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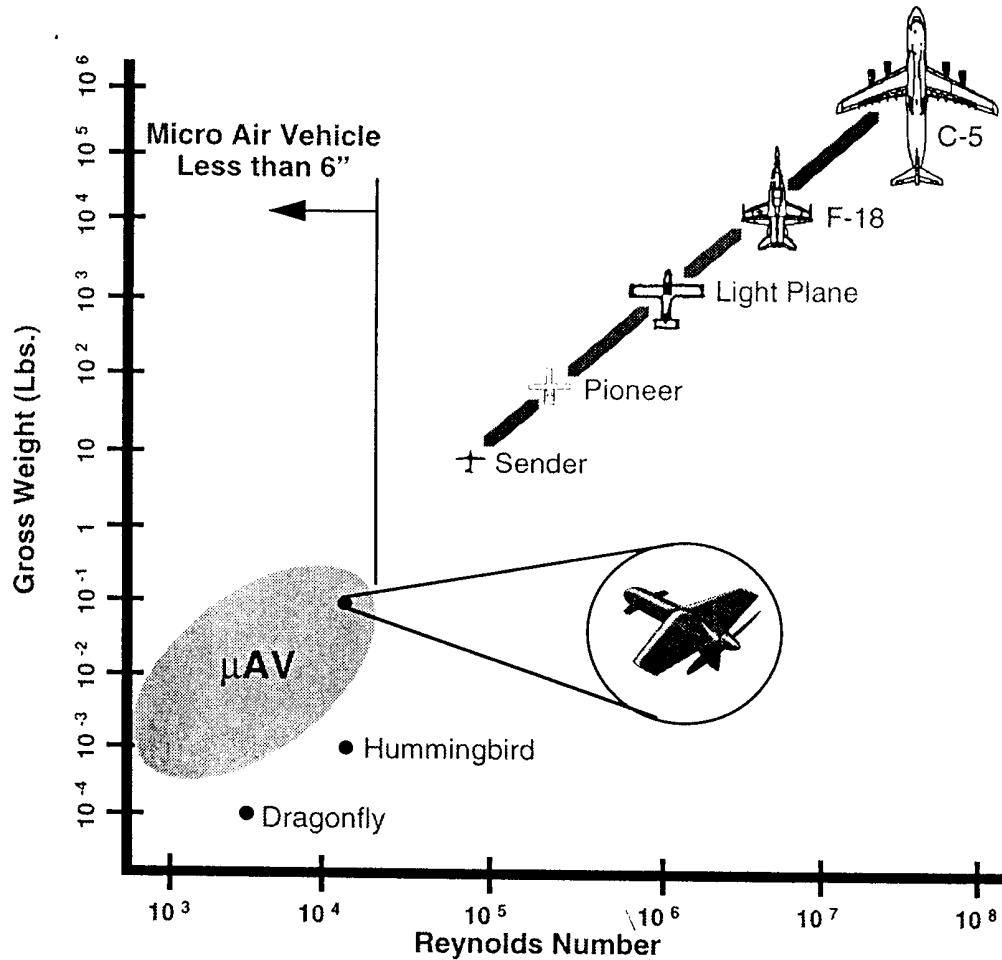
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Scope of This Talk

- Overview of Univ. Florida μ AV
- Summarize computational capabilities for fluid/structure interactions: membrane and surrounding viscous flow.
- Present the aerodynamics of self-excited membrane and MAV implications.
- Discuss the wing shape optimization for μ AV Applications.



Characteristics of μ AV



➤ Micro Air Vehicle (μ AV) smaller than 6", Speed 10m/s. Many applications.

➤ Low Reynolds number (10^4 - 10^5) condition: degraded L/D

➤ Flight environment intrinsically unsteady.

μ AV: Geometric & Aerodynamic Scaling

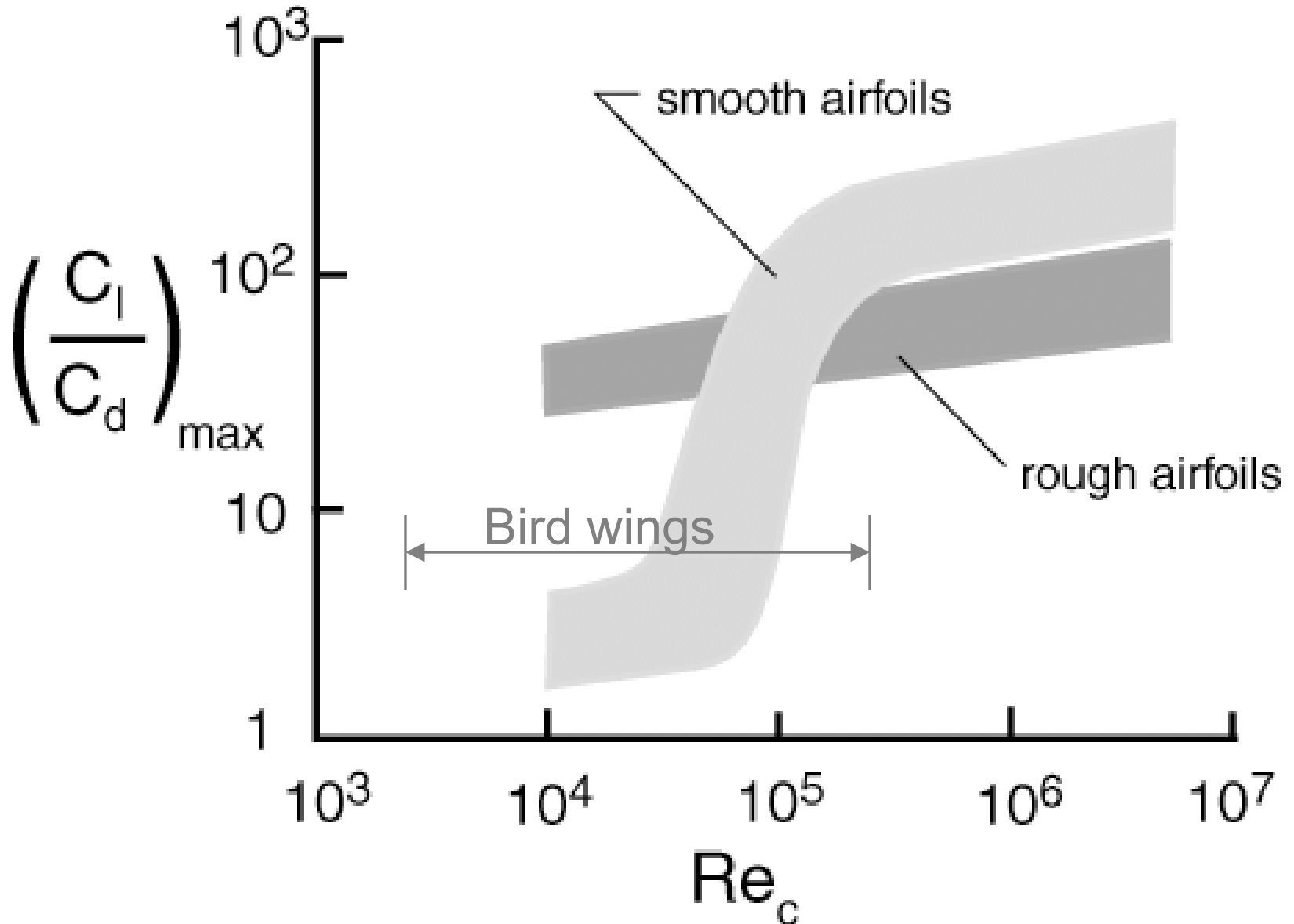
Geometric Scaling: If aerodynamics is unchanged, the power requirement decreases as the vehicle size is reduced.

