Adaptive Aeroelastic Wing Shape Optimization for High-Lift Configurations

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AGENDA

1. MOTIVATION
2. INTRODUCTION
3. FRAMEWORK
4. METHOD
5. RESULTS
6. FUTURE WORK
7. AKNOWLEDGEMENTS

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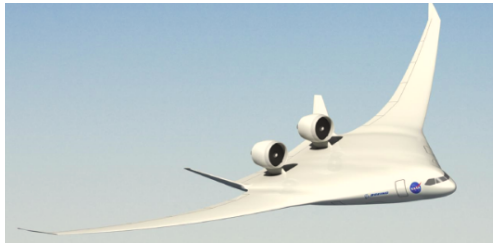
① MOTIVATION

- Global demands for more sustainable technologies ⇨ more energy-efficient airframes
- New generation aircraft concepts feature:
  - ✈ Better engine performance (quieter, cleaner)
  - ✈ Higher aerodynamic efficiency
  - ✈ Lighter materials (advanced composites)



THE CHALLENGES

- The use of composite materials increase airframe flexibility for same load capacity
- More flexible structures ⇨ can change aircraft optimal shape during flight

  ⇨ can degrade the aerodynamic efficiency
- Reduced rigidity can also ⇨ affect flight dynamic characteristics

  ⇨ reduce structural safety margins (flutter, etc)

① MOTIVATION

Example of flexibility of current composite aircraft

- Boeing 787 wing at 0-g load

Photo credits: YK , Kenneth Low (Airliners.net)

① MOTIVATION

Example of flexibility of current composite aircraft

- Boeing 787 wing at 1-g load

Photo credits: YK , Kenneth Low (Airliners.net)

12-ft wing tip deflection → ~12% of wing semispan

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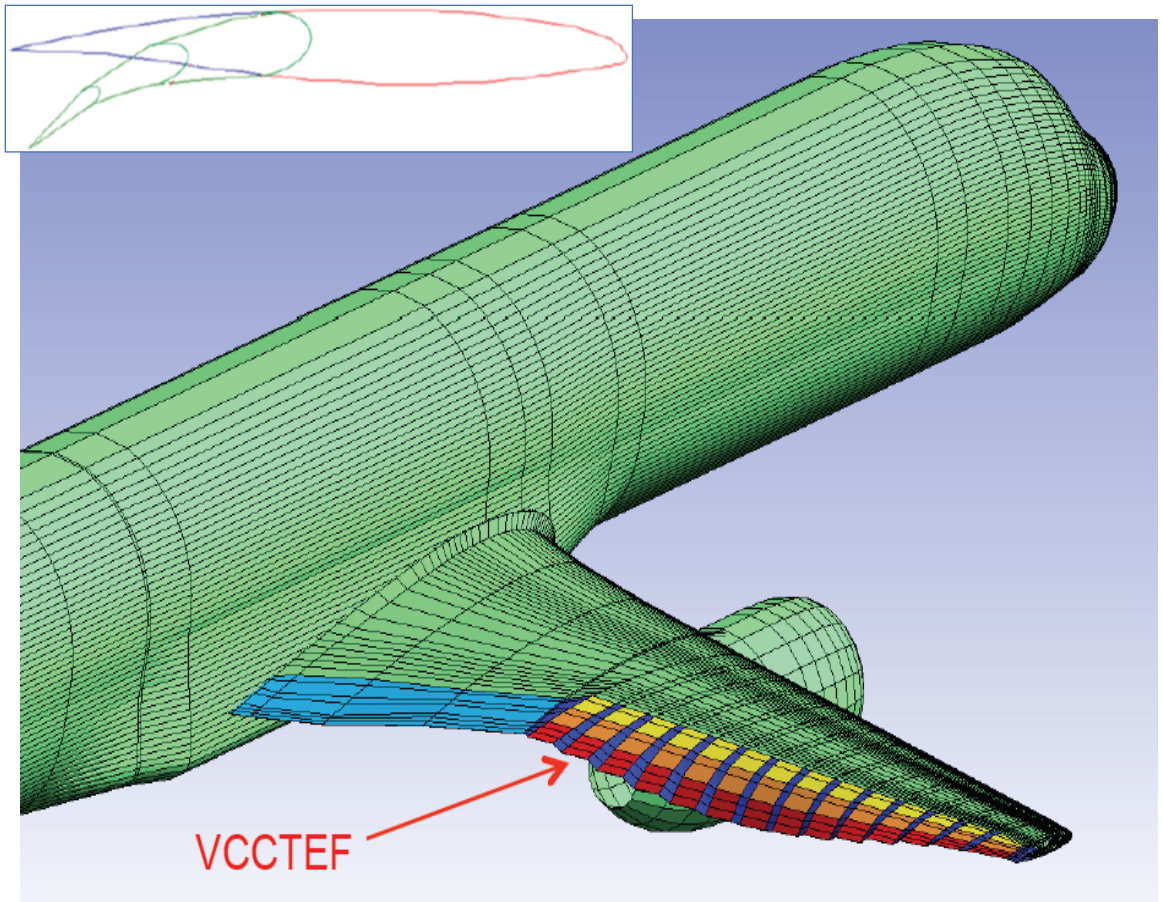
- A current research effort to address the aerodynamic efficiency/flight control issues of flexible wings:

  ⇨ Variable Camber Continuous Trailing-Edge Flap (VCCTEF)



Courtesy of The Boeing Co.

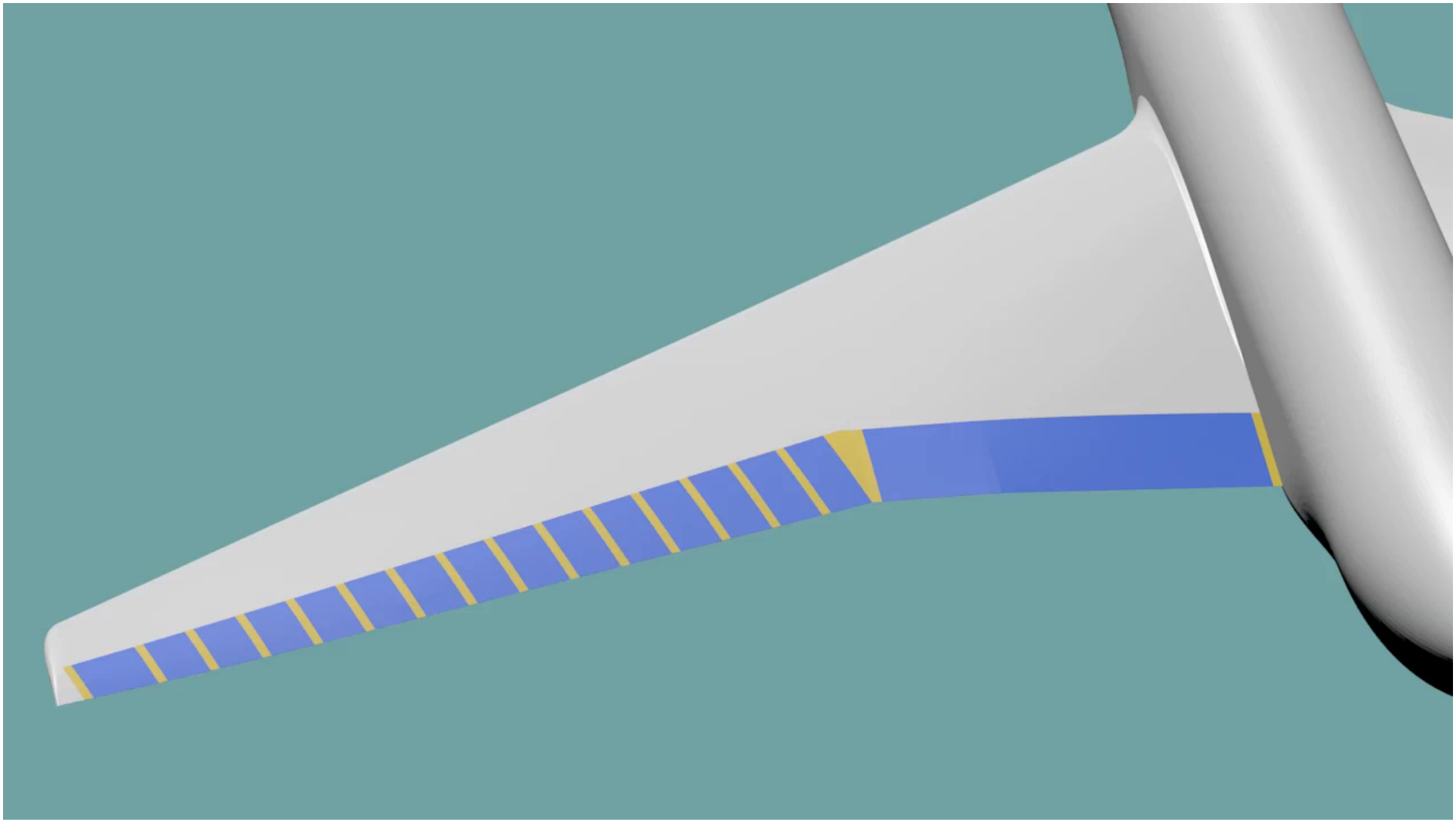
VCCTEF CONCEPT IDEA

⇨ Tailor the wing's spanwise load distribution

⇨ Aeroelastically re-adapt it back to the optimal shape, as conditions change during flight

②

VCCTEF Animation



Courtesy of Michael Aftosmis and David Rodriguez

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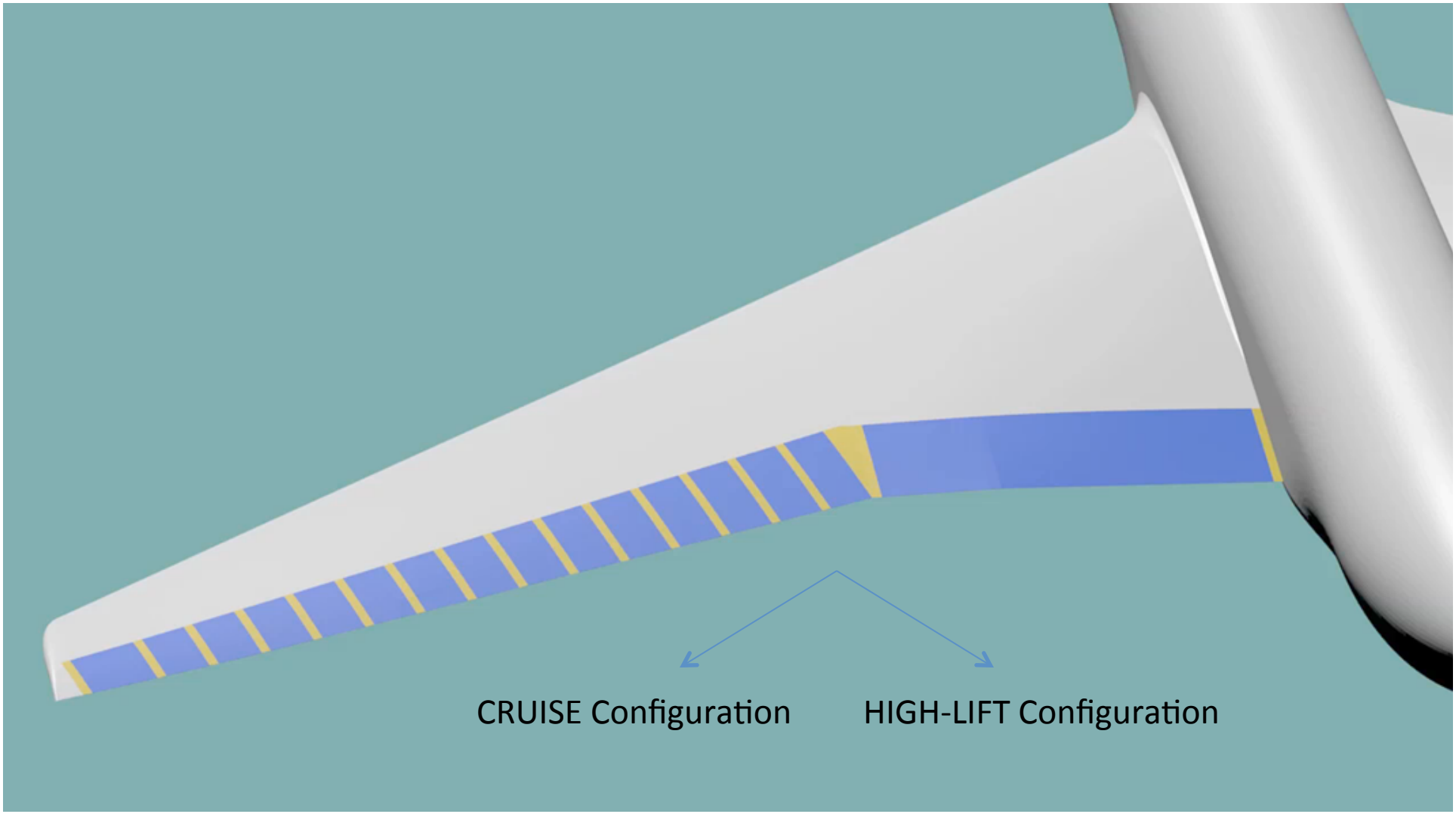
VCCTEF Animation



Courtesy of Michael Aftosmis and David Rodriguez

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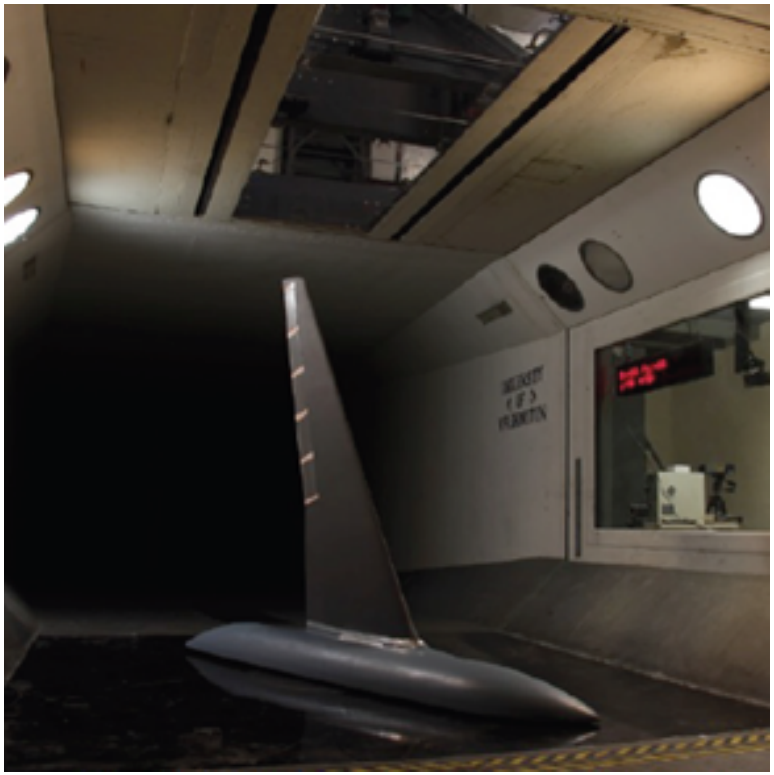
• Cruise Configuration Model

Computational Work in Drag Reduction Optimization ¥

- Sonia Lebofsky, Eric Ting, Nhan Nguyen (Vorview)
- Michael Aftosmis, David Rodriguez (Cart3D)



Courtesy of University of Washington

Experimental Work (Wind Tunnel Tests) *

- University of Washington (UW): Prof. Eli Livne, Nathan Precup
- Boeing: James Umes, Sr., Chester Nelson
- Model based on the Generic Transport Model (GTM) – B757 devised
- Designed to match flexibility of about 10% wing tip deflection

¥Lebofsky, S., Ting, E., Nguyen, N., "Aeroelastic Modeling and Drag Optimization of Aircraft Wing with Variable Camber Continuous Trailing Edge Flap", AIAA Aviation 2014, 32nd AIAA Applied Aerodynamics Conference

