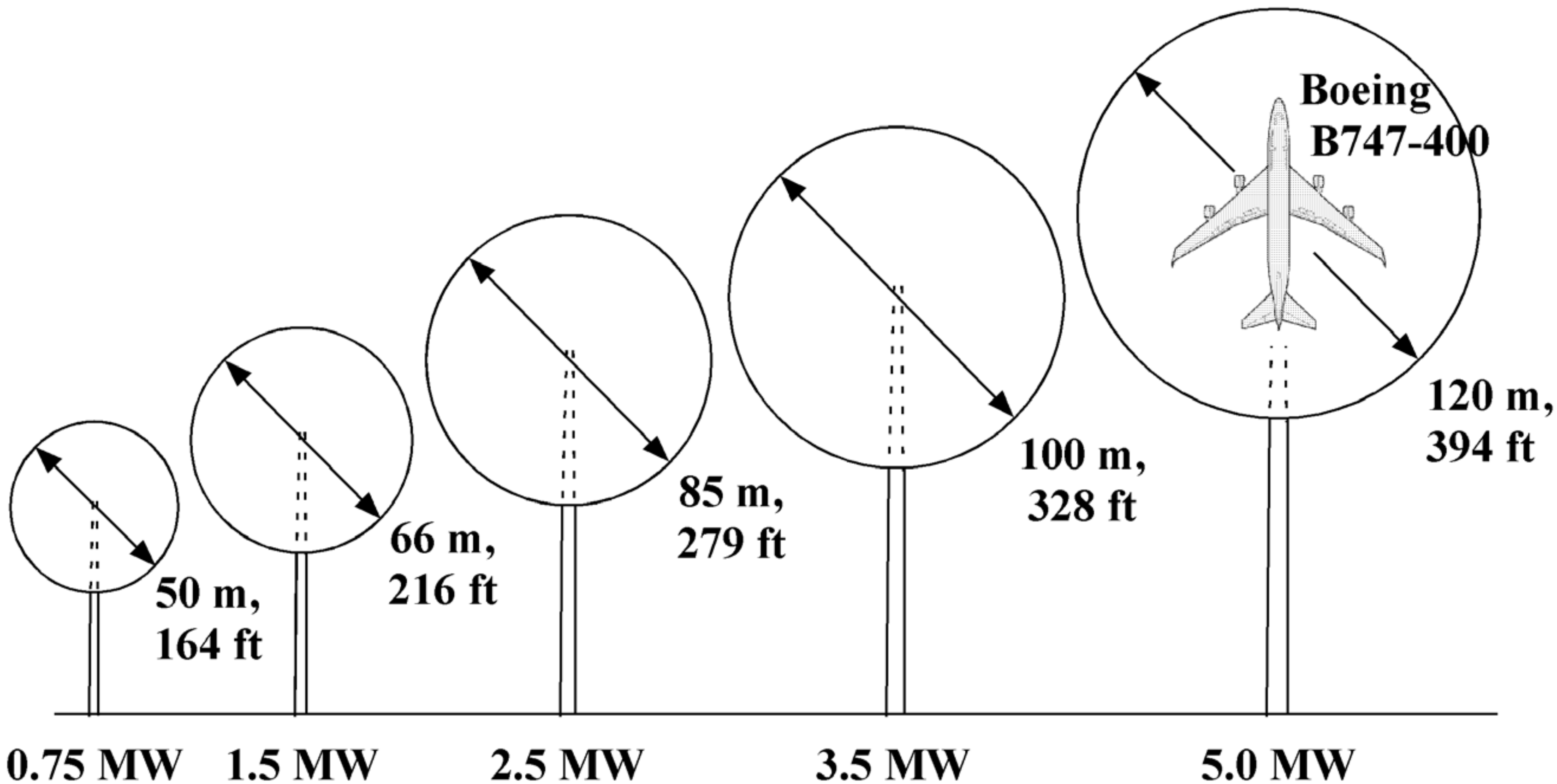
Blade Aerodynamics -
Passive and Active Load Control for Wind Turbine Blades

C.P. (Case) van Dam
Department of Mechanical & Aeronautical Engineering
University of California, Davis