Aerodynamic Scaling: Aerodynamic performance degrades as the vehicle size, and hence Re , decreases.

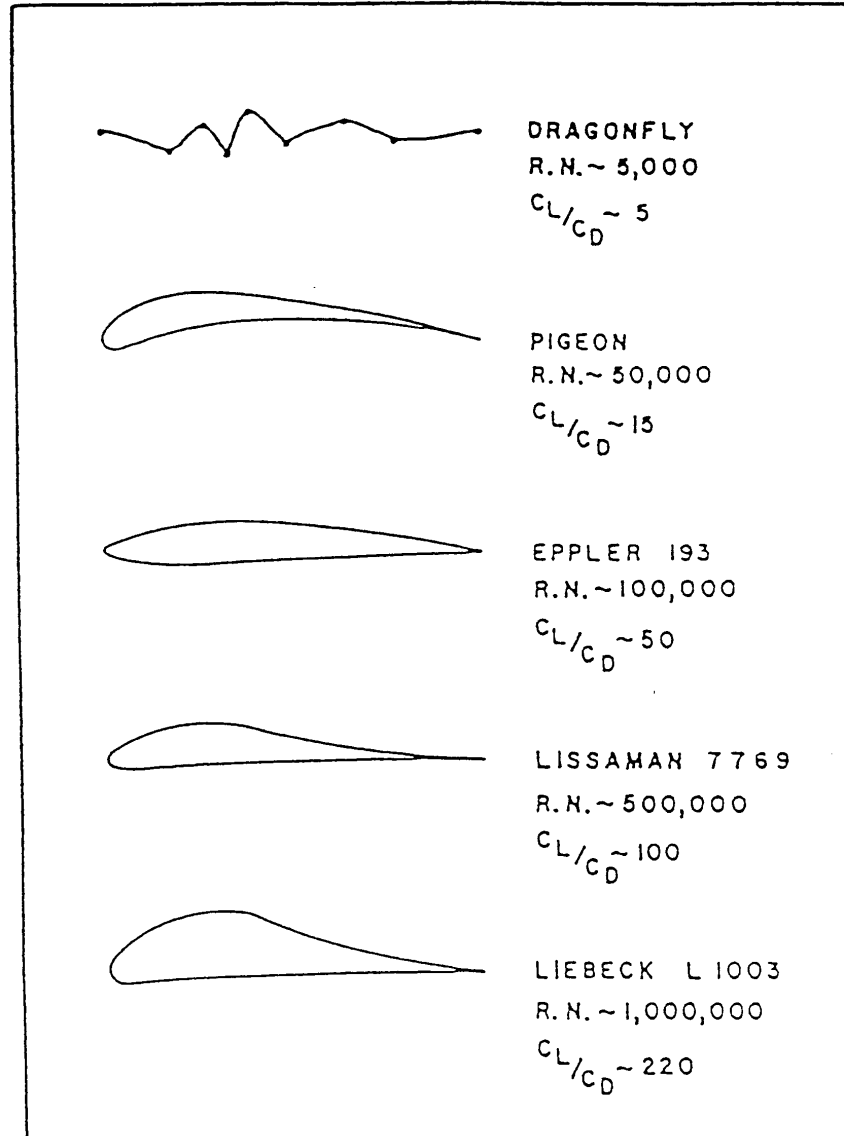
$$P=W \left(\frac{C_D}{C_L^{3/2}} \right) \sqrt{\left(\frac{2}{\rho} \right) \left(\frac{W}{S} \right)}$$

Low Reynolds Number Airfoils

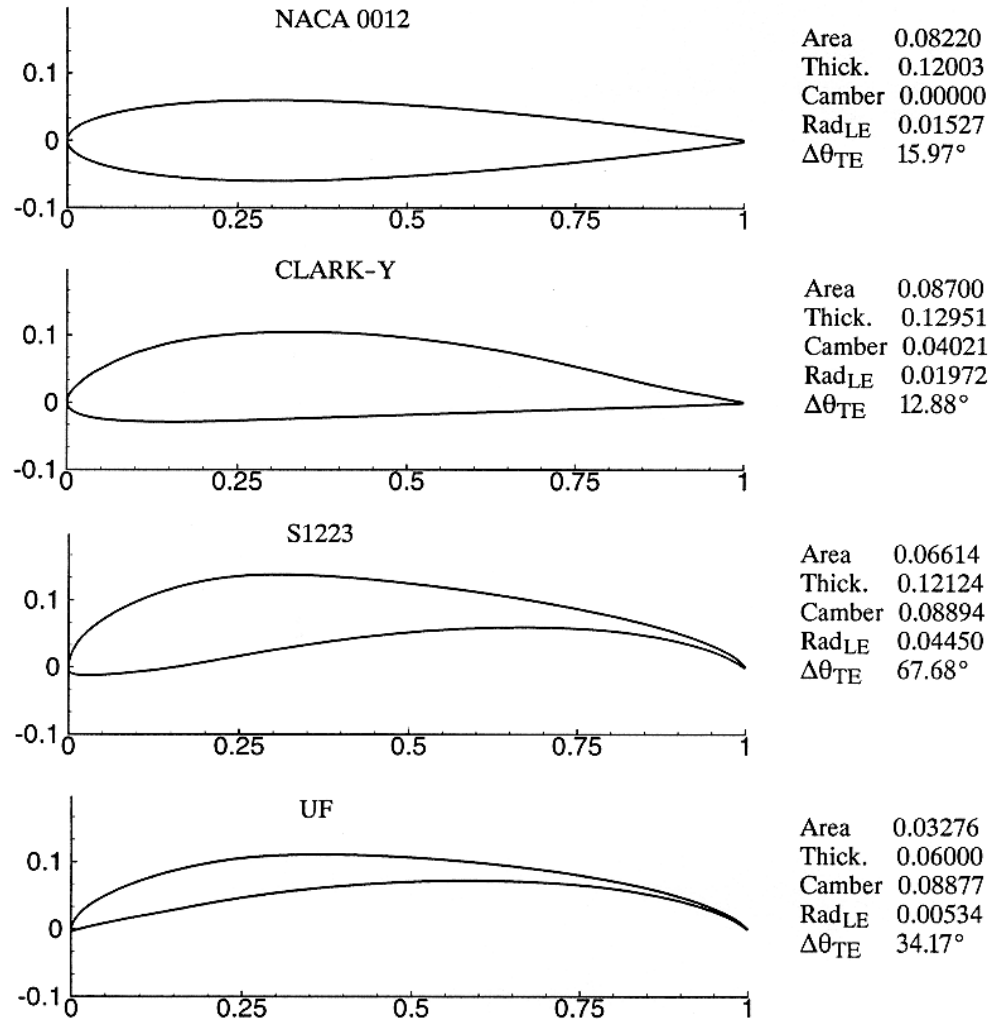
- Gusts affect small birds and μ AVs more than large ones