*Nguyen, N., Precup, N., Umes, J., Nelson, C., Lebofsky, S., Ting, E., Livne, E., "Experimental Investigation of a Flexible Wing with a Variable Camber Continuous Trailing Edge Flap Design", AIAA Aviation 2014, 32nd AIAA Applied Aerodynamics Conference

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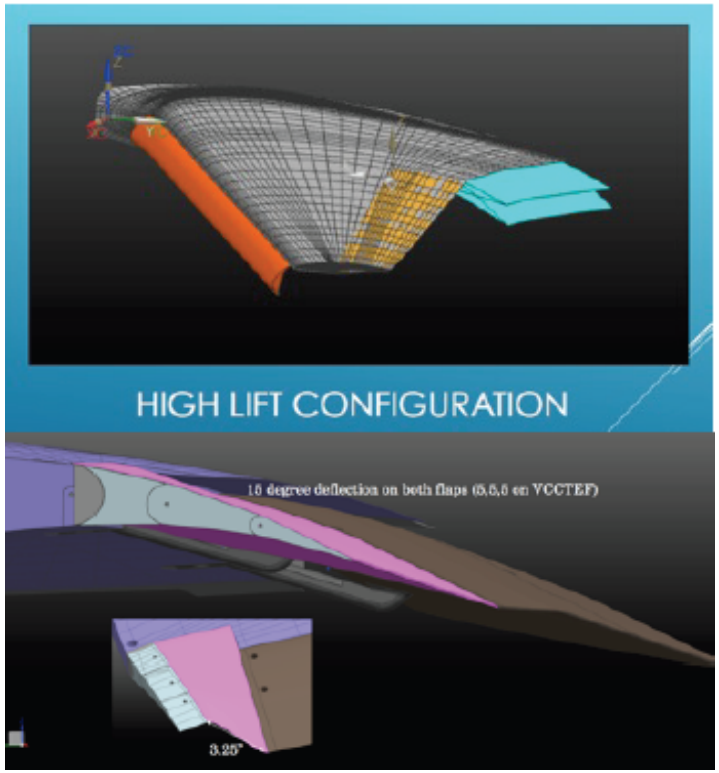
• High-Lift Configuration Model



Courtesy of University of Washington

Computational Optimization Framework

- Currently under development at NASA Ames
- Michael Aftosmis, David Rodriguez – OVERFLOW
- Challenges:

Grid deformation tool (surface/volume meshes)
Computational cost ro run RANS solvers

Experimental Work (Wind Tunnel Tests)

-UW: Prof. Eli Livne, Nathan Precup
- Currently being tested
- Includes a variable camber Krueger (VCK) Flap
- Single element slotted inboard flap
- 3-chordwise-segment VCCTEF elsewhere

②

- High-Lift Configuration Model

Courtesy of University of Washington

②

• Objective

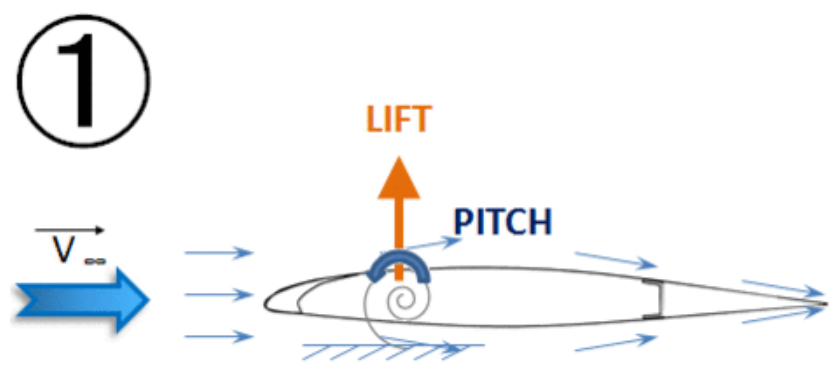
Develop an aeroelastic framework ⇨ quick turnaround multidisciplinary optimization of a flexible wing with variable camber continuous trailing edge flap (VCCTEF) for high-lift configurations (takeoff and landing)

• Potential Modeling Complications

➢ Optimizing flexible wings for high-lift can be counterintuitive

➢Flap deflections increase not only the loads but also the nose-down pitching moment

➢ Nose-down moment loads tend to twist the wing downwards, thereby decreasing angle of attack and lift (similar to control reversal)



• Requirements

- Develop a low-fidelity 3D aerodynamic code capable of handling stall characteristics (Cl, Cm)
- Couple structural code to calculate static wing deflection
- Allow fast computation for optimization purposes

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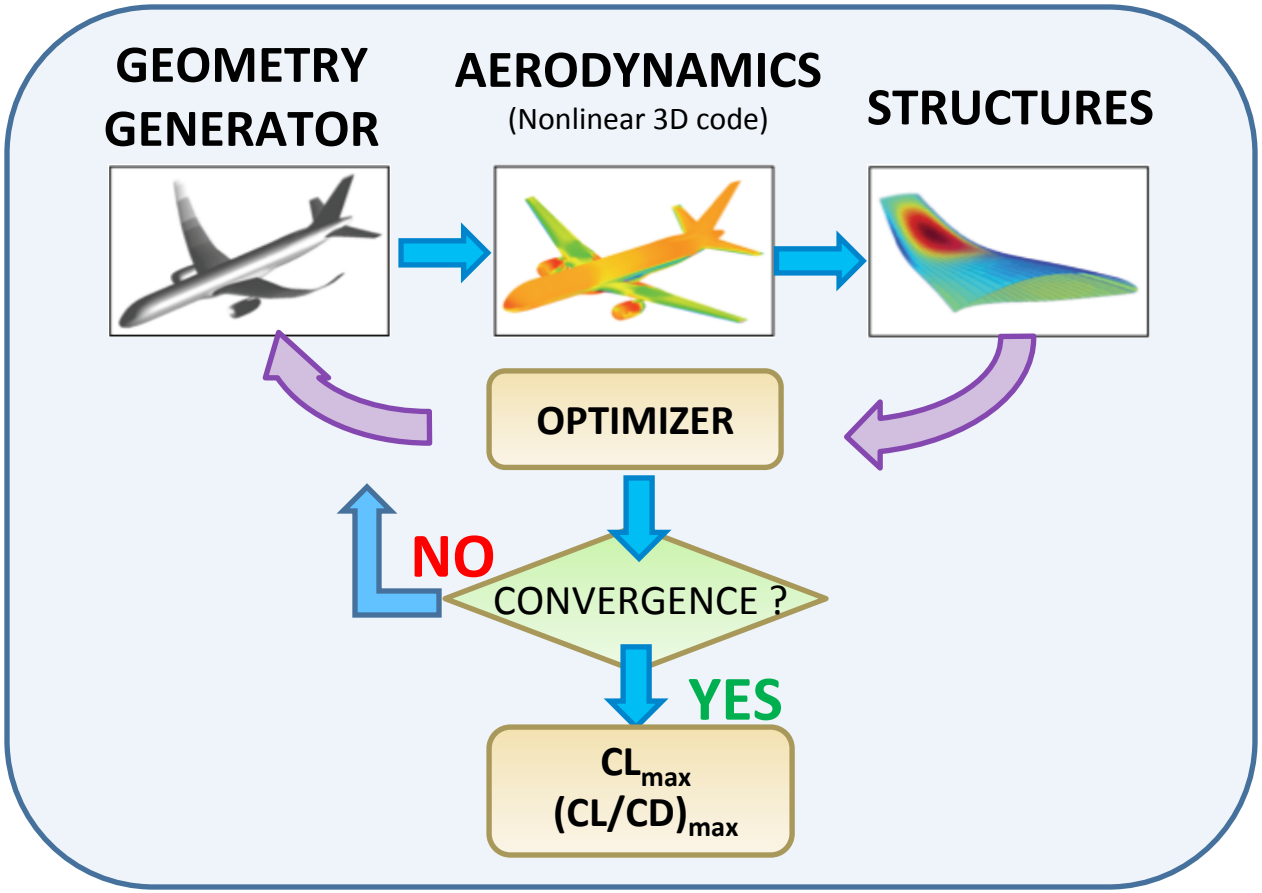
③ FRAMEWORK

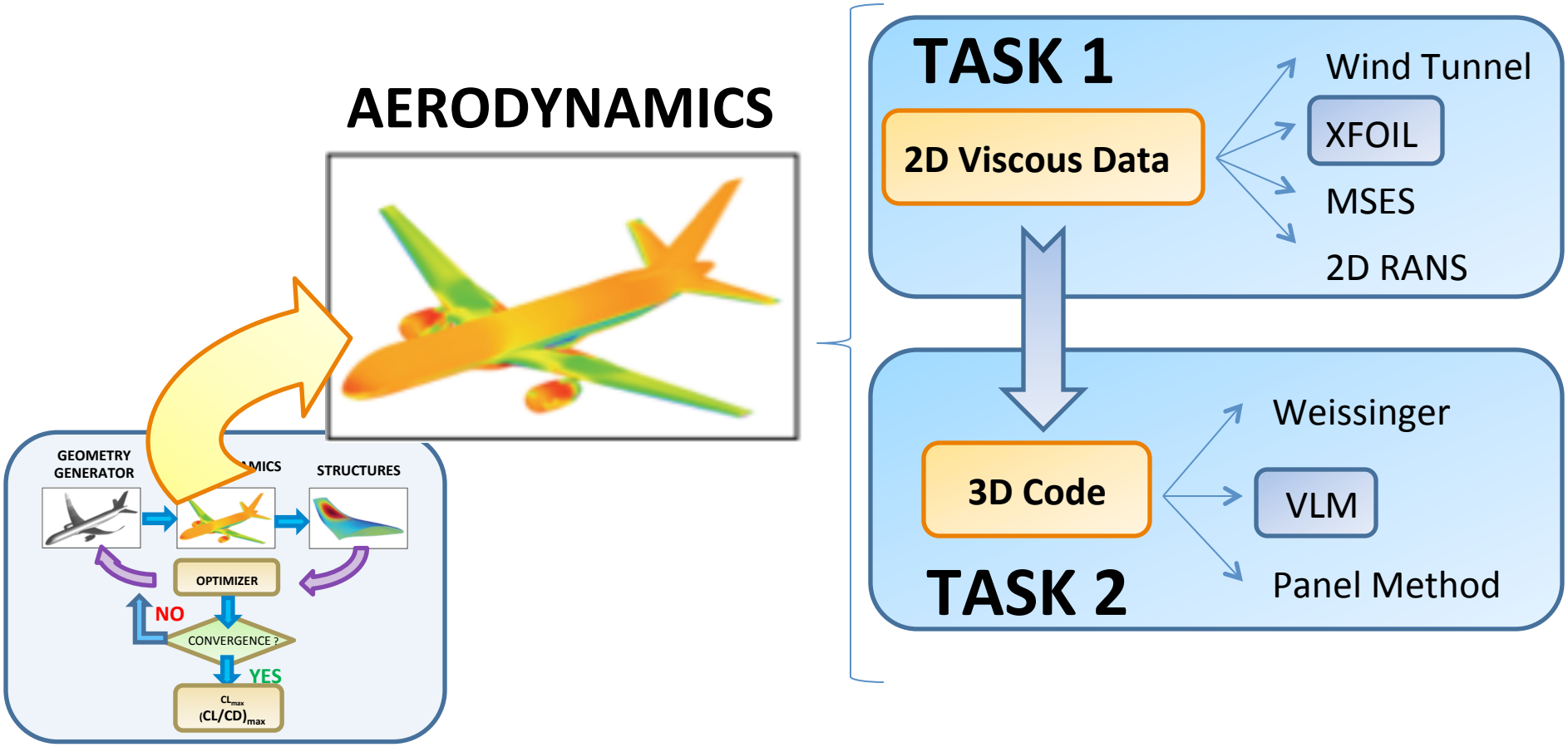
Multidisciplinary Optimization Framework Strategy:

- Coupled aerodynamics/structures
- Static aeroelastic calculations
- Optimizes flap deflection schedule for:
  - CL_{max}, or
  - $(CL/CD)_{max}$



③ FRAMEWORK

Low-fidelity aerodynamic code structure:



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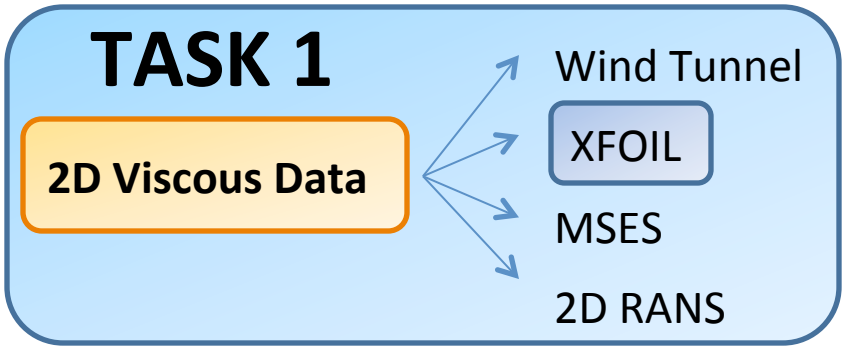
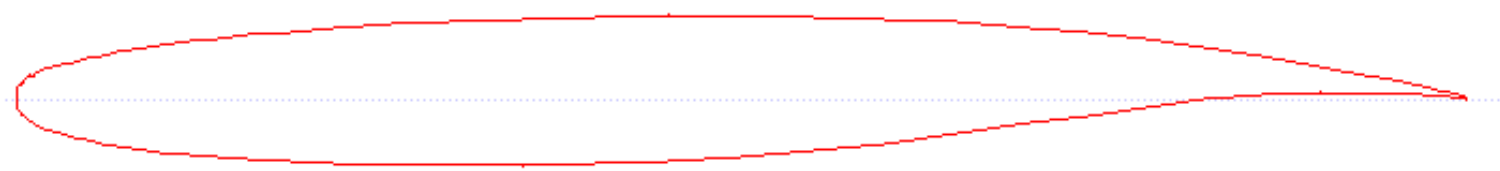


2D solver to obtain sectional viscous data (XFOIL)

- Baseline Airfoil example: 'bacj.dat' (supercritical) publicly available at UIUC – Airfoil Database

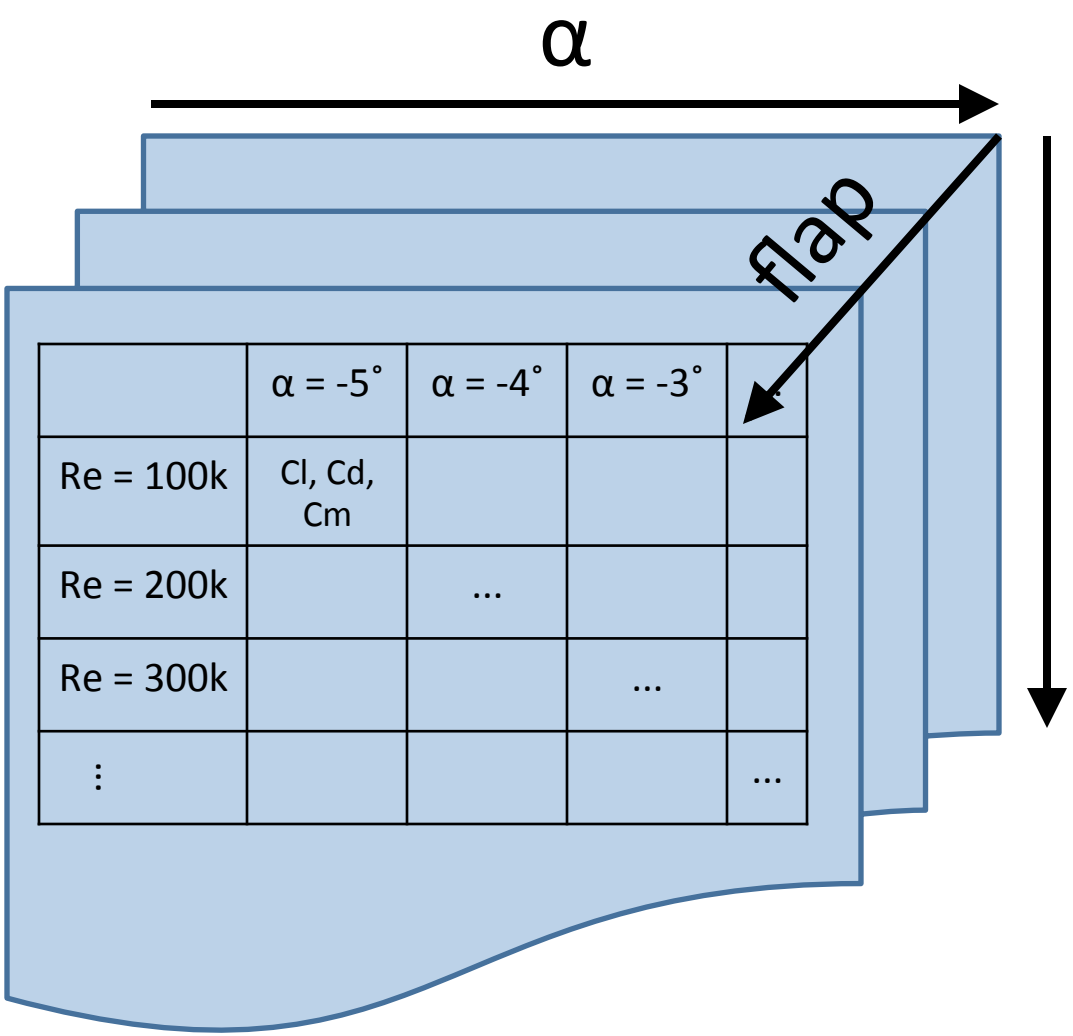


```
%BOEING AIRFOIL J
Thickness          =  10.07%
Max. Thick.pos.    =  40.00%
Max. Camber        =   1.73%
Max. Camber pos.   =  78.00%
Number of Panels   =  99
```

④ METHOD

TASK 1 2D Viscous Data → XFOIL

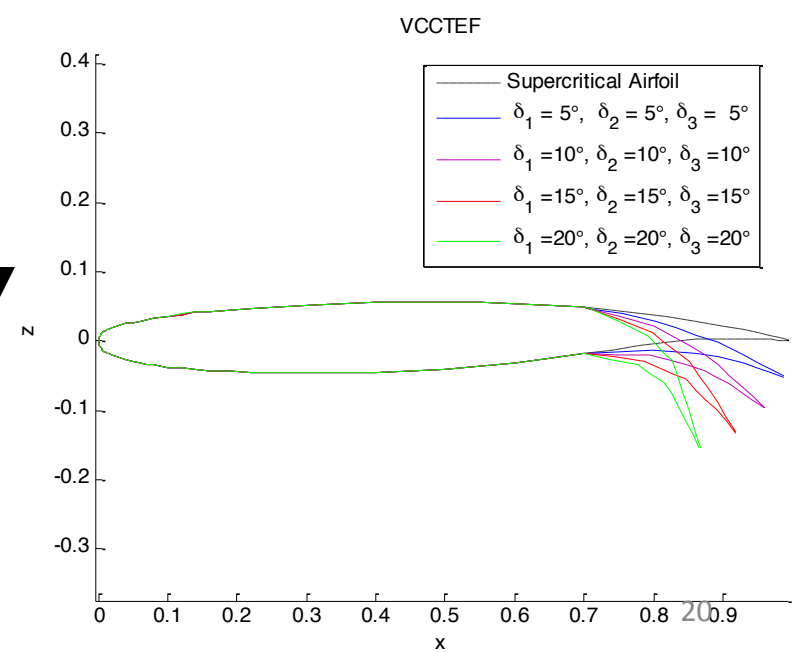
- Build a 2D Viscous Aerodynamic Data Bank



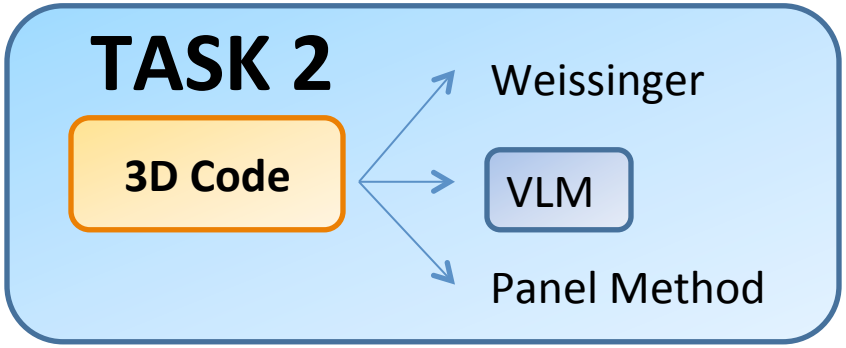
	α = -5˚	α = -4˚	α = -3˚	…
Re = 100k	Cl, Cd, Cm			
Re = 200k		…		
Re = 300k			…	
⋮				…

Offline Calculations - XFOIL

- Re = 100k - 1.1M (UWAL model, chords)
- AoA = -5˚ – 25˚ (Cl, Cd, Cm)

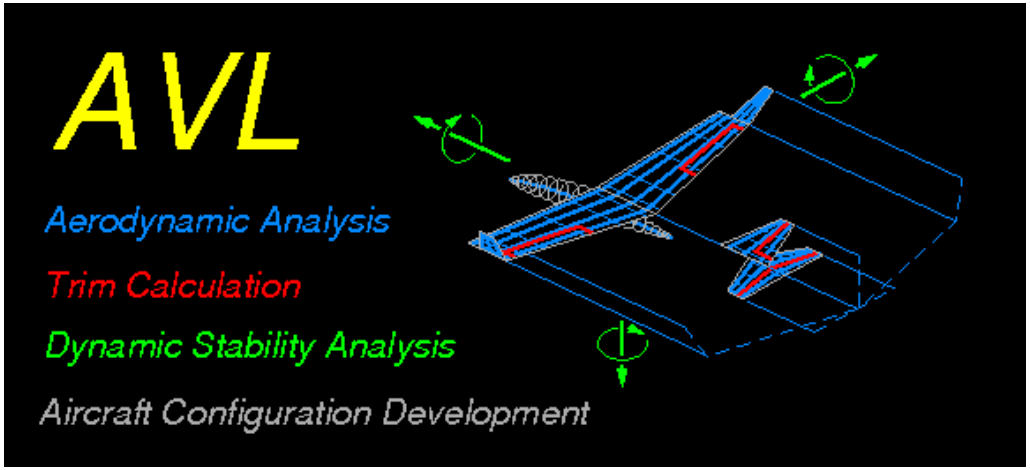


④ METHOD



Vortex Lattice Method code chosen

- AVL – Athena Vortex Lattice*
- Publicly available (open source)
- Validated



*Mark Drela, Harold Youngreen – MIT
Based on the classic work of Lamar (NASA codes), E. Lan and L. Miranda (VORLAX)

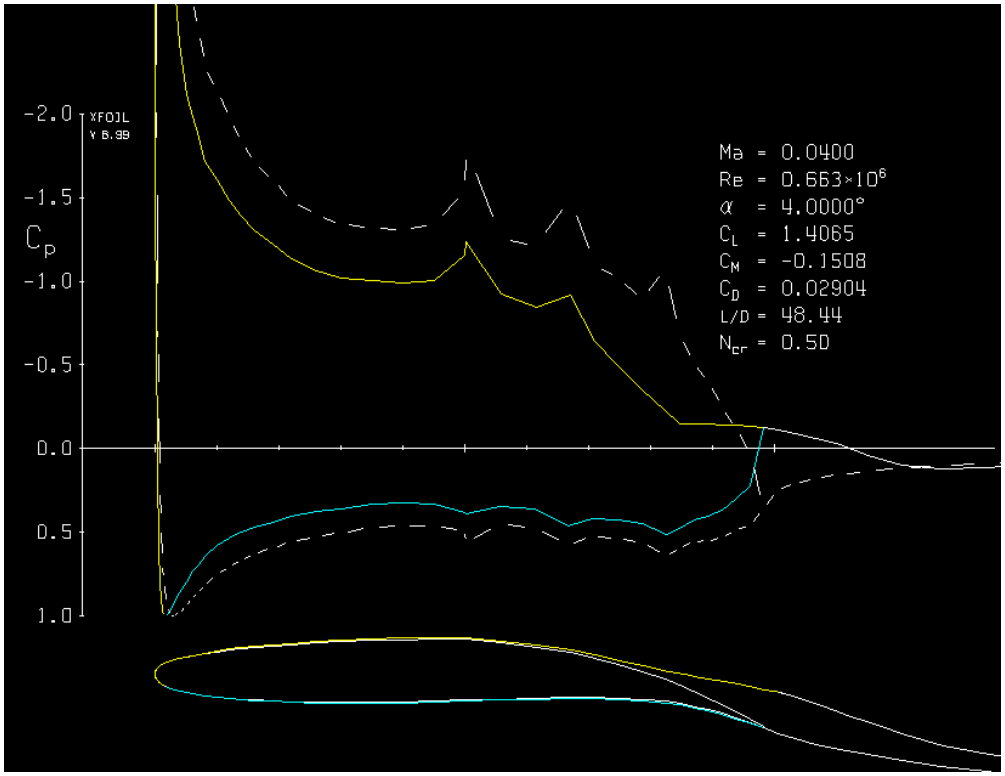
Nonlinear Vortex Lattice Method

- Lower computational cost and lower fidelity compared to a Navier-Stokes solver
- Iteratively changes wing's local incidence/camber to match Cl/C_m from 2D viscous data

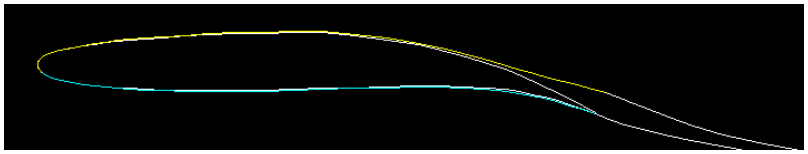
Decambering Method Inspiration

- XFOIL – Boundary Layer Thickness Growth

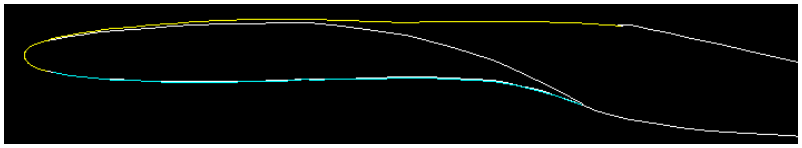
α = 4˚



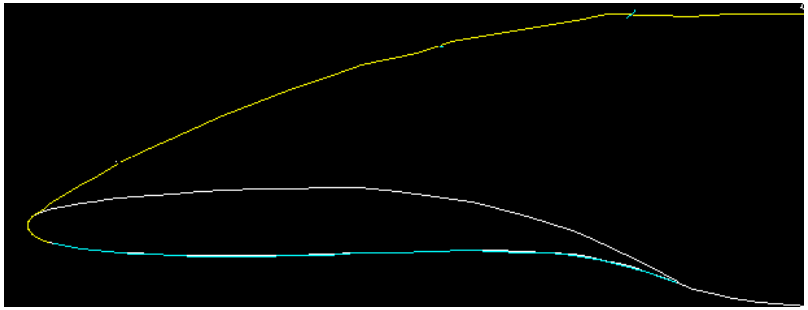
α = 0˚



α = 12˚



α = 18˚



④ METHOD

TASK 2 3D Code → VLM

DETAILS: THE DECAMBERING APPROACH

1) Input Aircraft Geometry and Run AVL (Linear VLM code)
2) Get Cl, C_m and downwash angles (ω) along span
3) For each station (strip) calculate local α_{eff}
4) Calculate gradients/sensitivities (Jacobian):
   - ∂ Cl in each station i due to incidence (δ_1) perturbation p at station j
   - ∂ C_m in each station i due to incidence (δ_1) perturbation p at station j
   - ∂ Cl in each station i due to camber (δ_2) perturbation p at station j
   - ∂ C_m in each station i due to camber (δ_2) perturbation p at station j

$$J = \begin{pmatrix} J_{l1} & J_{l2} \\ J_{m1} & J_{m2} \end{pmatrix}$$

$$(J_{l1})_{i,j} = \frac{\partial \Delta C_{l_i}}{\partial \delta_{1,j}} \qquad (J_{l2})_{i,j} = \frac{\partial \Delta C_{l_i}}{\partial \delta_{2,j}}$$

$$(J_{m1})_{i,j} = \frac{\partial \Delta C_{m_i}}{\partial \delta_{1,j}} \qquad (J_{m2})_{i,j} = \frac{\partial \Delta C_{m_i}}{\partial \delta_{2,j}}$$

5) Multivariable Newton-Raphson Iteration to compute δ_1 and δ_2

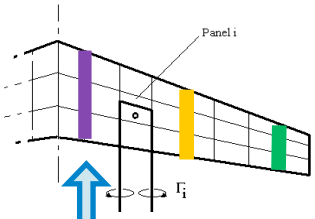
$$J \quad . \quad \delta x = -F$$

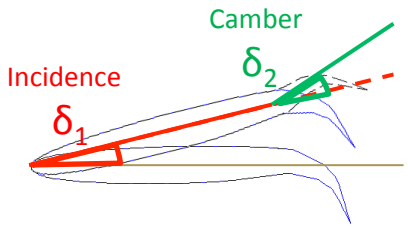
6) Change incidence δ_1 and camber δ_2 in each station and rerun