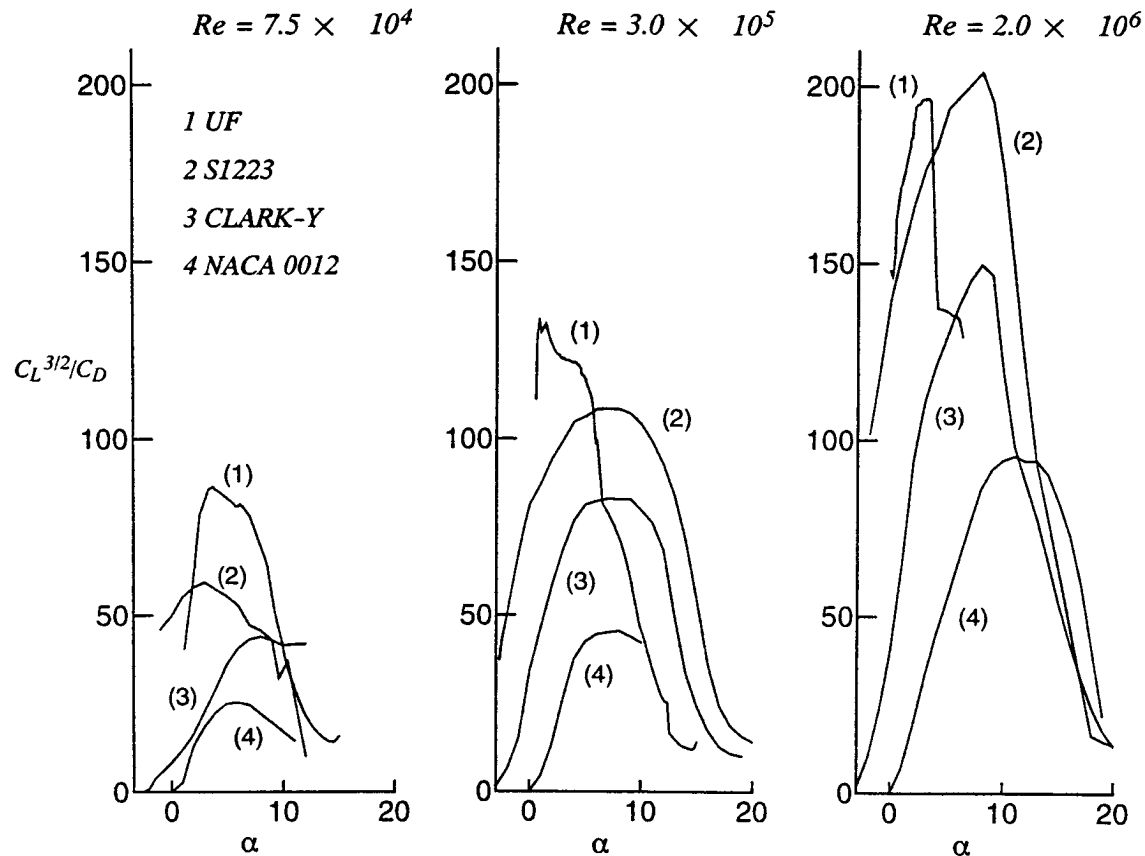
Representative Low-Reynolds-Number Airfoils (from Lissaman)



Selected Airfoil Profiles



Effects of Re, Airfoil Shape, and AoA on Power Index

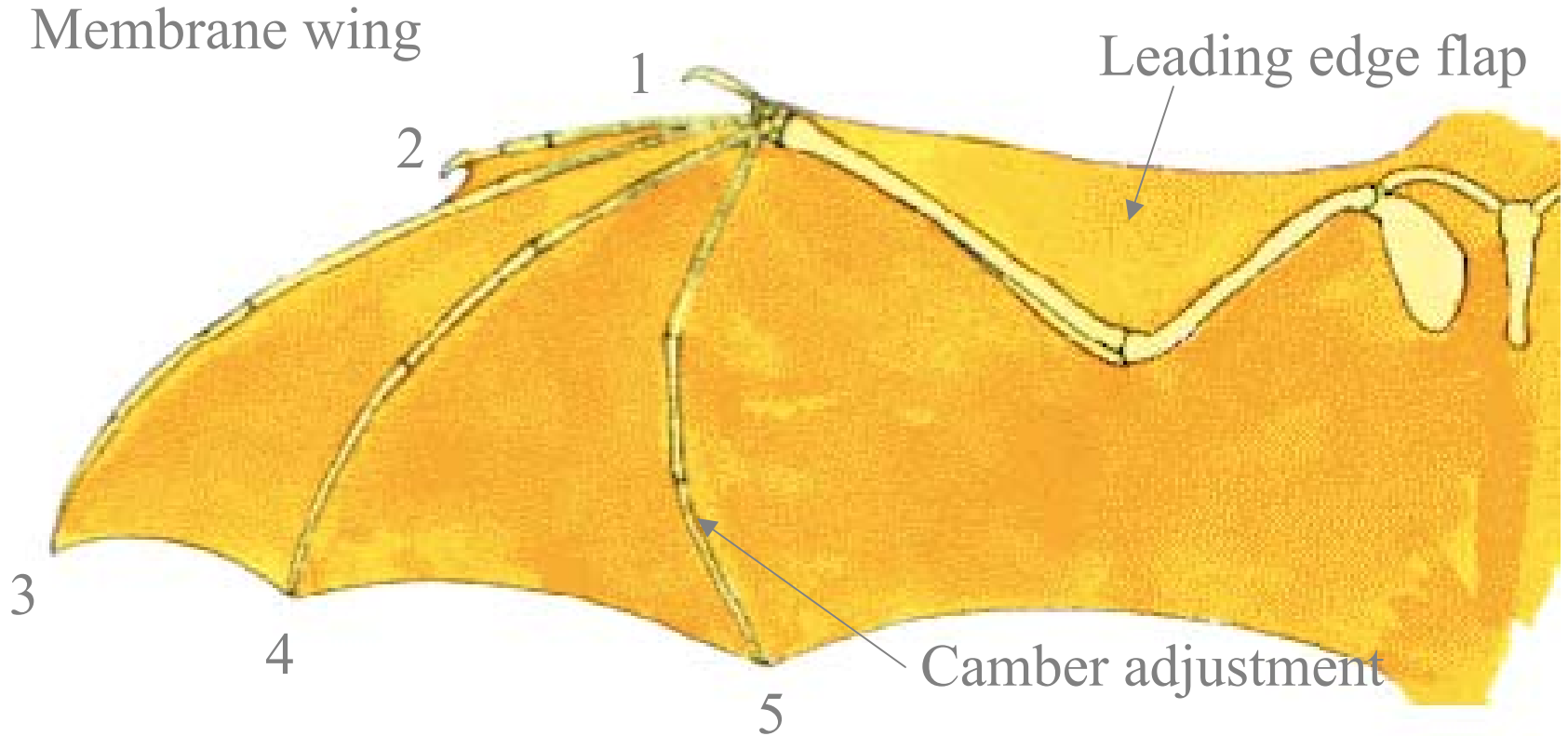


Membrane-Based μ AV Concept at U. Florida

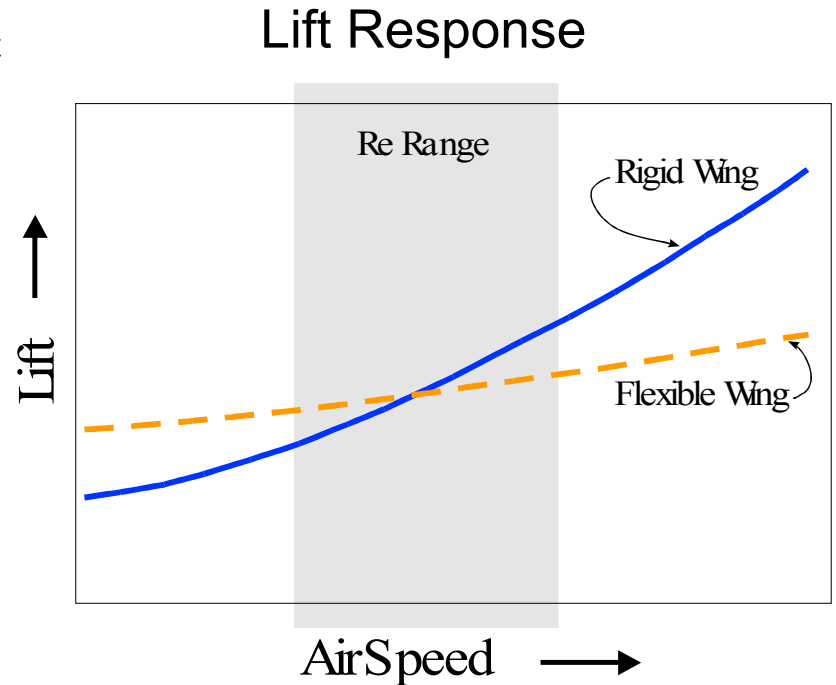
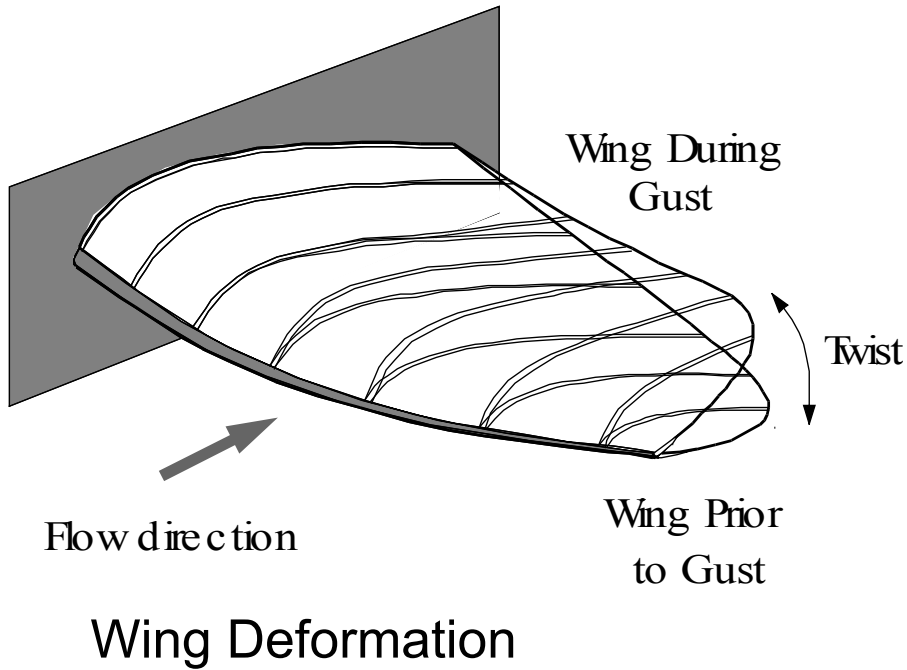


- Wingspan: 6 inches
- Length: 5.5 inches
- Weight w/payload, video camera: 2 ounces
- Range: 0.5 mile with off the shelf components
- Endurance: 10 minutes
- Speed Range: 10 – 35 miles/hour
- Propulsion: electric motor
- Batteries: rechargeable Lithium polymer
- Altitude: up to 500 feet AGL

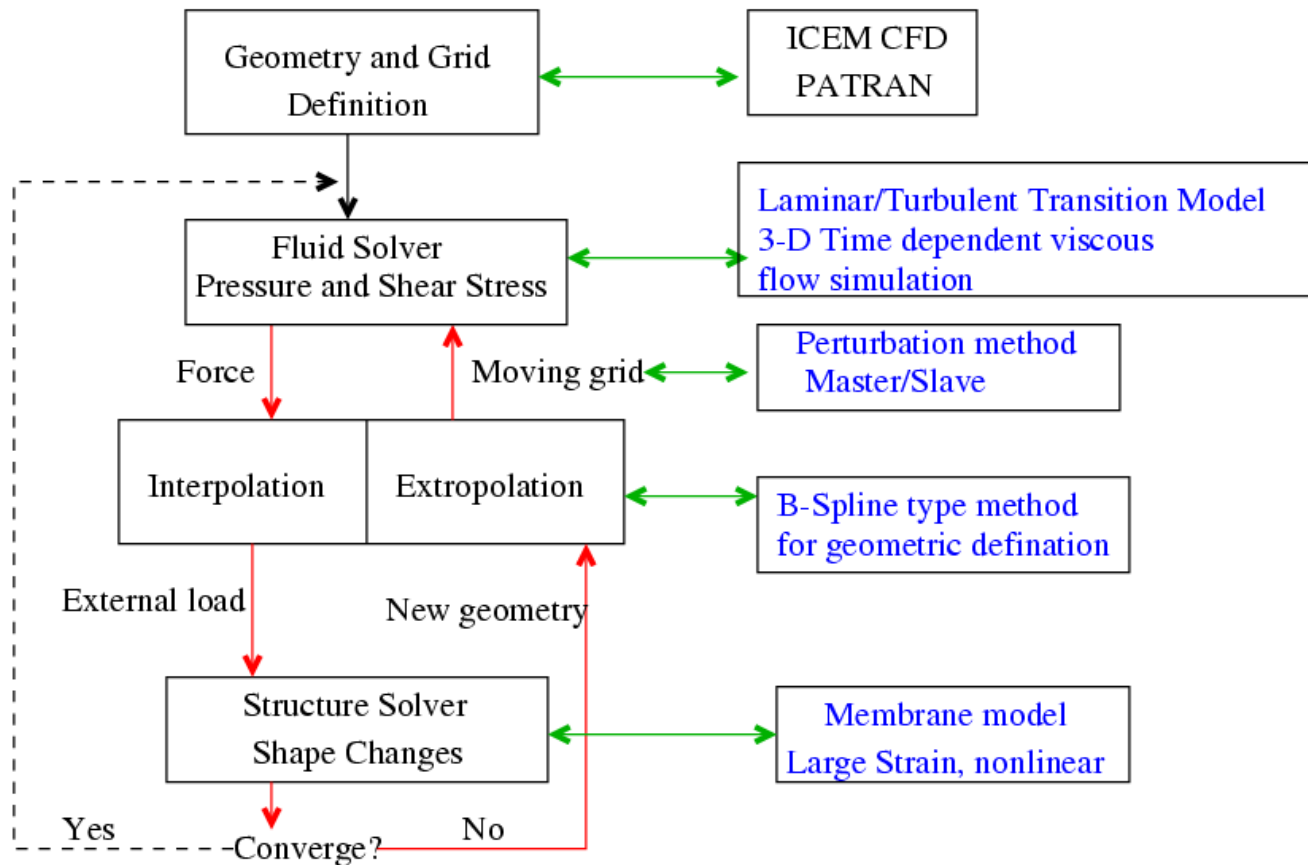
Bat Wing Morphology



Adaptive Washout for Gust Suppression



Computational Fluid/Structure Interaction



- **Fluid solver:** Calculate the external force.
- **Structure solver:** Calculate the shape change.
- **Moving boundary:** Regenerate the CFD grid
- **Interface:** Exchange information between fluid and structure solvers.

Approach

➤ Structure model

- Dynamic membrane model with finite element.
- Expect substantial deformation: nonlinearity.