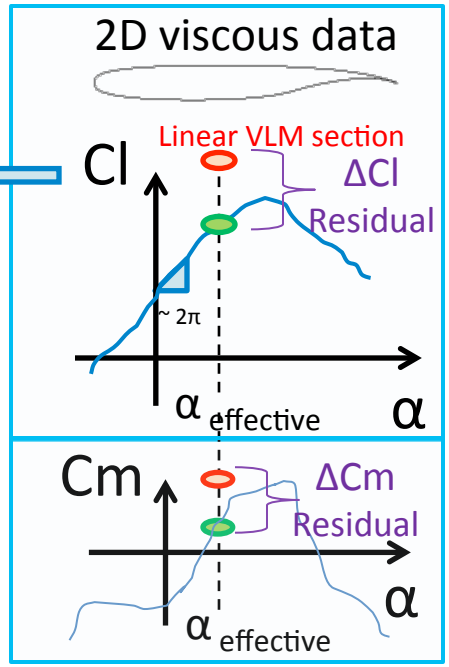
STOP CRITERION

$$| \, Cl_{(section)} - Cl_{2D\ Visc}(\alpha_{eff}) \, | < 0.001$$

$$| \, C_m(section) - C_{m\ 2D\ Visc}(\alpha_{eff}) \, | < 0.001$$



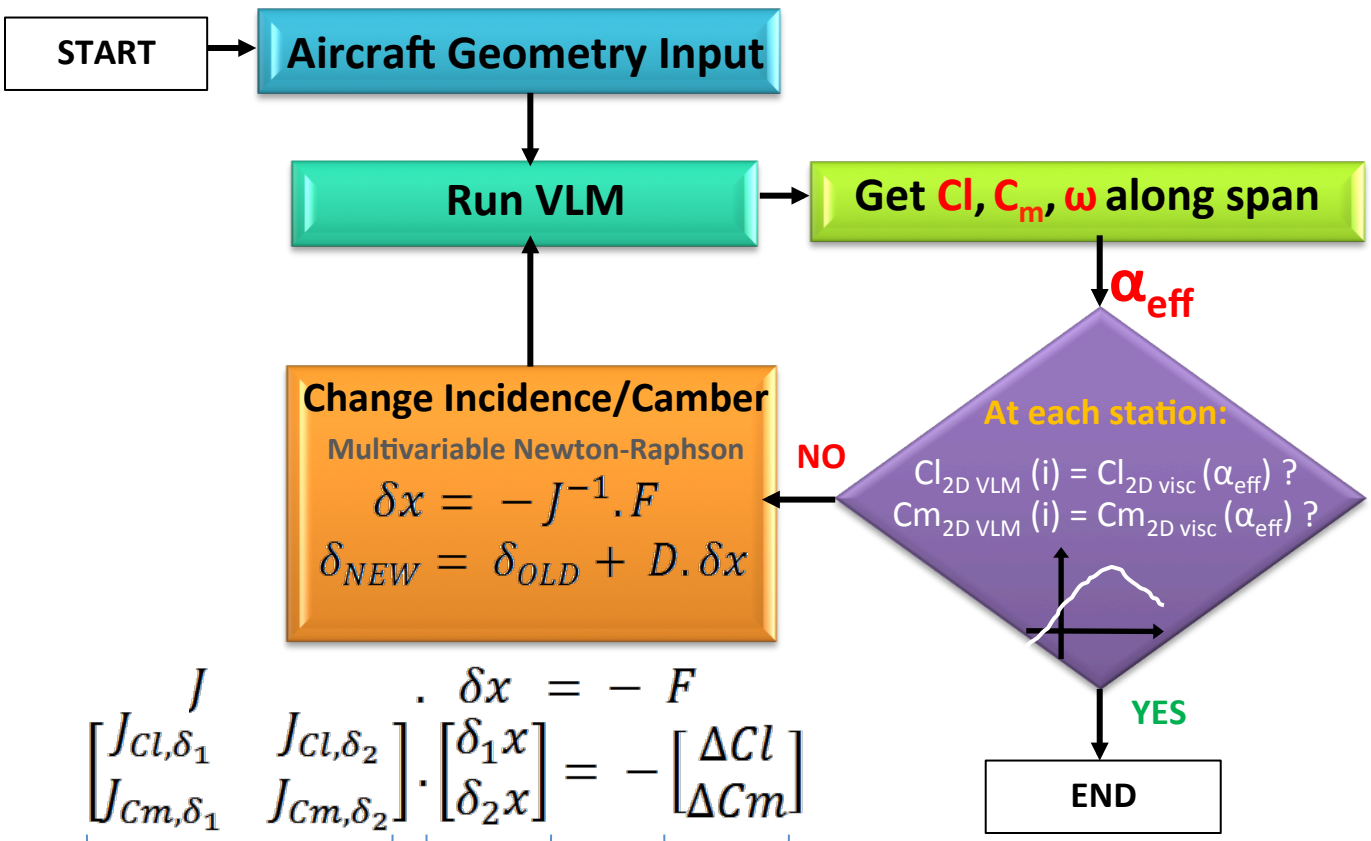




2003 – Funded by NASA Langley – North Carolina State University

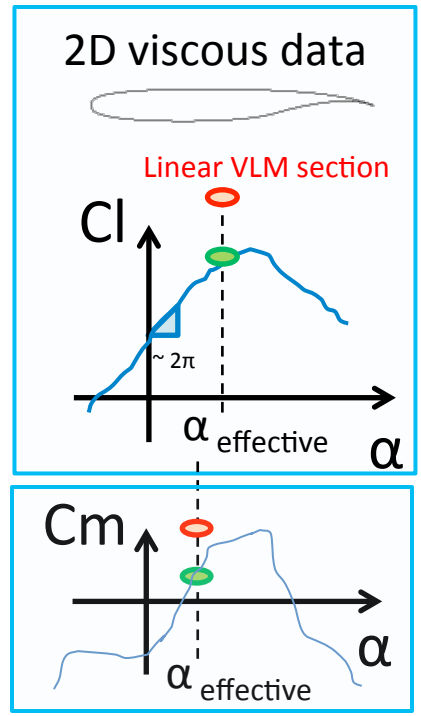
*Mukherjee, R., Gopalarathnam, A., Kim. S., "AN ITERATIVE DECAMBERING APPROACH FOR POST-STALL PREDICTION OF WING CHARACTERISTICS USING KNOWN SECTION DATA", AIAA 2003, 41st AIAA Aerospace Sciences Meeting

DETAILS: THE DECAMBERING APPROACH



$$\underbrace{\begin{bmatrix} J_{Cl,\delta_1} & J_{Cl,\delta_2} \\ J_{Cm,\delta_1} & J_{Cm,\delta_2} \end{bmatrix}}_{\text{Jacobian Matrix (Gradients/Sensitivities)}} \cdot \underbrace{\begin{bmatrix} \delta_1 x \\ \delta_2 x \end{bmatrix}}_{\text{Incidence/ Camber Corrections}} = -\underbrace{\begin{bmatrix} \Delta Cl \\ \Delta Cm \end{bmatrix}}_{\text{Residuals (ERROR)}}$$

$$J \cdot \delta x = -F$$

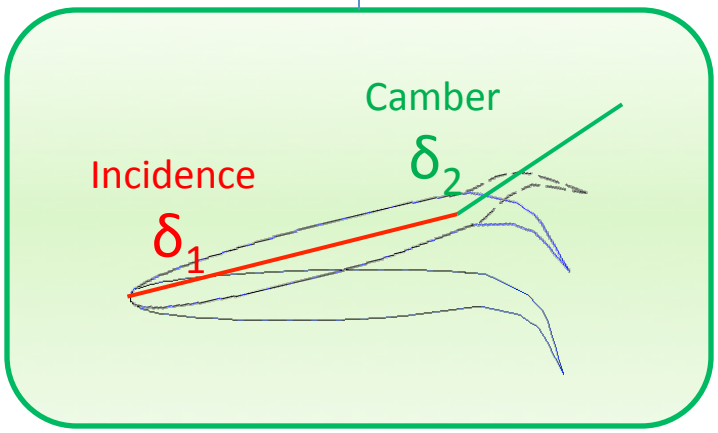


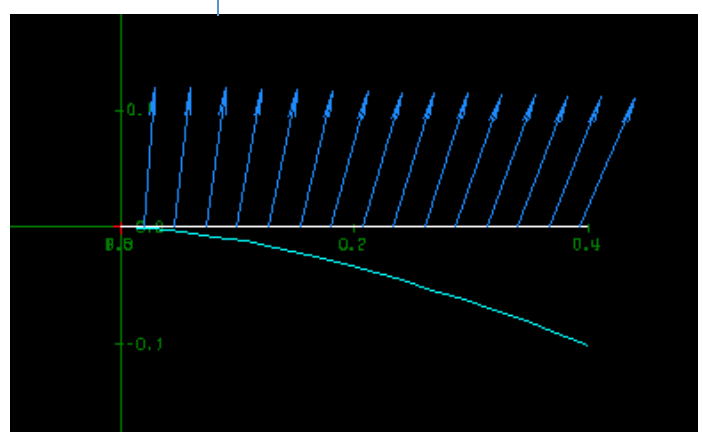
*Mukherjee, R., Gopalarathnam, A., Kim. S., "AN ITERATIVE DECAMBERING APPROACH FOR POST-STALL PREDICTION OF WING CHARACTERISTICS USING KNOWN SECTION DATA", AIAA 2003, 41st AIAA Aerospace Sciences Meeting

For Improved Efficiency…

- All decambering variables can be dealt with using the RHS only
- Avoid matrix inversion every iteration

$$[AIC][\Gamma] = [V_{\infty}.n + V_{ind\perp}]$$





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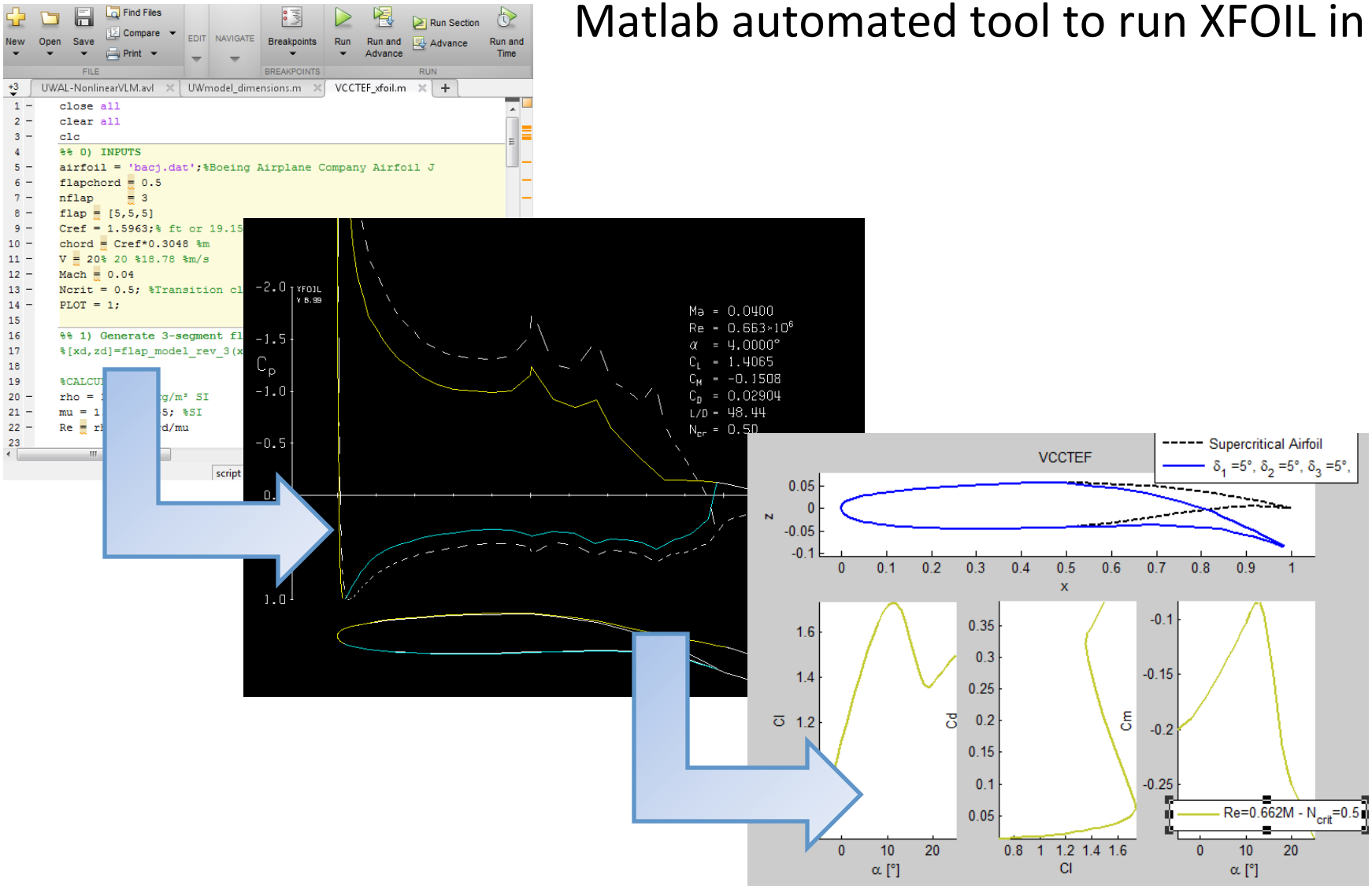
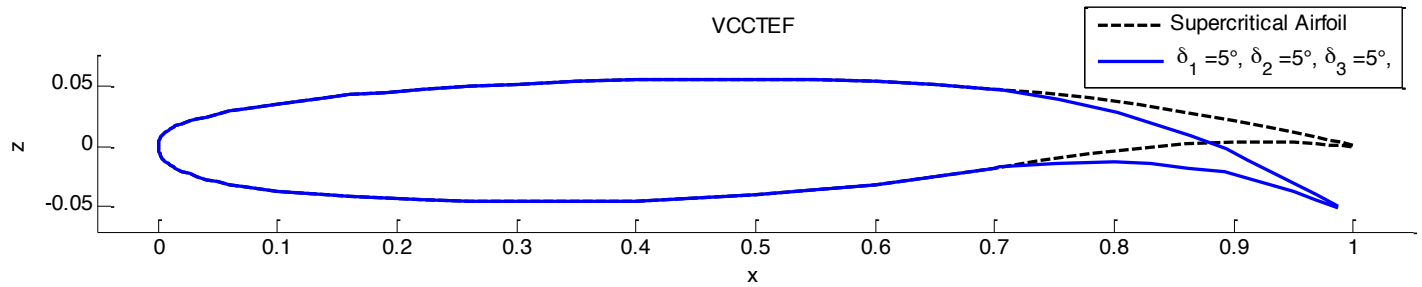
5 RESULTS