➤ Fluid flow solver

- A pressure-based method for 3-D full Navier-Stokes equations

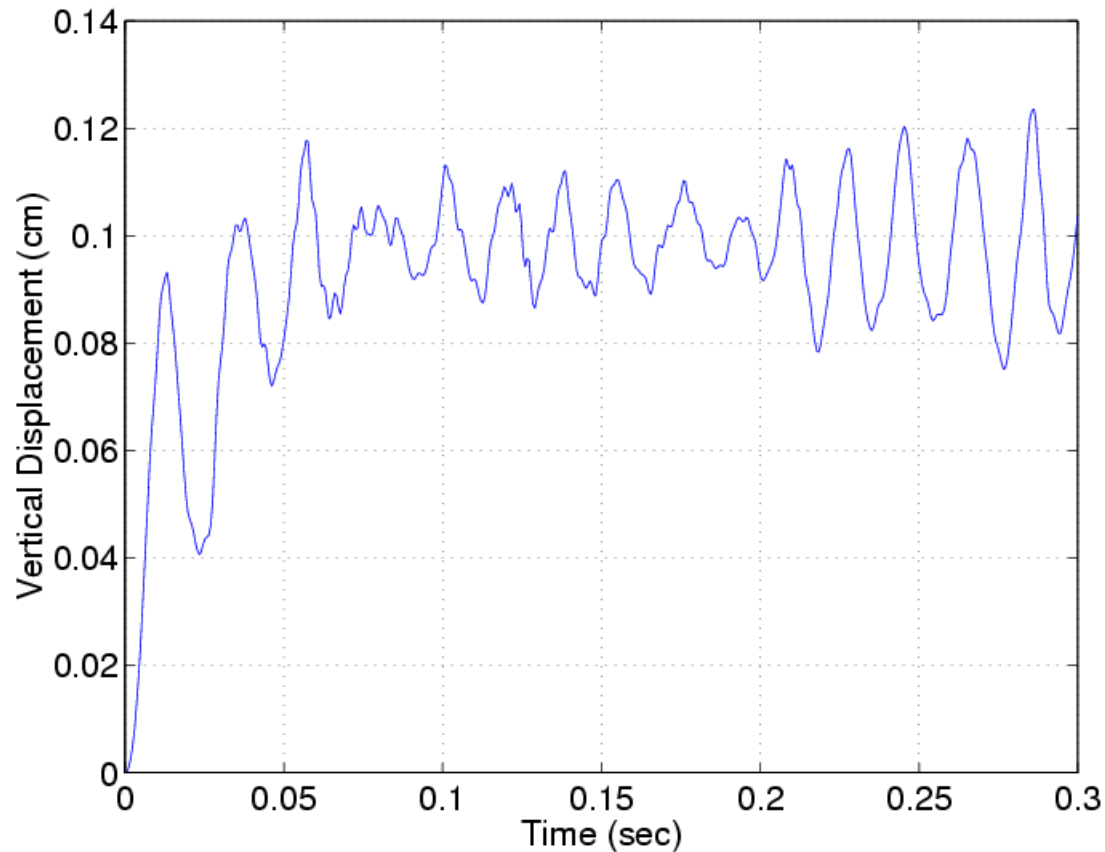
➤ Grid regeneration

- 3-stage algebraic TFI-like method.

➤ Interpolation

- Thin Plate Spline (TPS) interpolation method

Displacement of trailing edge at mid-span

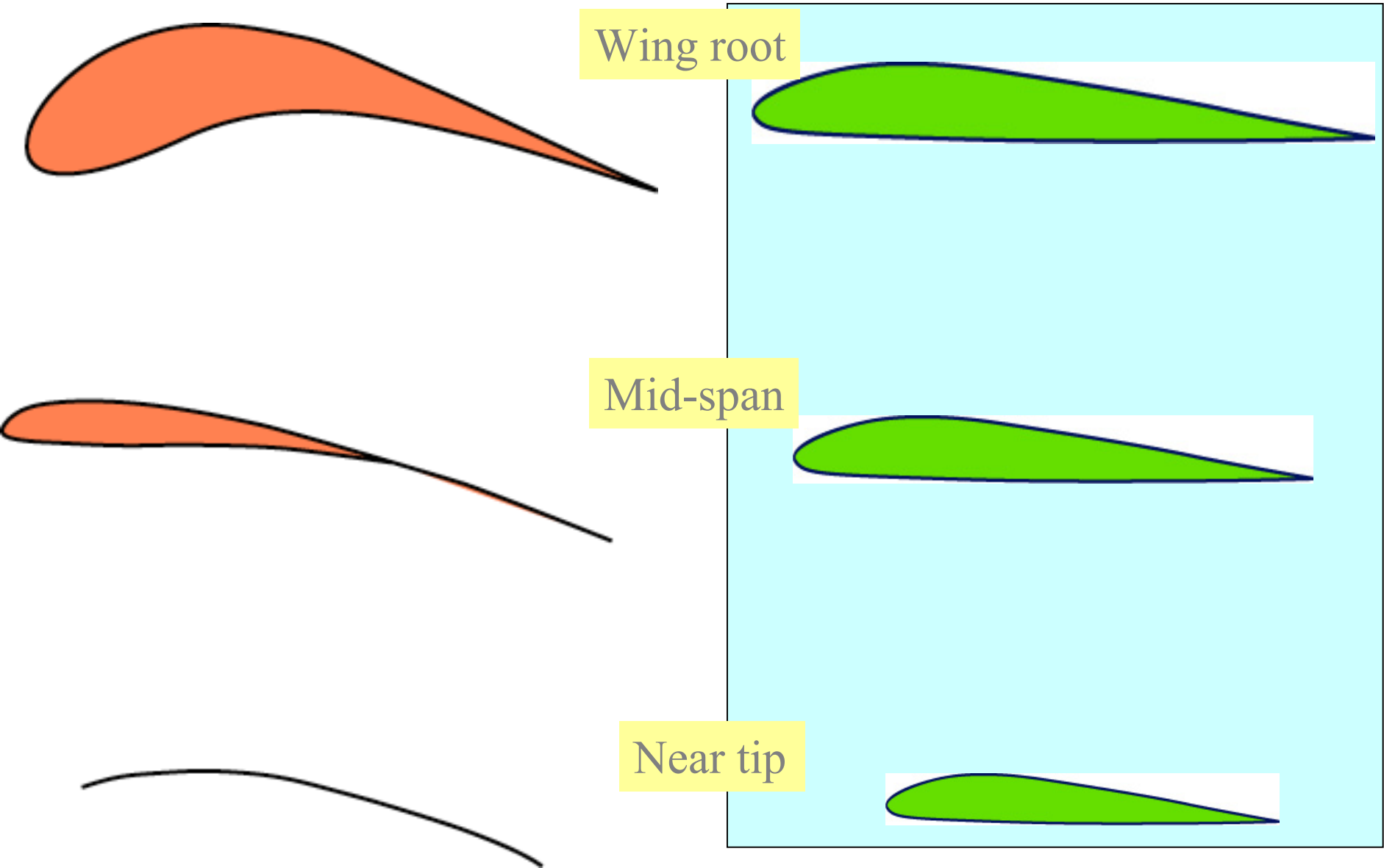


- Steady Free Stream, $Re=9 \times 10^4$, $AoA=6^\circ$
- Periodic oscillation of the trailing edge point.
- Frequency=67Hz. (Typical wind gust: 1 Hz)
- The effective angle of attack reduced.

Wing Cross Section: Optimization?

Pigeon wing

Conventional Wing



Optimization Scope and Approach

Minimize C_D / C_L

Subject to

1: $C_L \geq C_{L\text{baseline}}$

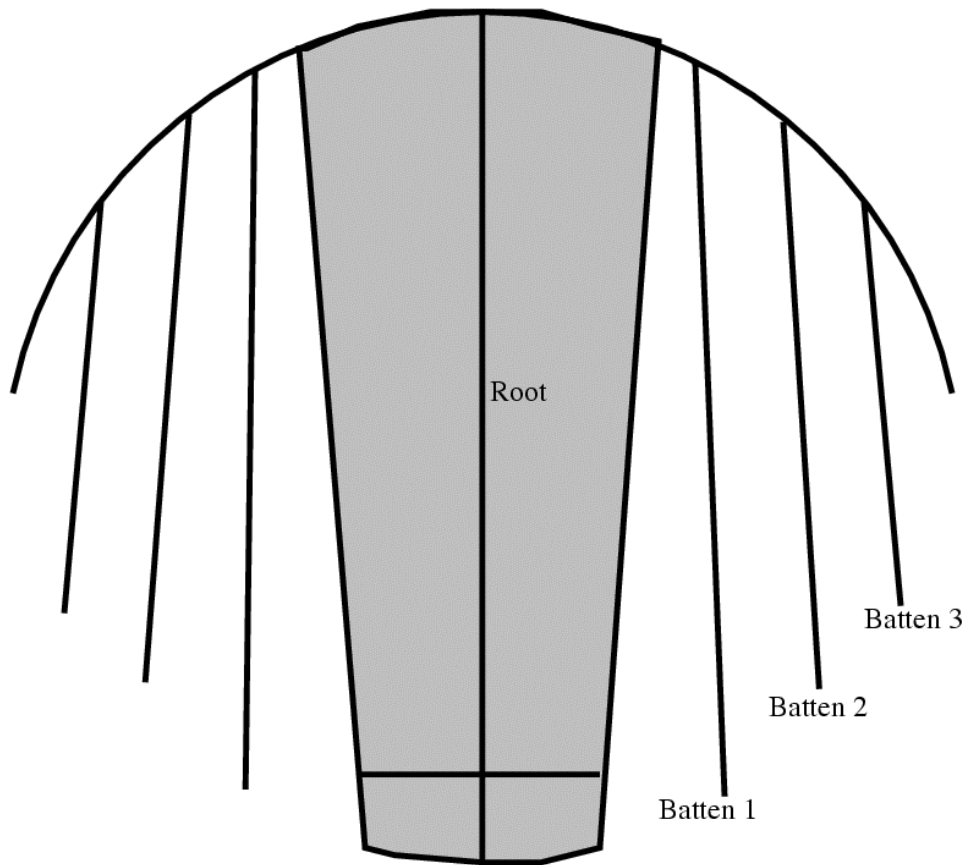
2: Convexity constraint:
$$Y_1 \geq \frac{Y_2 + y_2 - Y_0}{x_2 - x_0}(x_1 - x_0) + y_0 - y_1 + \varepsilon$$

3: $Y_i^L \leq Y_i \leq Y_i^U, \quad i = 1, N$

- Maximize L/D; Maintain lift; Keep cross-section convex.
- A direct optimization of membrane wing is time-demanding: Optimize the rigid wing as a surrogate.
- Design Optimization Tools (DOT) used as the optimizer.
- An automatic grid regeneration tool is used to regenerate the CFD grid as each analysis.

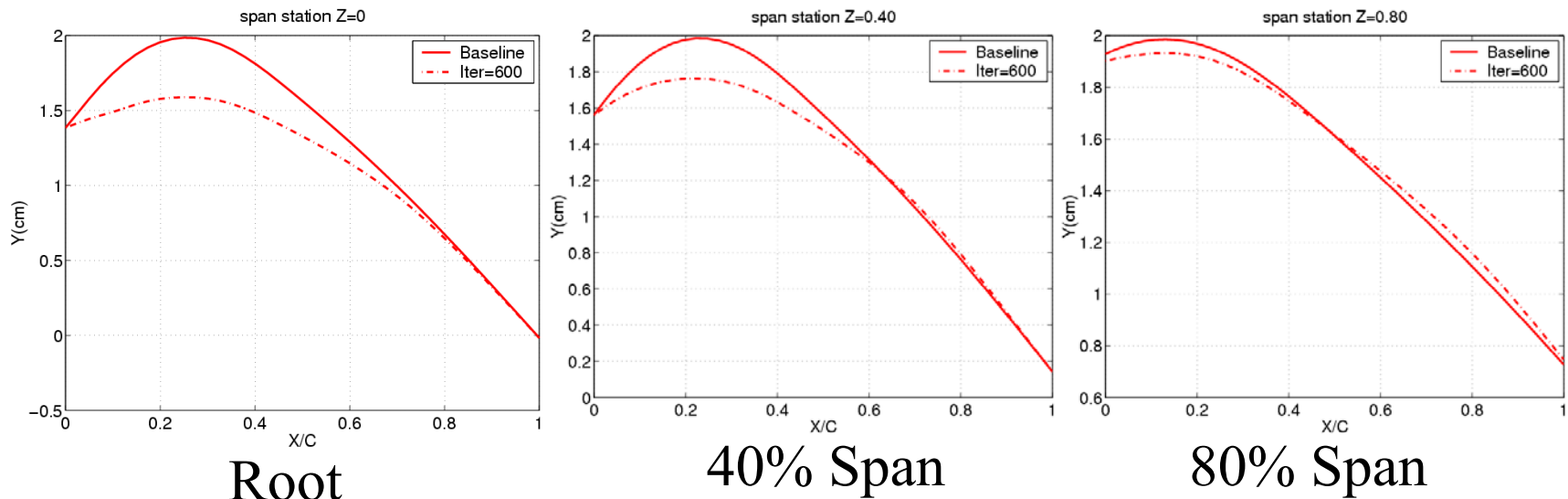


Choice of Design Variables



- The baseline design is based results from Xfoil (Drela): which uses a two-equation boundary layer integral formulation & inviscid-BL coupling.
- 6 Design Variables: Three each on batten1 and 2.

Airfoil Shapes in Spanwise Direction



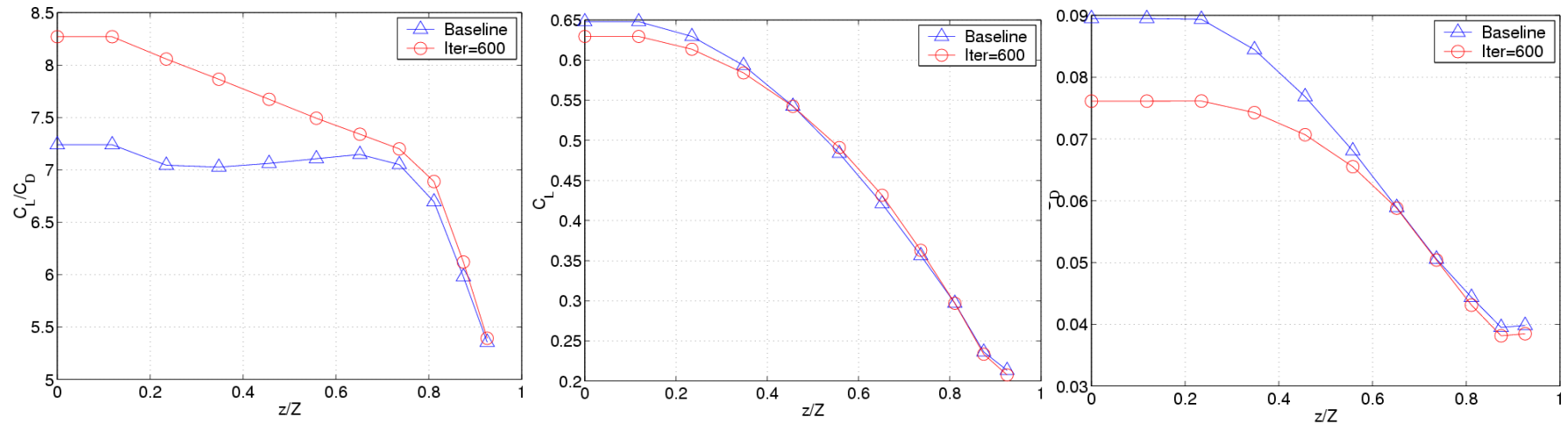
➤ Compared to the baseline, camber decreases near the root while increases near the tip.