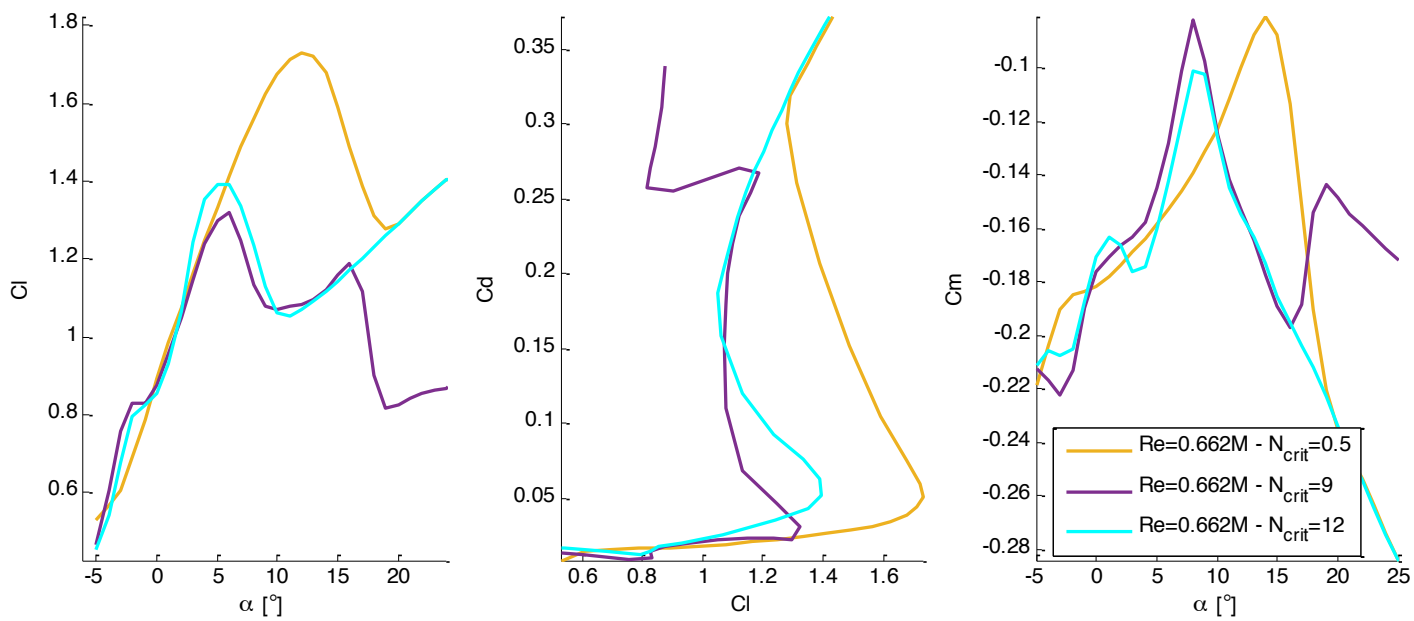
TASK 1 2D Viscous Data → XFOIL

Matlab automated tool to run XFOIL in Batch



Effect of Boundary Layer Transition – $N_{critical}$ Method

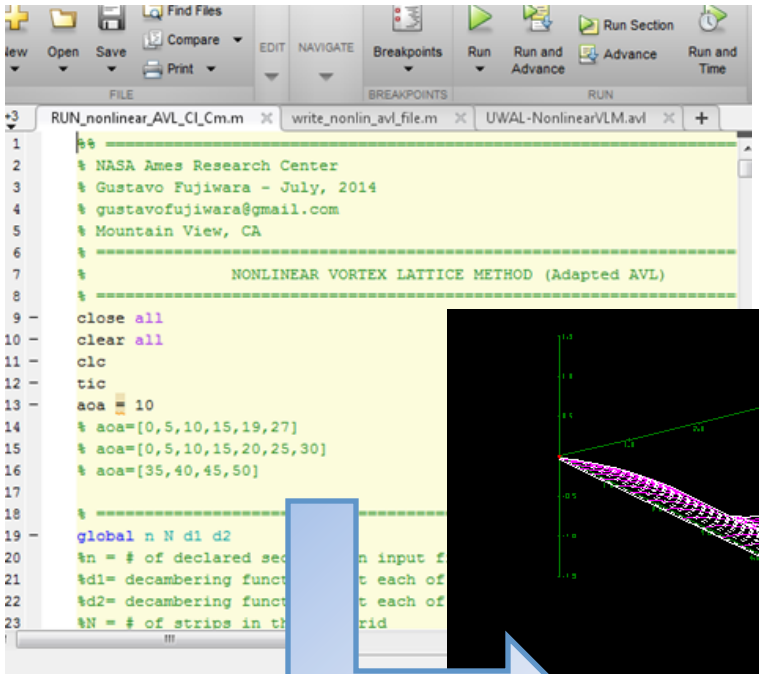


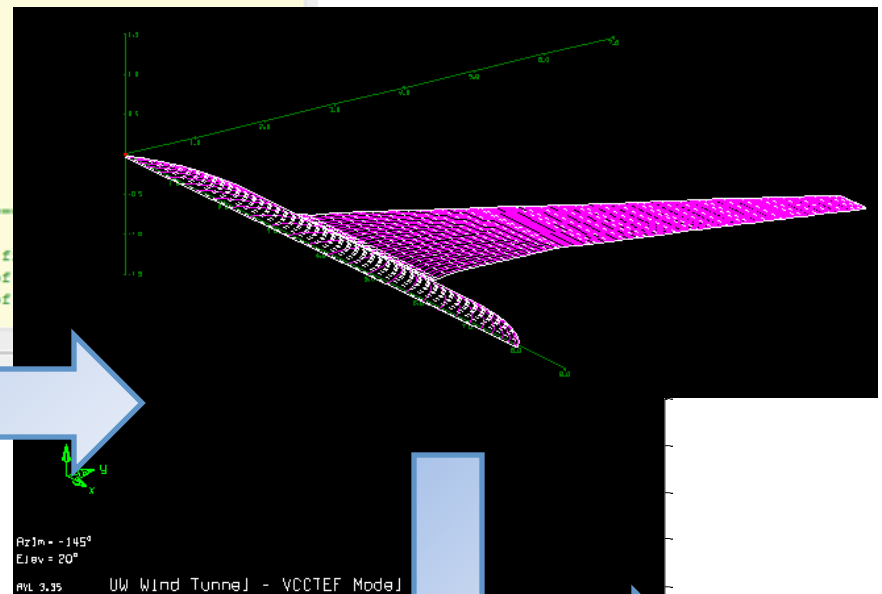


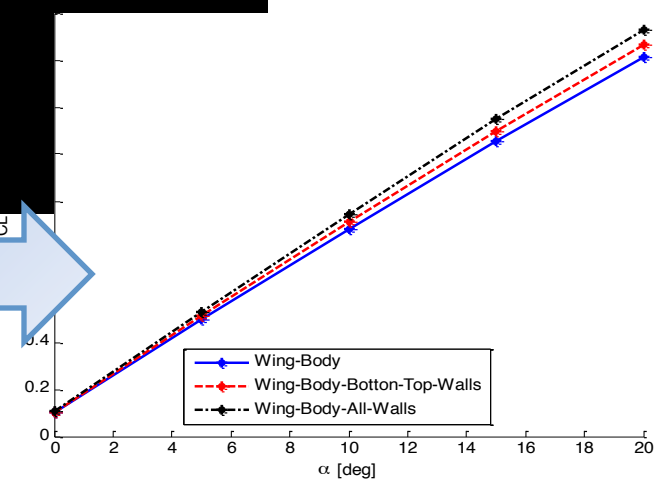
⑤ RESULTS

TASK 2 3D Code → VLM

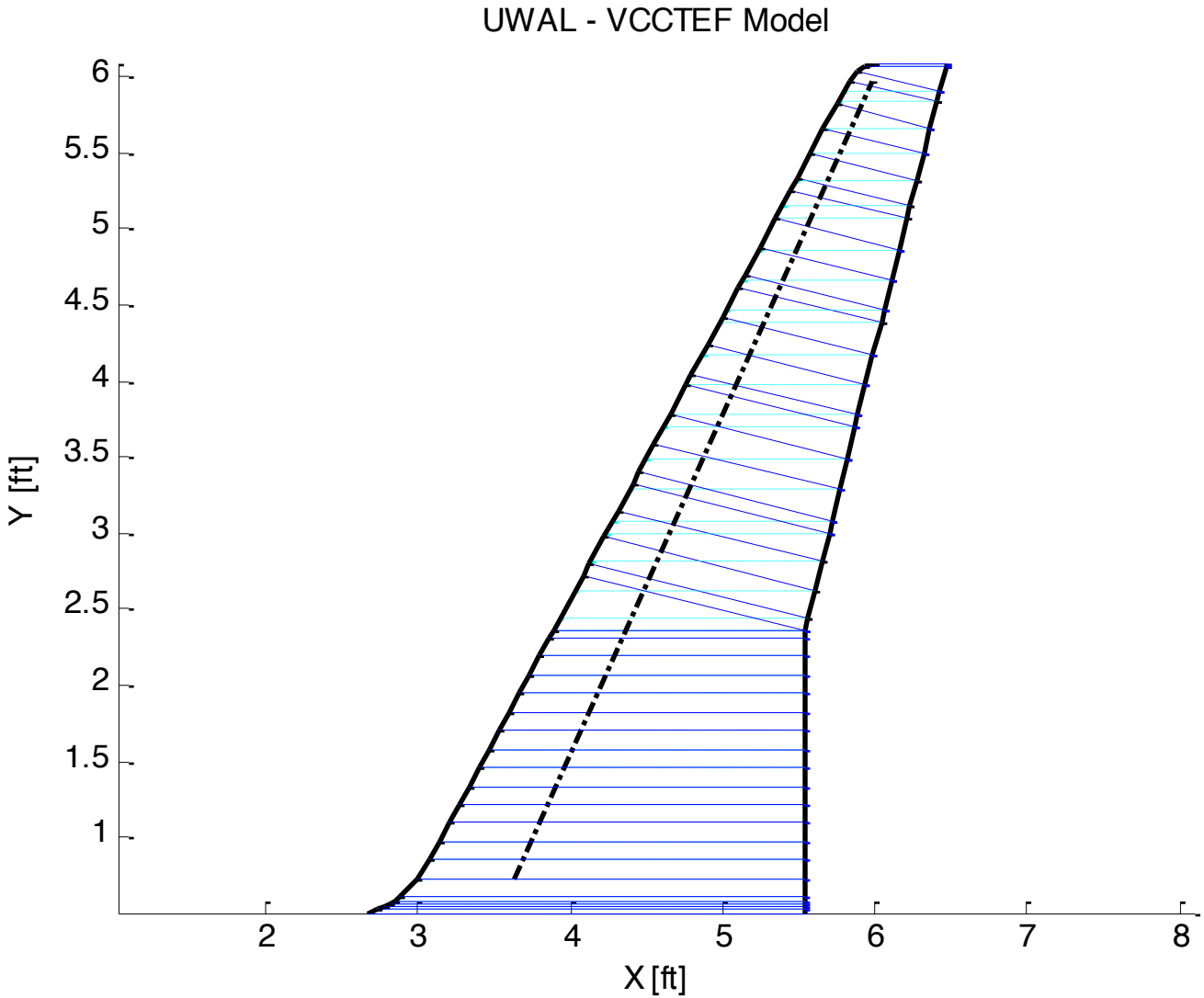
Matlab automated tool to run AVL



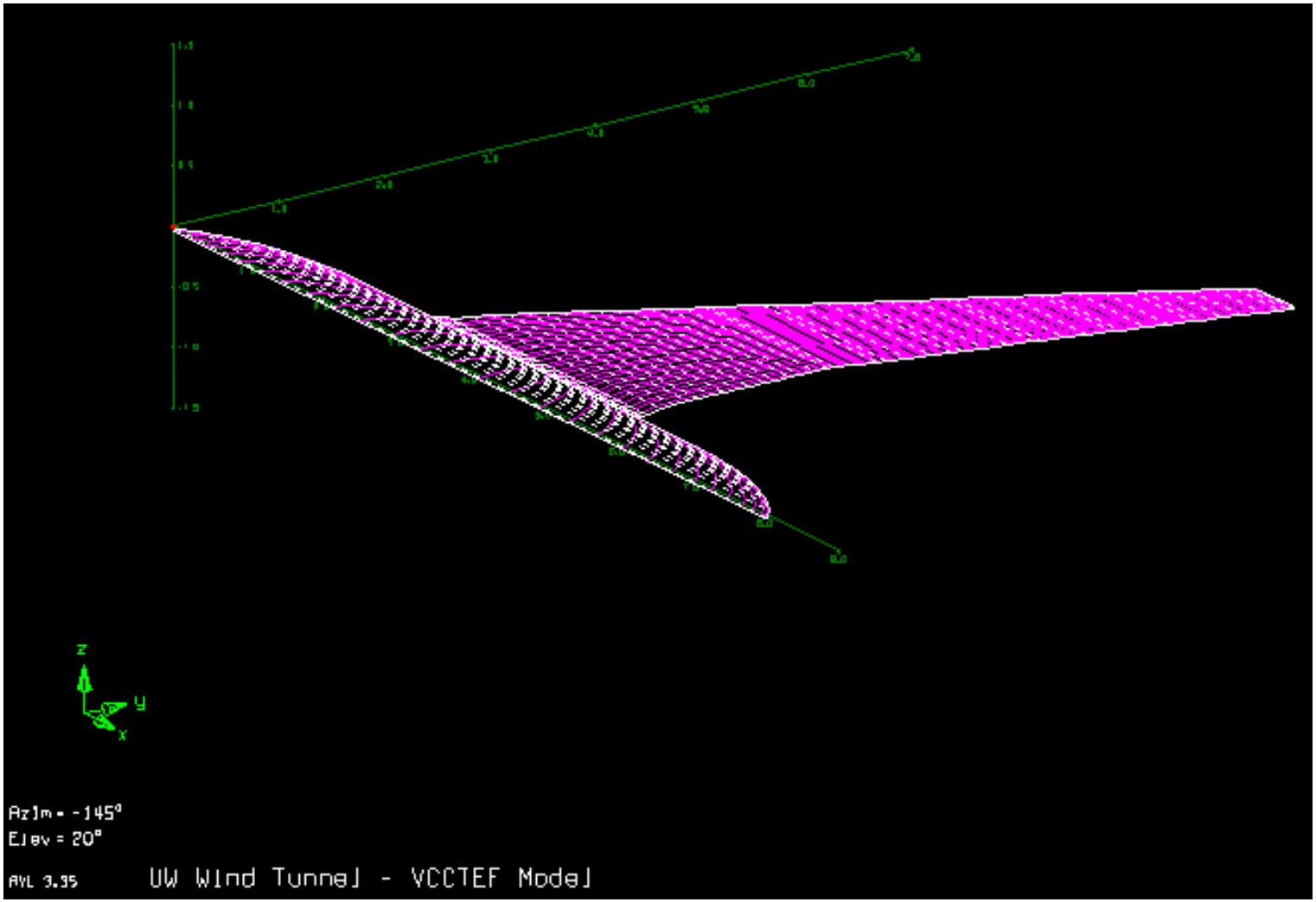




Streamwise Cuts Conversion



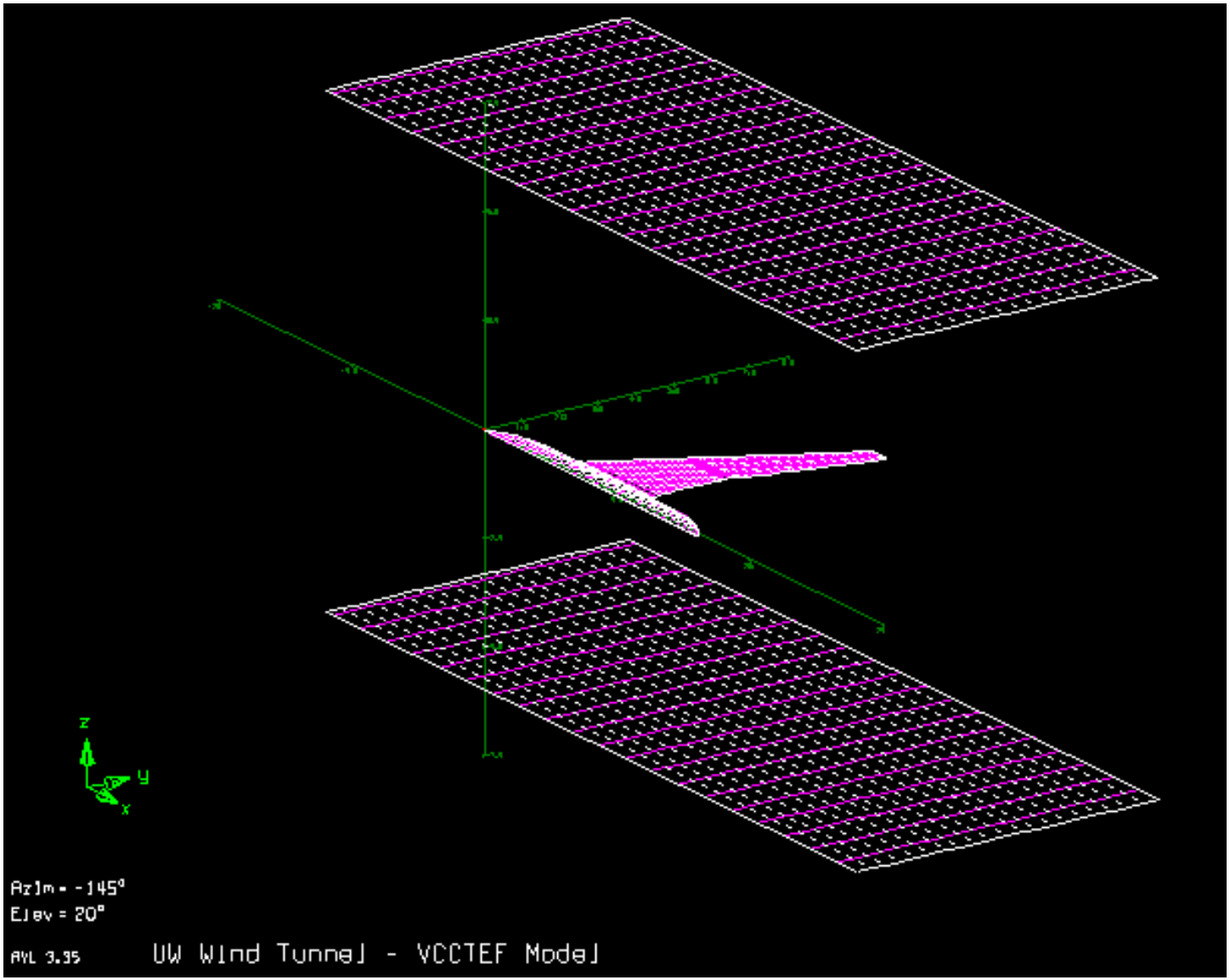
Half Wing-Body Symmetry Condition



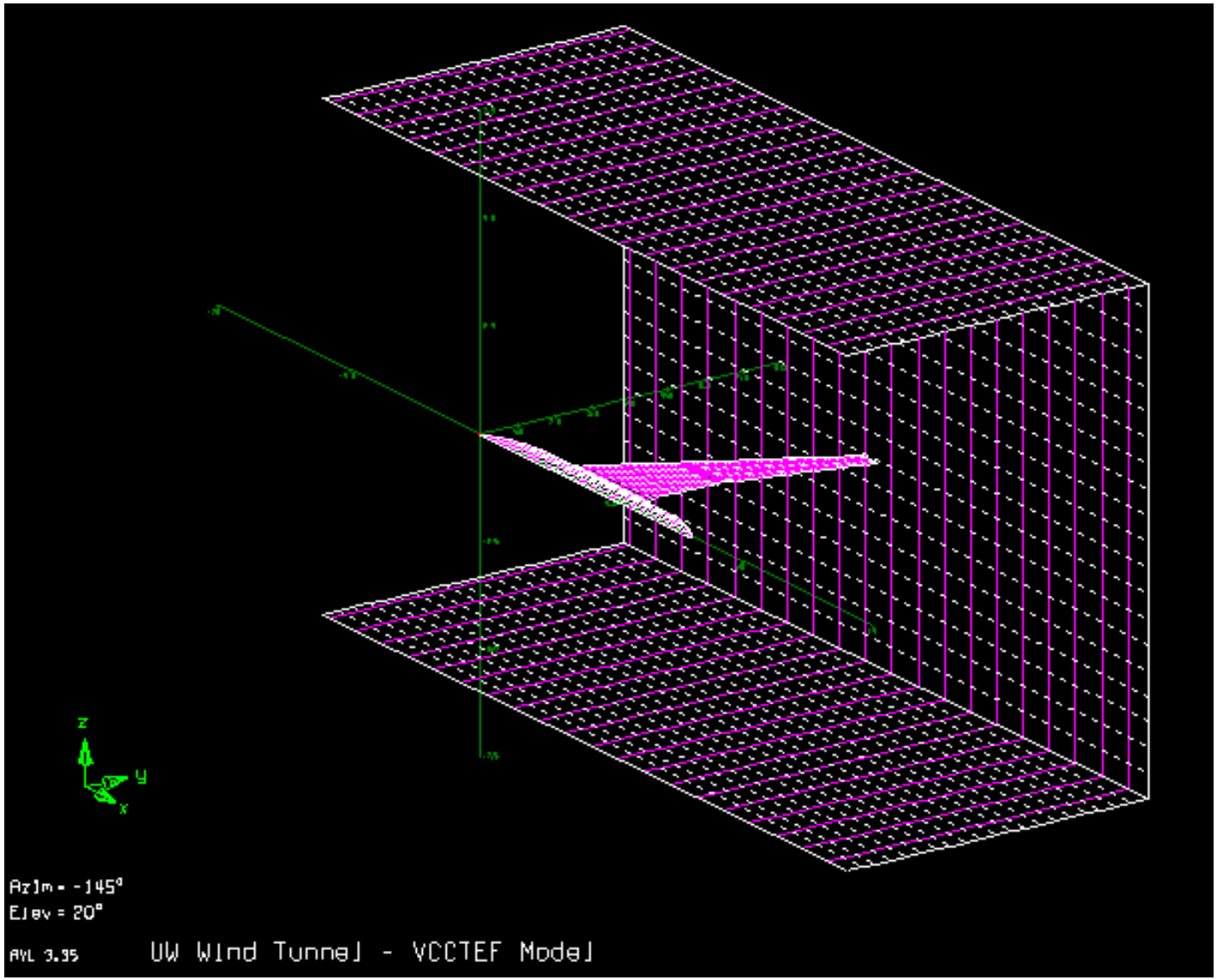
⑤ RESULTS

TASK 2 3D Code → VLM

Half Wing-Body Symmetry Condition + Top/Bottom Walls Only

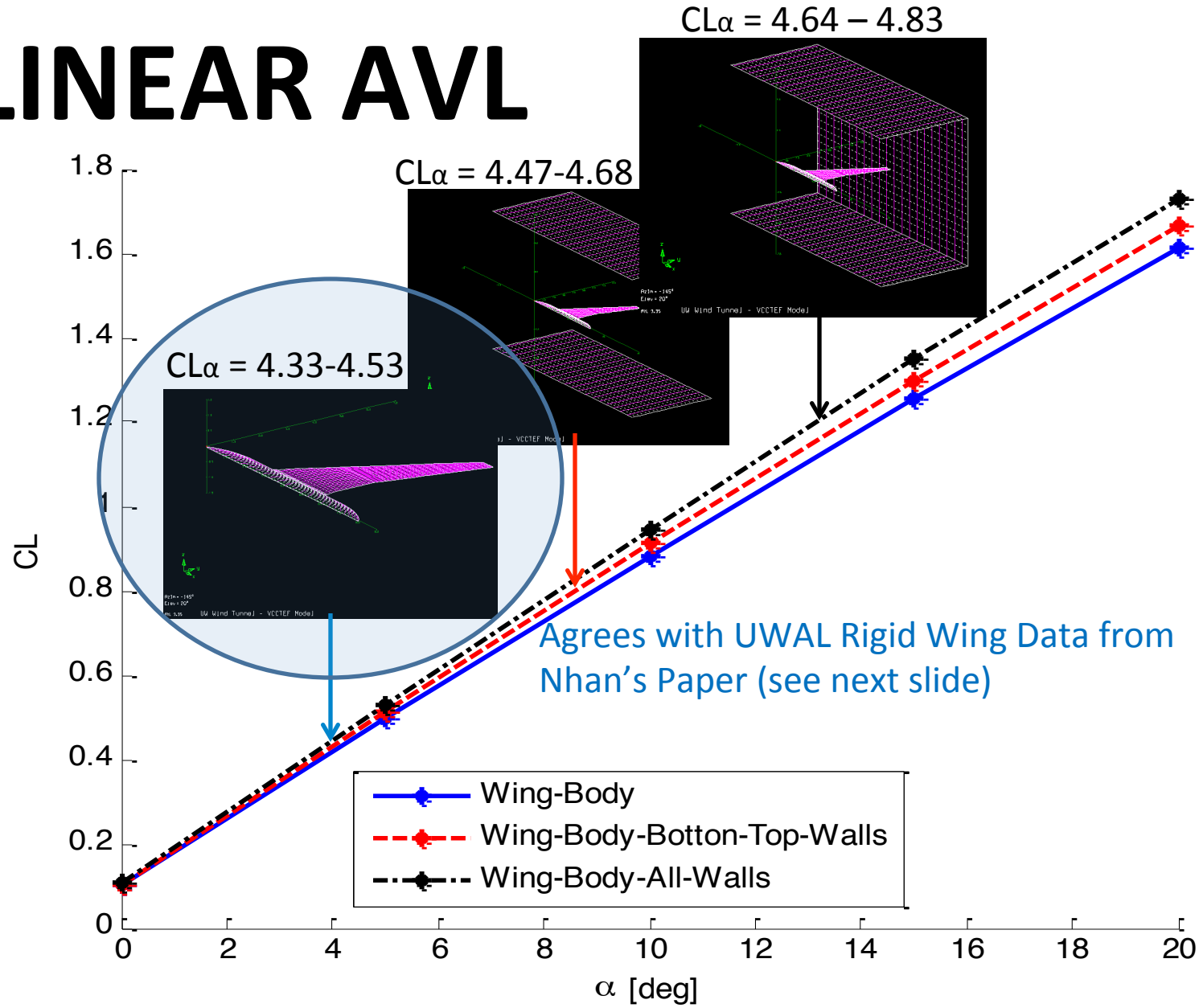


Half Wing-Body Symmetry Condition + All Walls



TASK 2 3D Code → VLM

LINEAR AVL



⑤ RESULTS

TASK 2 3D Code → VLM