➤ Overall, the camber is still higher at the root (4.8%) than at the tip (4%).

➤ In optimization we maintain angle of attack at 6° .

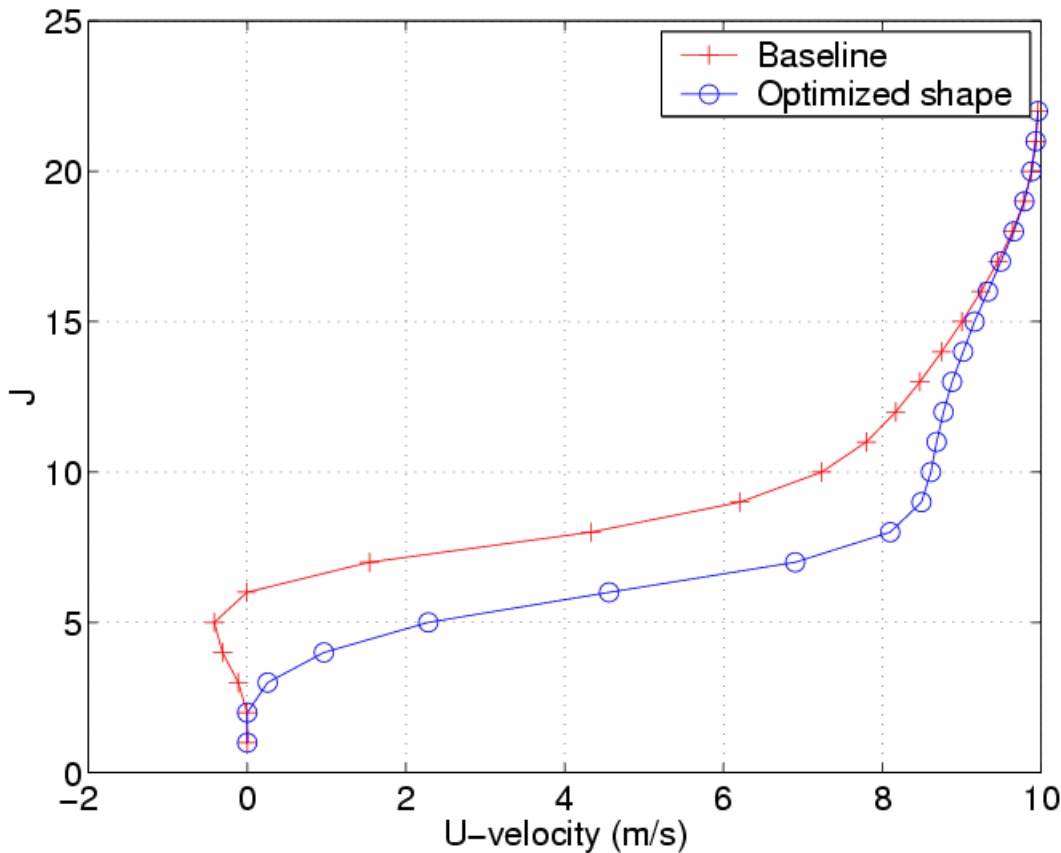


Spanwise Aerodynamics at Design Point: Rigid Wing at $\text{AoA}=6^\circ$



- Optimization can improve L/D .
- The improvement is largely located within 70% of the inner wing.
- Lift coefficient maintains the same even though camber reduces.
- The improvement is largely due to lower form drag.

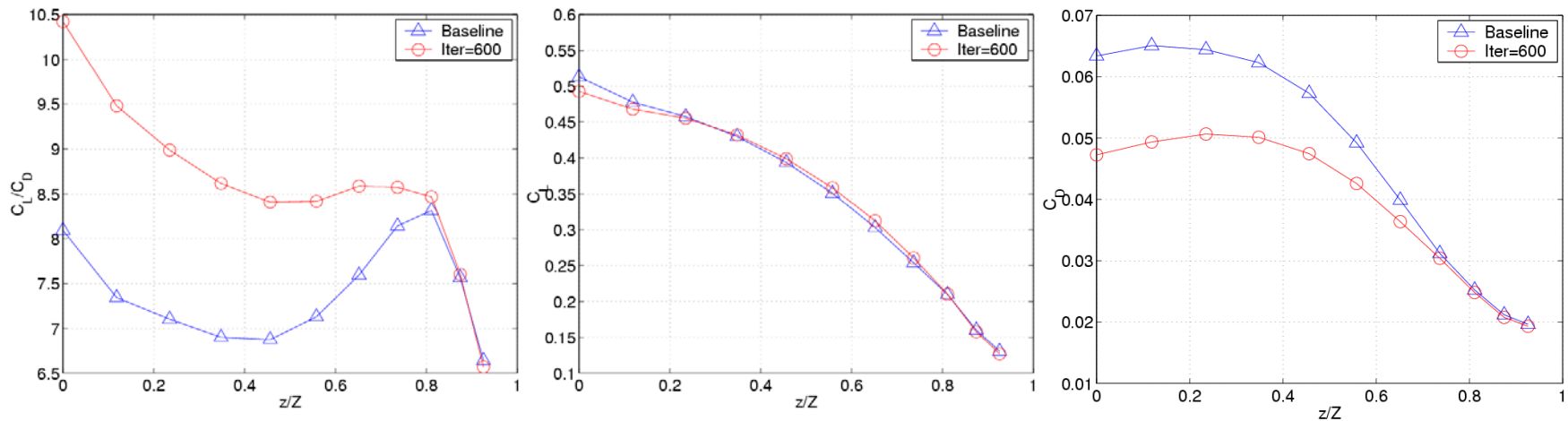
Velocity Profile Near Root: Rigid Wing



➤ $AoA=6^\circ$

➤ The optimized wing suppresses the flow separation.

Spanwise Aerodynamics at Off-Design Point: Rigid Wing at $AoA=3^\circ$

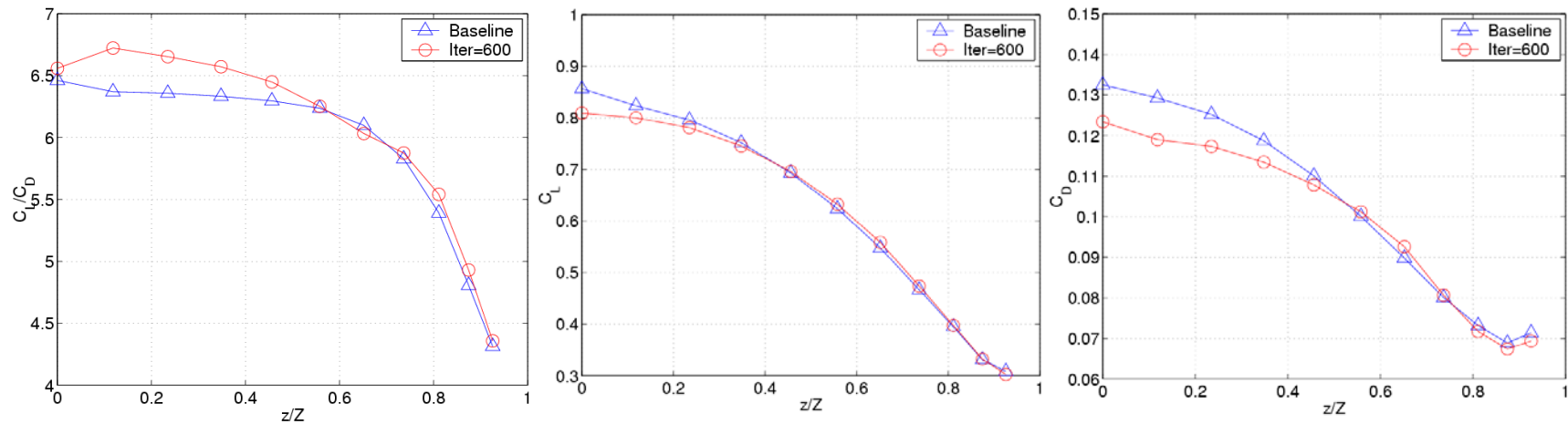


➤ The improvement is substantial at low AoA , and consistent with the design point, is largely located within 70% of the inner wing.