- Reconstructed data for a rigid wing based on flexible wing tunnel data
- Data corrected for wind tunnel walls

UWAL RIGID - Paper
CLα = 4.49

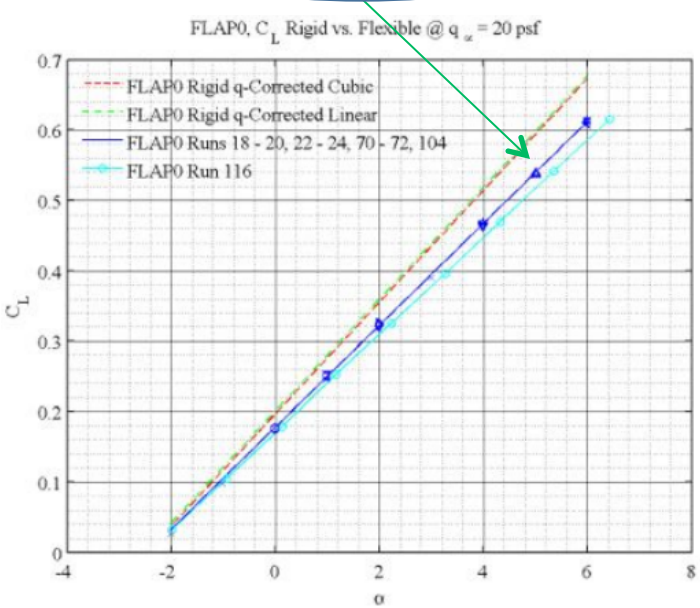


Fig. 59 - FLAP0 Runs 18 - 20, 22 - 24, 70 - 72, 104 C_L of Flexible and Rigid Wing

UWAL RIGID - Paper
CLα = 4.31

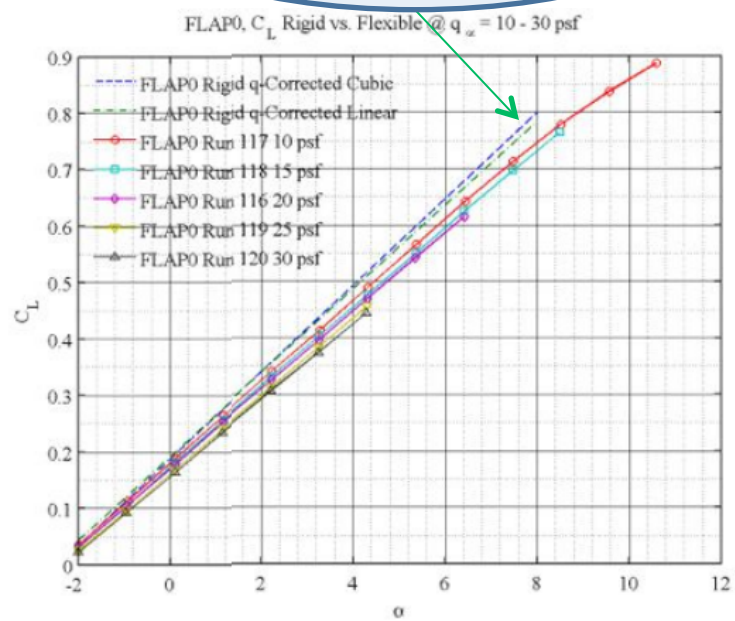


Fig. 57 - FLAP0 Runs 116 - 120 C_L of Flexible and Rigid Wing

*Nguyen, N., Precup, N., Umes, J., Nelson, C., Lebofsky, S., Ting, E., Livne, E., "Experimental Investigation of a Flexible Wing with a Variable Camber Continuous Trailing Edge Flap Design", AIAA Aviation 2014, 32nd AIAA Applied Aerodynamics Conference

NON-LINEAR AVL

- Code Modifications to Include:
  - Maximum 2D Cl and Non-linearities in lift (near stall)
  - Viscous drag (profile + skin friction)

Validation with Experimental Data

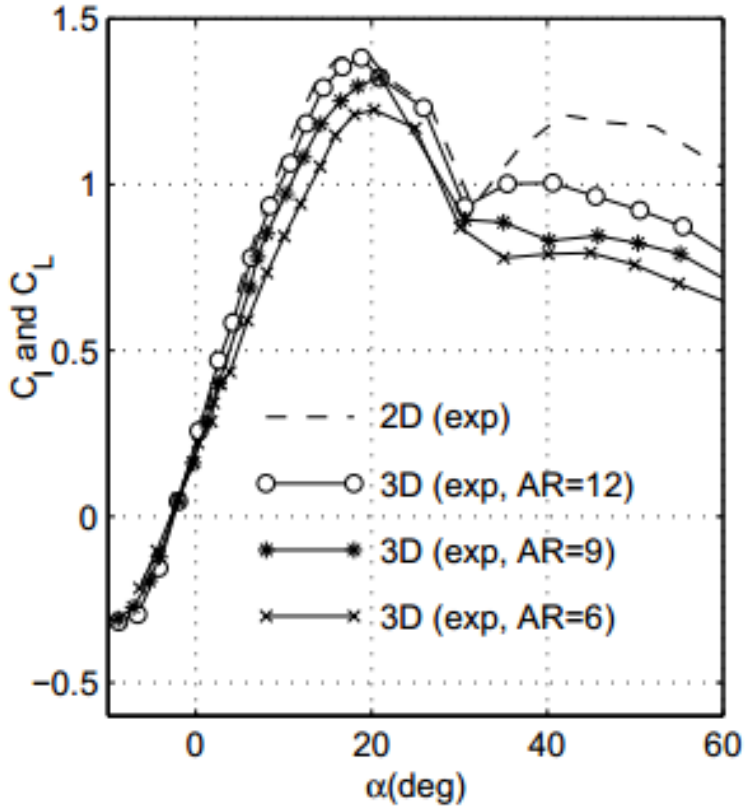
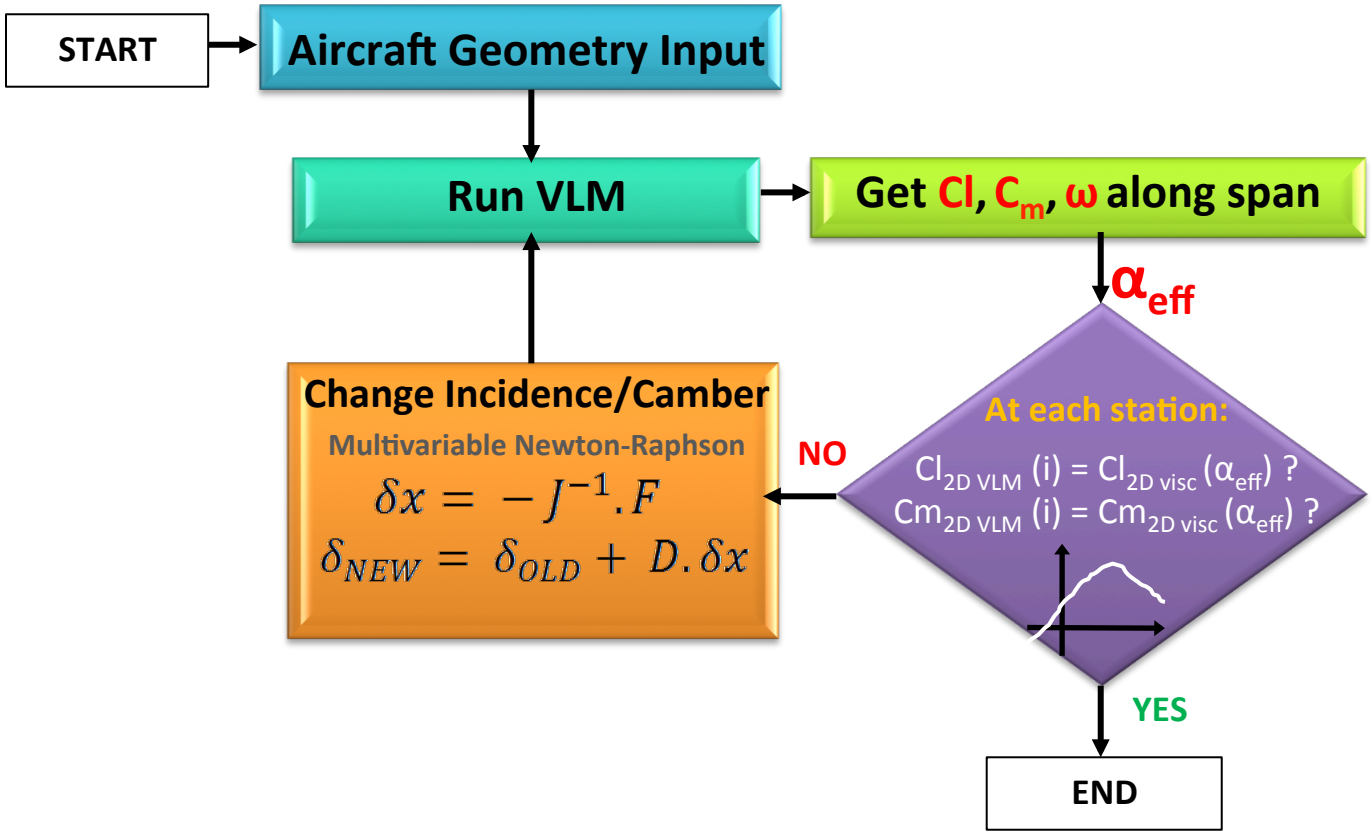