➤ Same as the design point, the lift maintains the same even though camber reduces, and the improvement is largely due to lower form drag.

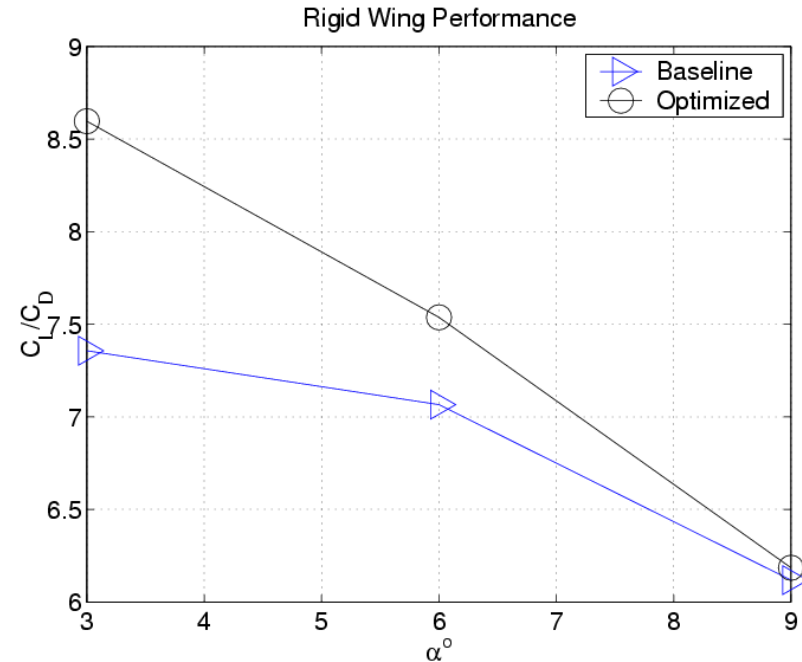
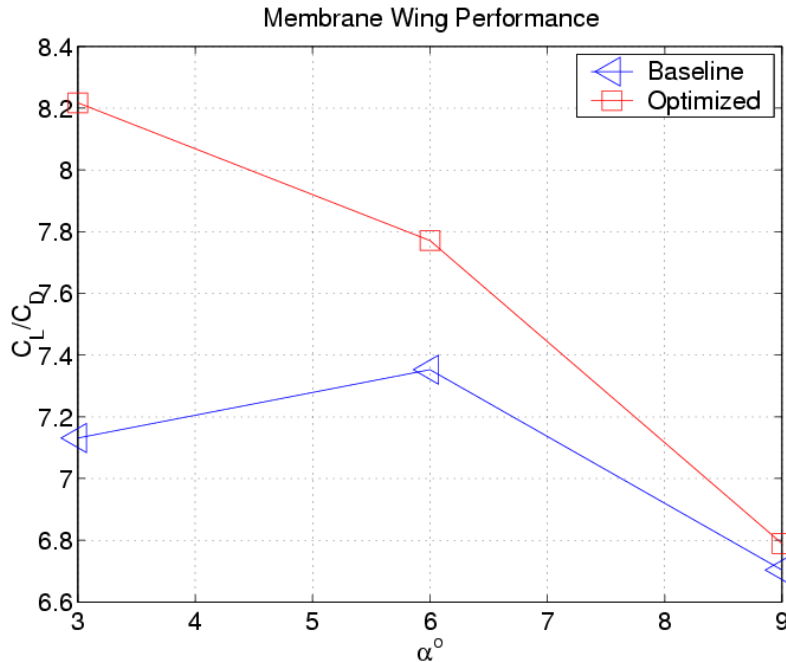


Spanwise Aerodynamics at Off-Design Point: Rigid Wing at $\text{AoA}=9^\circ$



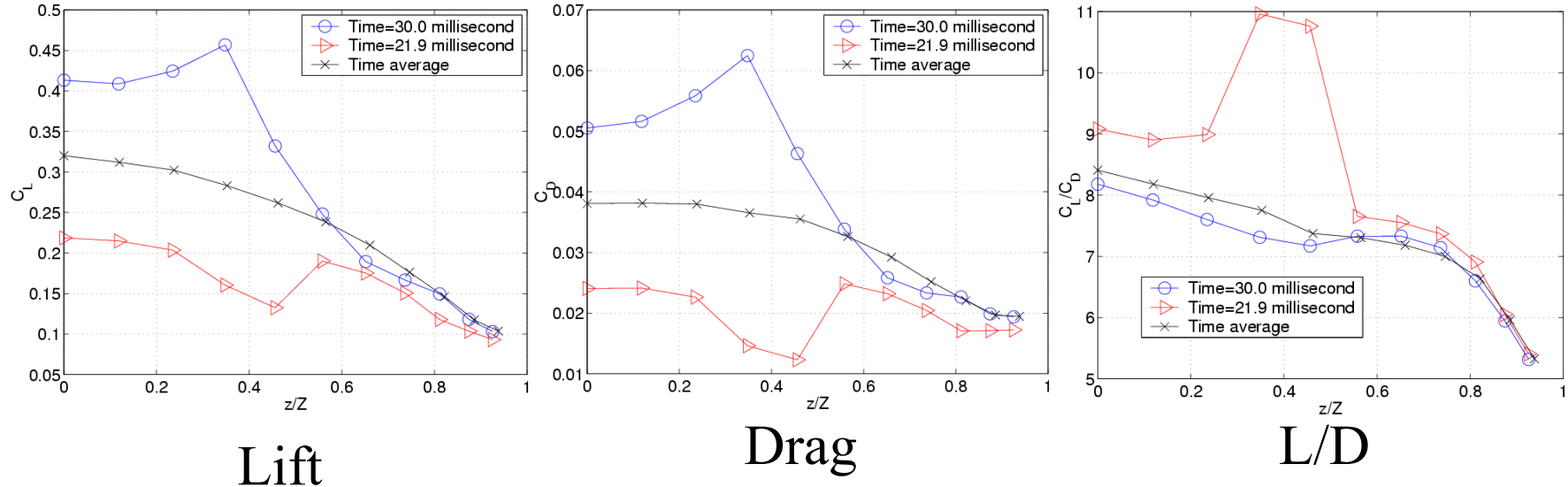
➤ At large AoA, improvement with the optimized shape diminishes.

Aerodynamics Between Membrane & Rigid Wings



- Optimized shape improves L/D consistently.
- Optimized membrane wing varies less in L/D versus AoA.

Optimized Membrane Wing at $AoA=6^\circ$



➤ While there seem substantial variations in time, the frequency (about 70Hz) is higher than that environmental fluctuation or vehicle response.

Outstanding Issues/Opportunities

- Optimized materials properties for passive flow control.
- Sensor and simplified aerodynamic model to facilitate autonomous flight control.
- Detailed wind tunnel measurements and numerical simulations to assess the unsteady flight environment.
- Efficient propulsion.