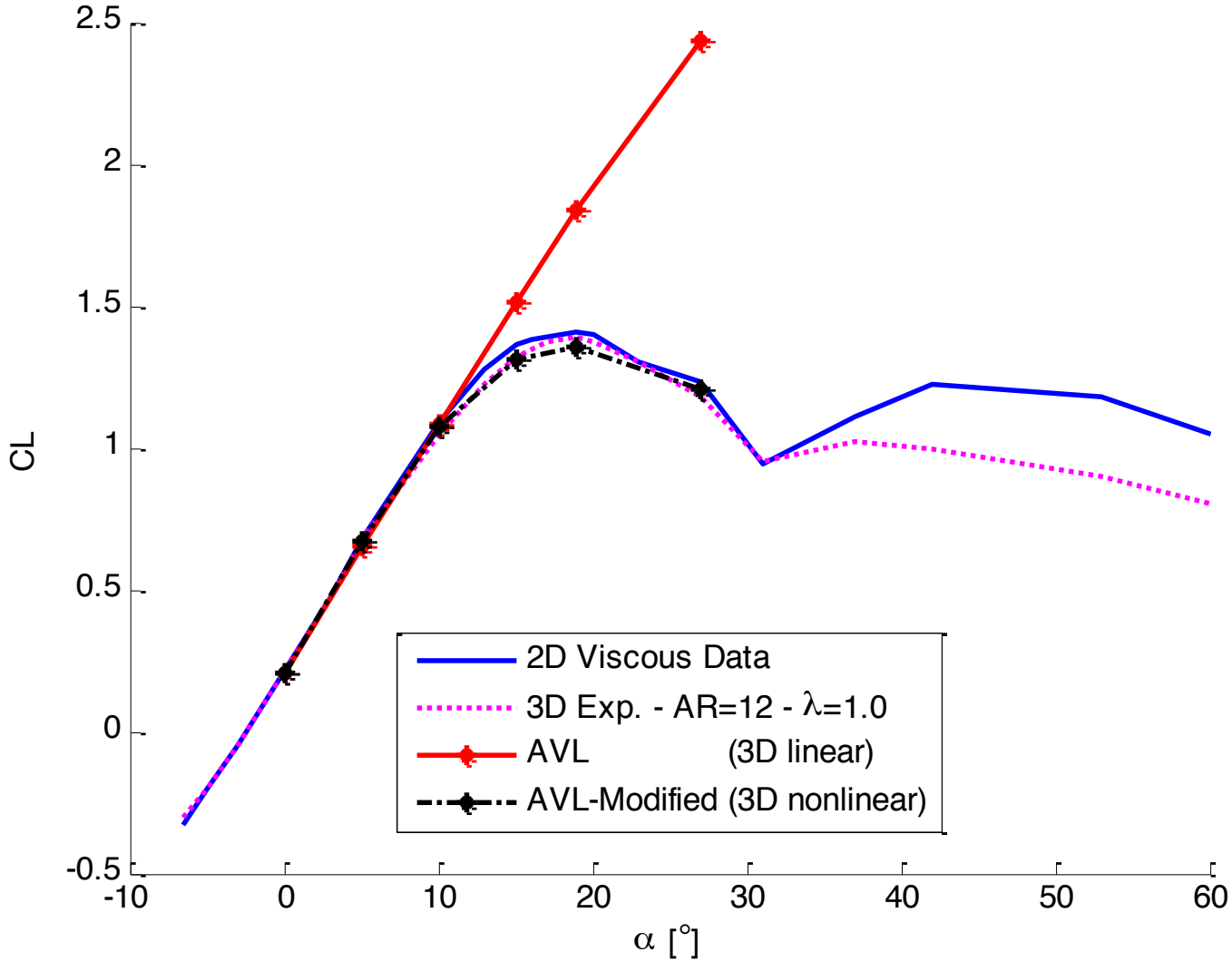
Figure 4.25: Wing C_L-α predicted from experiment for rectangular wings of aspect ratios 12, 9 and 6 using a NACA 4415 airfoil at Reynolds number of 0.5 million.

*Mukherjee, R., Gopalarathnam, A., Kim. S., "AN ITERATIVE DECAMBERING APPROACH FOR POST-STALL PREDICTION OF WING CHARACTERISTICS USING KNOWN SECTION DATA", AIAA 2003, 41st AIAA Aerospace Sciences Meeting

Validation with Experimental Data

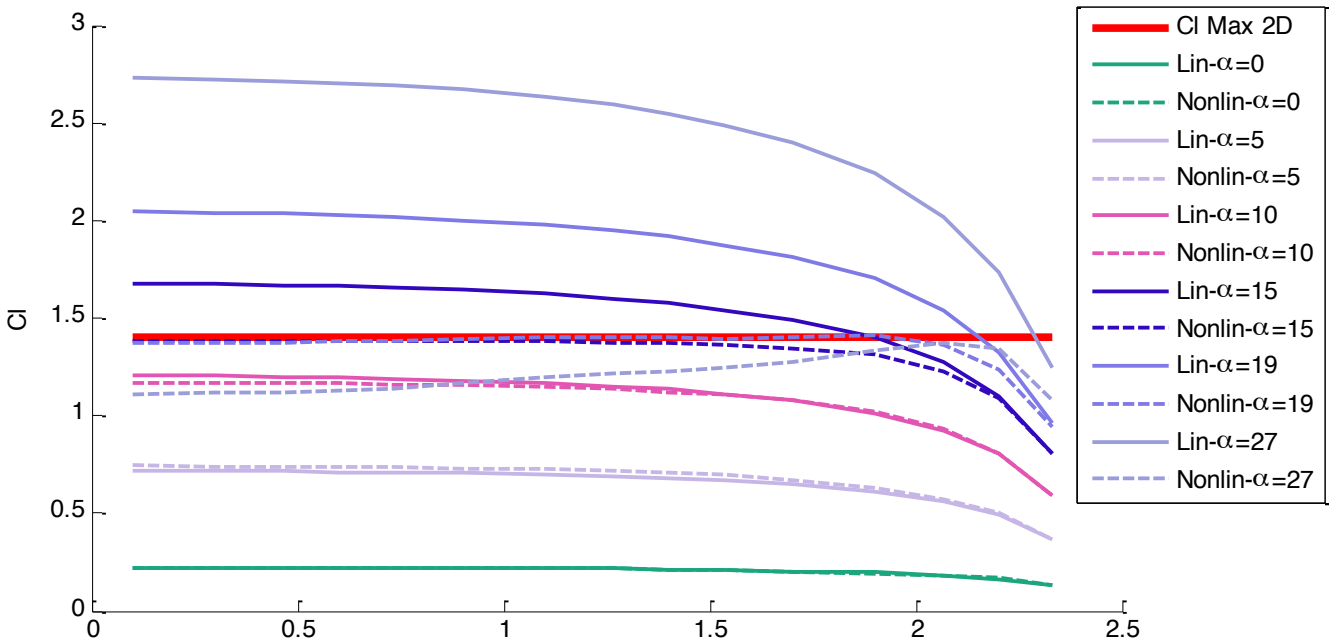


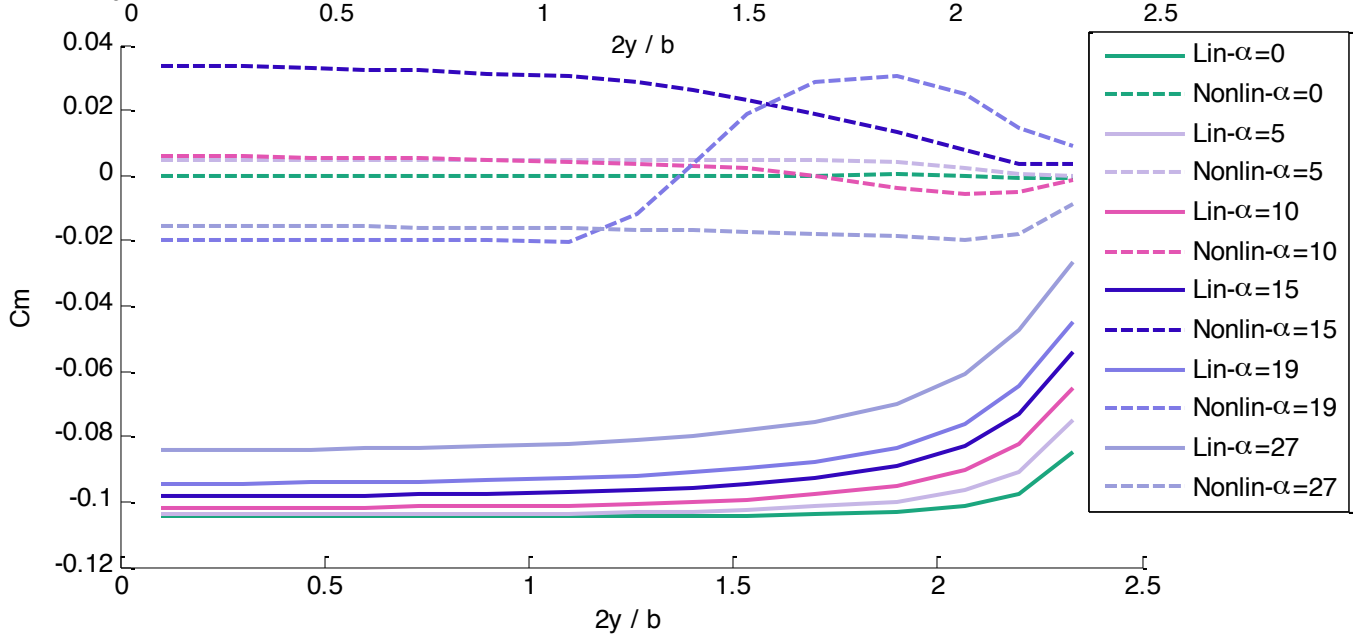
Validation with Experimental Data



⑤ RESULTS

TASK 2 3D Code → VLM

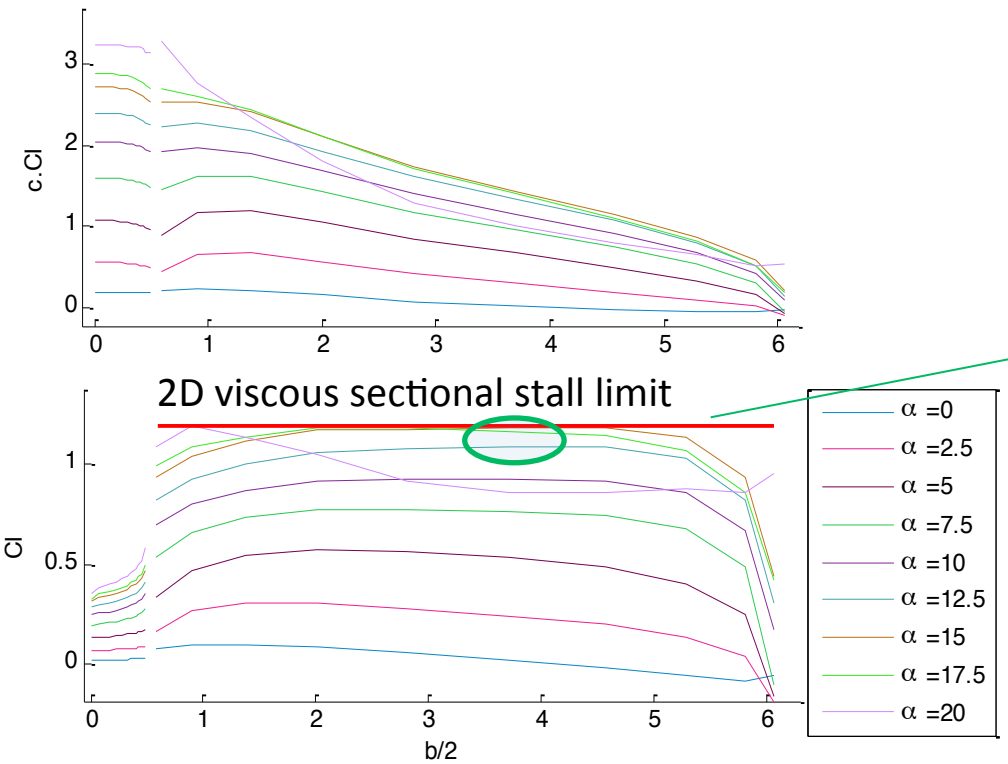


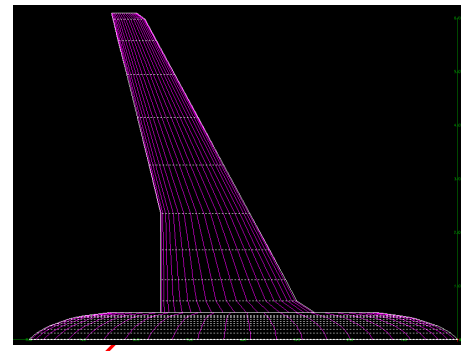


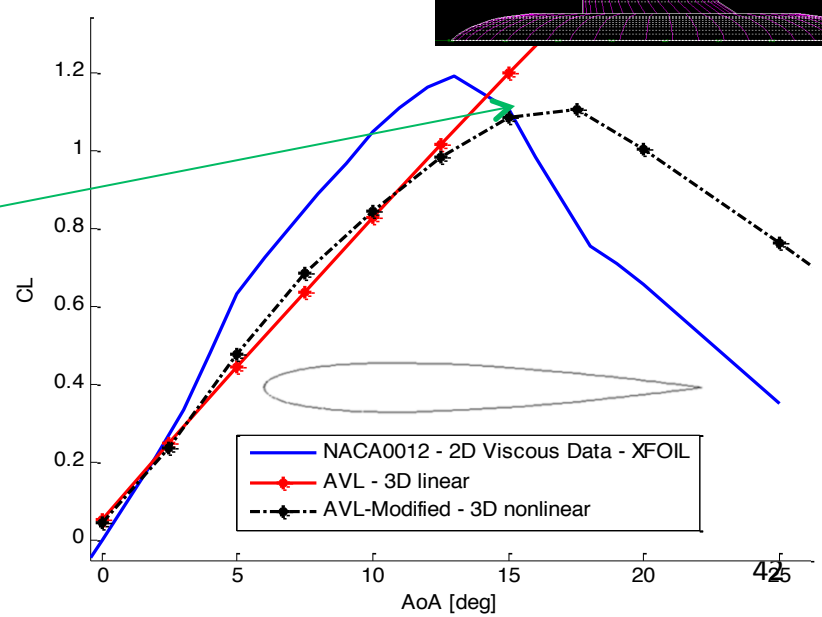
⑤ RESULTS

TASK 2 3D Code → VLM

- UWAL Model Geometry with NACA0012 sectional data
- The developed Nonlinear Vortex Lattice code results:
  - CL_α: slope agreement with the linear prediciton for the finite wing
  - Cl x span: good agreement with theory. As angle of attack increases, the stations increase local lift coefficient until they reach the maximum 2D Cl from the viscous data, yielding the 3D stall behavior and propagation characteristics of the $CL_x\alpha$ curve







This summer so far …

- Established a multidisciplinary optimization framework strategy

- Developed a low-fidelity nonlinear 3D aerodynamic tool
  - Using known sectional data
  - Capable of capturing CL_{max} and handling stall
  - Modified an existing Vortex Lattice Method code (AVL)

- Results showed successful prediction of 3D nonlinear aerodynamic characteristics, while maintaining low computational cost

AGENDA

1 MOTIVATION

2 INTRODUCTION

3 FRAMEWORK

4 METHOD

5 RESULTS

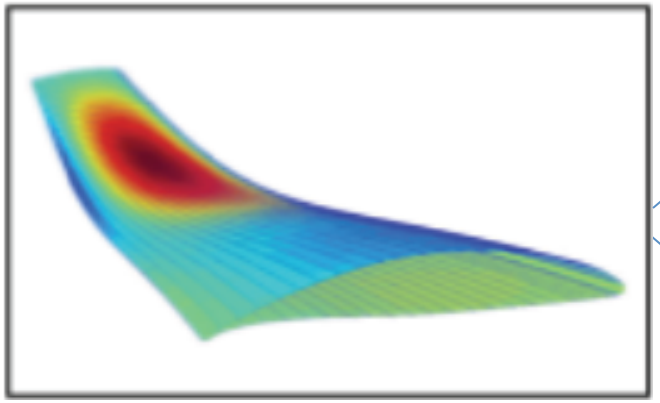
6 FUTURE WORK

7 AKNOWLEDGEMENTS

⑥ FUTURE WORK

Program the structural code

STRUCTURES

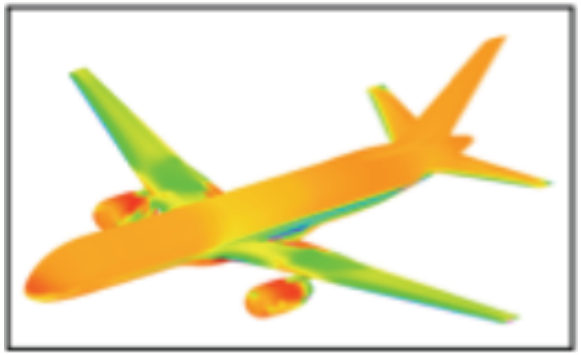


Galerkin Method

FEM

Modify the aerodynamic tool

AERODYNAMICS



2D Viscous Data

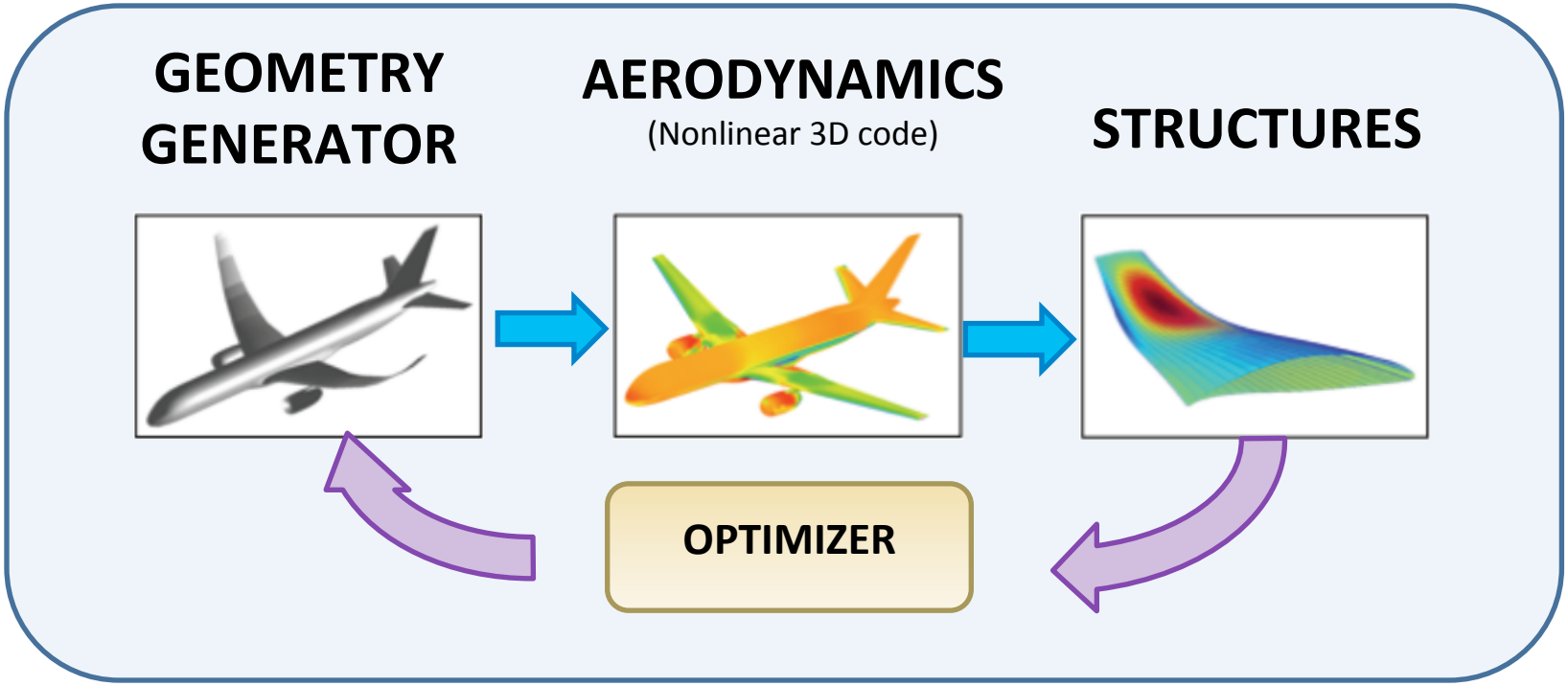
- ~~XFOIL~~
- 2D RANS (OVERFLOW)

3D Code

- ~~VLM (AVL)~~
- VLM (Vorview)
- Panel (Panair)

⑥ FUTURE WORK

Integrate aero/structural code with the optimizer



⑦ AKNOWLEDGEMENTS

THANK YOU

- NASA ARM – Fixed Wing Project
- Adaptive Aeroelastic Shape Control (AASC) under Aerodynamic Efficiency sub-project

- Dr. Cetin Kiris
- NASA AMS Division:
  Michael Aftosmis, David Rodriguez, others
- Dr. Nhan Nguyen
- NASA Intelligent Systems Division:
  Ezra Tal, Sonia Lebofsky, Eric Ting, others
- Dr. Michael Bragg, Dr. Eli Livne at the University of Washington

BACKUP SLIDES

Nonlinear Weissinger

- Swept Wing 2D and 3D CFD data

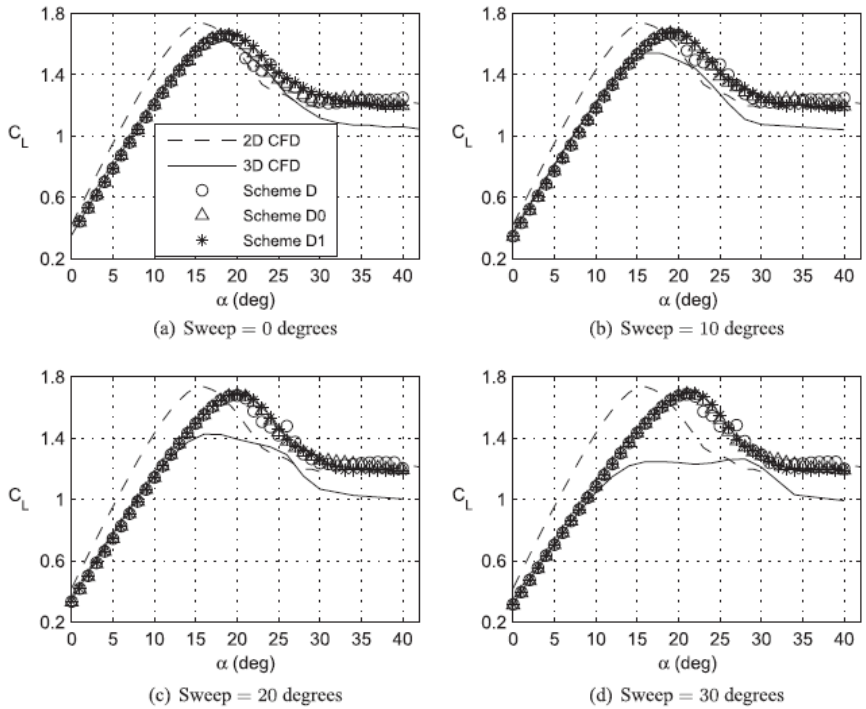


Figure 16. Wing-only C_L-α curves from schemes D, D0, and D1 compared with CFD for the four aft-sweep angles.

The results are from CFD computed at a Re = 3.0 M for NACA 4415 airfoil
Wing: AR = 12, Taper =1 (constant-chord wing)

Source: Paul, R. C., Gopalarathnam, A., "Iteration schemes for rapid post-stall aerodynamic prediction of wings using a decambering approach", INTERNATIONAL JOURNAL FOR NUMERICAL METHODS IN FLUIDS, Int. J. Numer. Meth. Fluids (2014), Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/fld.3931

CFD Data

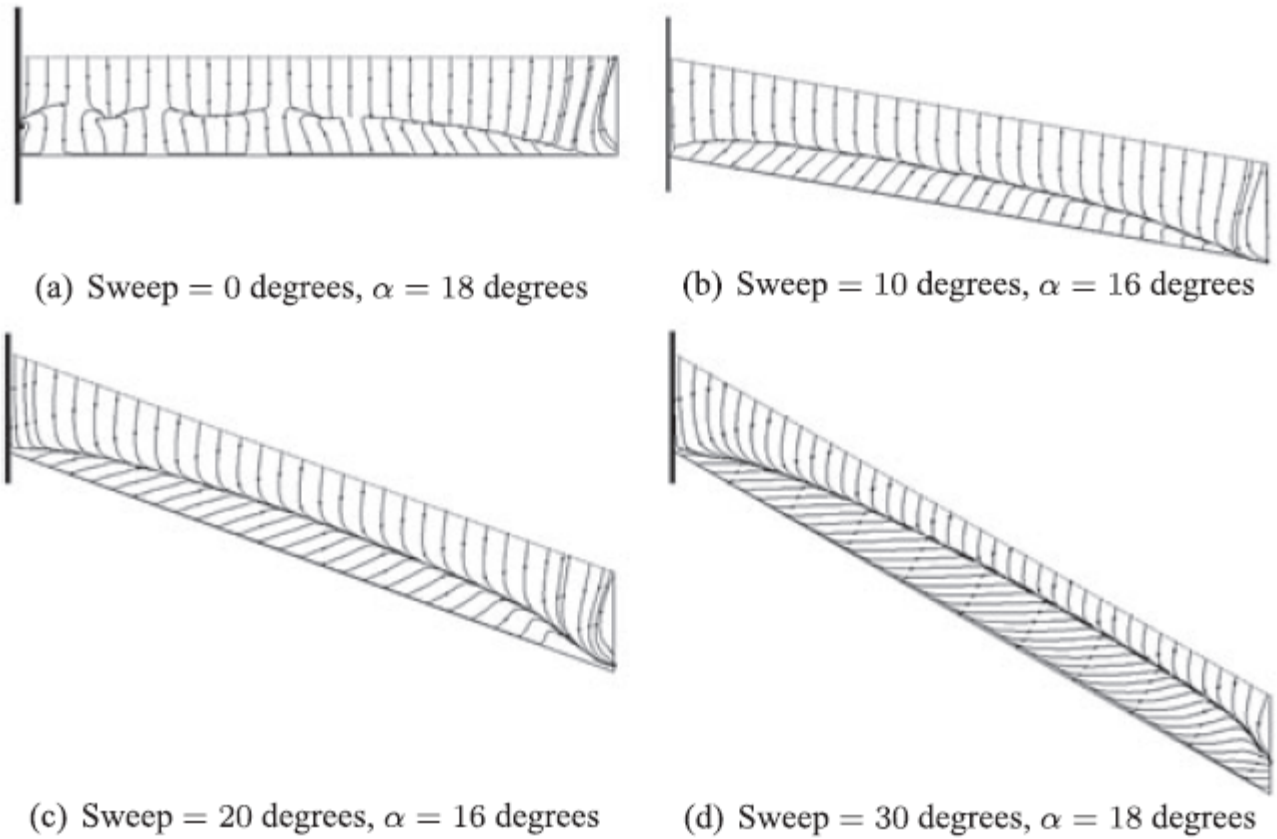


Figure 17. Upper-surface flow visualizations on the wings from CFD at $C_{L,\max}$. Right side of each wing is shown.

Source: Paul, R. C., Gopalarathnam, A., "Iteration schemes for rapid post-stall aerodynamic prediction of wings using a decambering approach", INTERNATIONAL JOURNAL FOR NUMERICAL METHODS IN FLUIDS, Int. J. Numer. Meth. Fluids (2014), Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/fld.3931

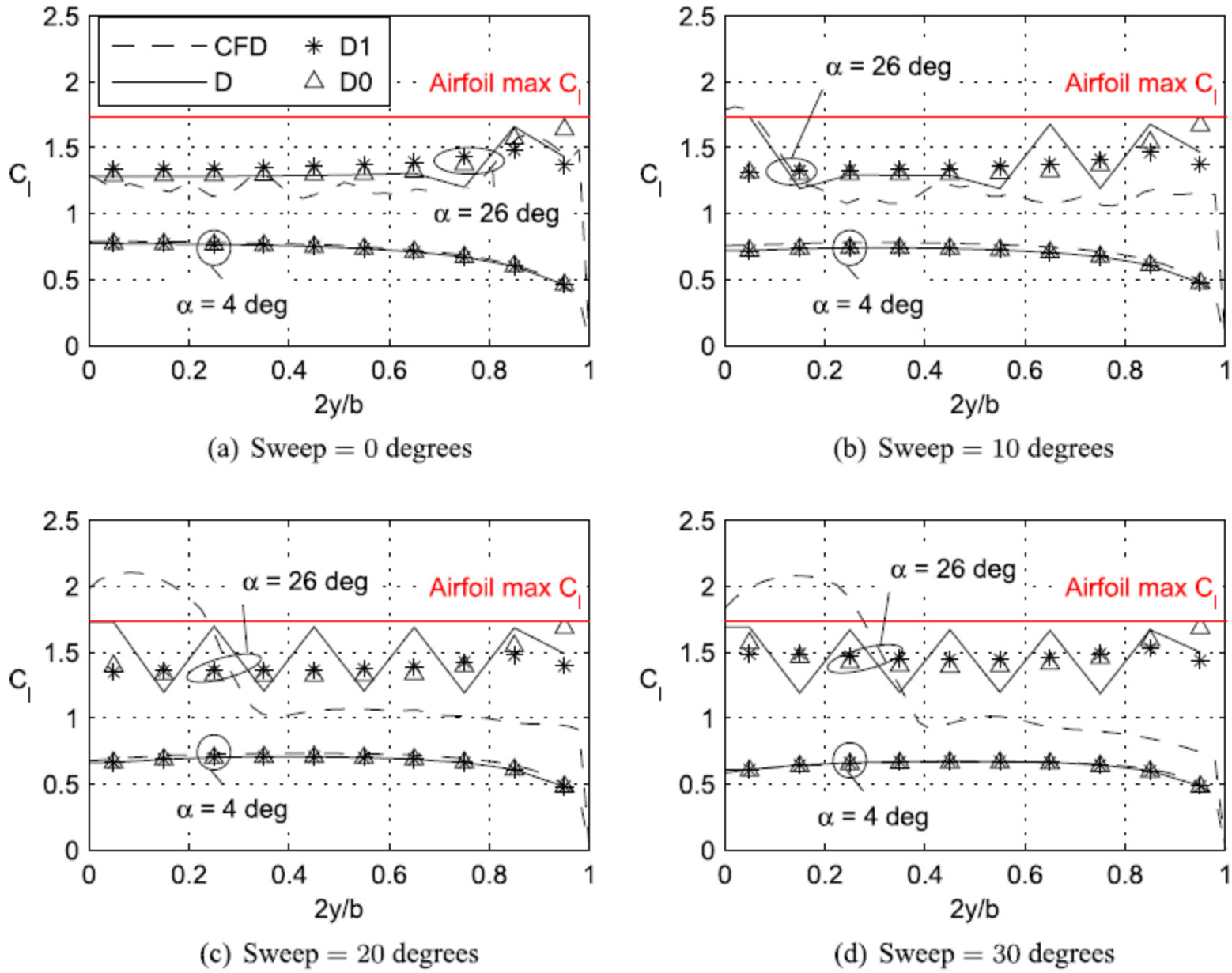


Figure 18. Comparison of wing C_l distributions for $\alpha = 4°$ and $26°$ from schemes D, D0, and D1 with CFD results for the four sweep angles.

Source: "Iteration schemes for rapid post-stall aerodynamic prediction of wings using a decambering approach" - 2014 - International Journal for Numerical Methods in Fluids - Wiley Online Library