California Wind Energy Collaborative

HAWT Size and Power Trends



Motivation

- Novel approaches are needed to reduce growth in blade mass with blade length
  - Mass $\propto$ Length^3 whereas Power $\propto$ Length^2
- Blade design methodology must be adapted to deal with resulting design challenges:
  - Past: Aero design → Structural design
  - Required: Structural design → Aero design
- With design focus on turbine mass and cost for given performance, need arises for passive and active techniques to control the flow and the loads on the blades/turbine
- To maximize the overall system benefits of these techniques, load control should be included from the onset
- This presentation will summarize passive and active flow/load control techniques

Outline

- Passive flow/load control
  - Overview of concepts
  - Blunt trailing edge/flatback airfoils
- Active flow/load control
  - Overview of concepts
  - Microtab concept
- Concluding remarks

UCDAVIS

Problem Faced by Industry

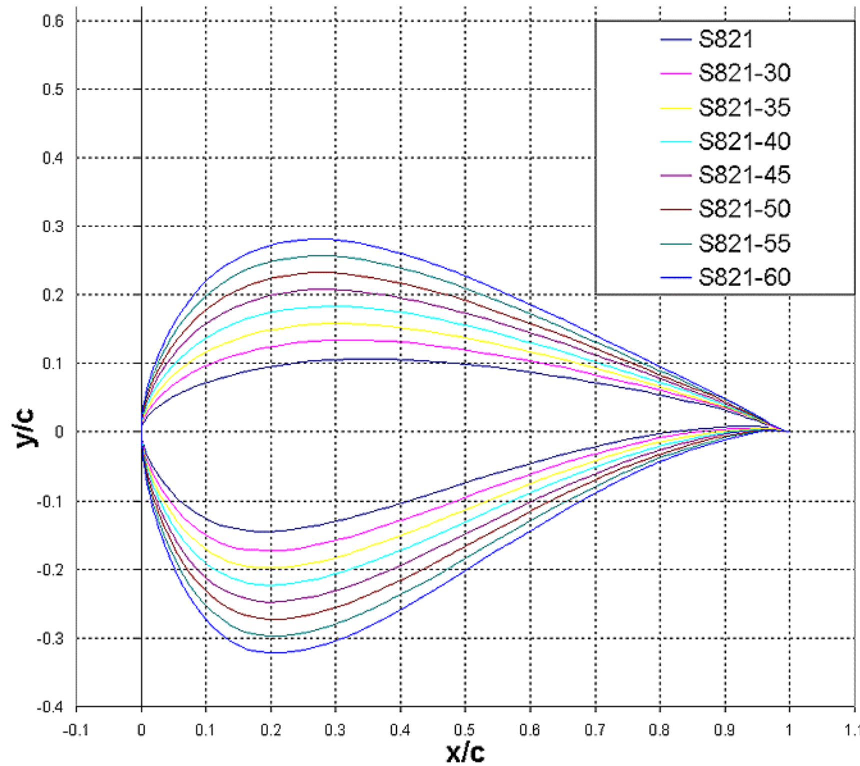
- Wind turbines must be low cost and require little maintenance
- Wind turbines flows are complicated:
  - Ill-defined inflow
  - Wide range of operating conditions
  - Rotating lifting surfaces
  - Flexible structures
  - Transitional blade flows
  - Low Mach numbers
- Tool box of blade designers inhibits accurate analysis flows/loads and implementation of flow/load control:
  - Wind tunnel testing of blade section shapes with or without flow/load control is time consuming and expensive
  - Wind tunnel testing of rotors is nearly impossible
  - 2D computational tools largely based on viscous/inviscid flow theory
    - Steady flow
    - Smooth surface
    - Limited flow separation
  - 3D computational tools largely based on blade element & momentum (BEM) theory
- Rapid turnover in turbine designs limits opportunity to learn from mistakes

Passive Flow/Load Control

- Passively control the flow/loading to:
  - improve the performance of the turbine
  - mitigate the loads on the structure
  - reduce the stress levels in the structure
- Passive control techniques:
  - Laminar flow control
  - Passive porosity
  - Riblets
  - Vortex generators
  - Stall strips
  - Gurney flaps
  - Serrated trailing edges
  - Aeroelastic tailoring
  - Special purpose airfoils (restrained max. lift; high lift; blunt trailing edge)
- Passive load control is extensively used in wind turbine design, for the most part focused on power production

Airfoil Thickness Study

- Baseline airfoil is S821 (t/c = 24%)
- Camber distribution is constant
- Maximum thickness ratio is systematically increased from 0.24 to 0.60



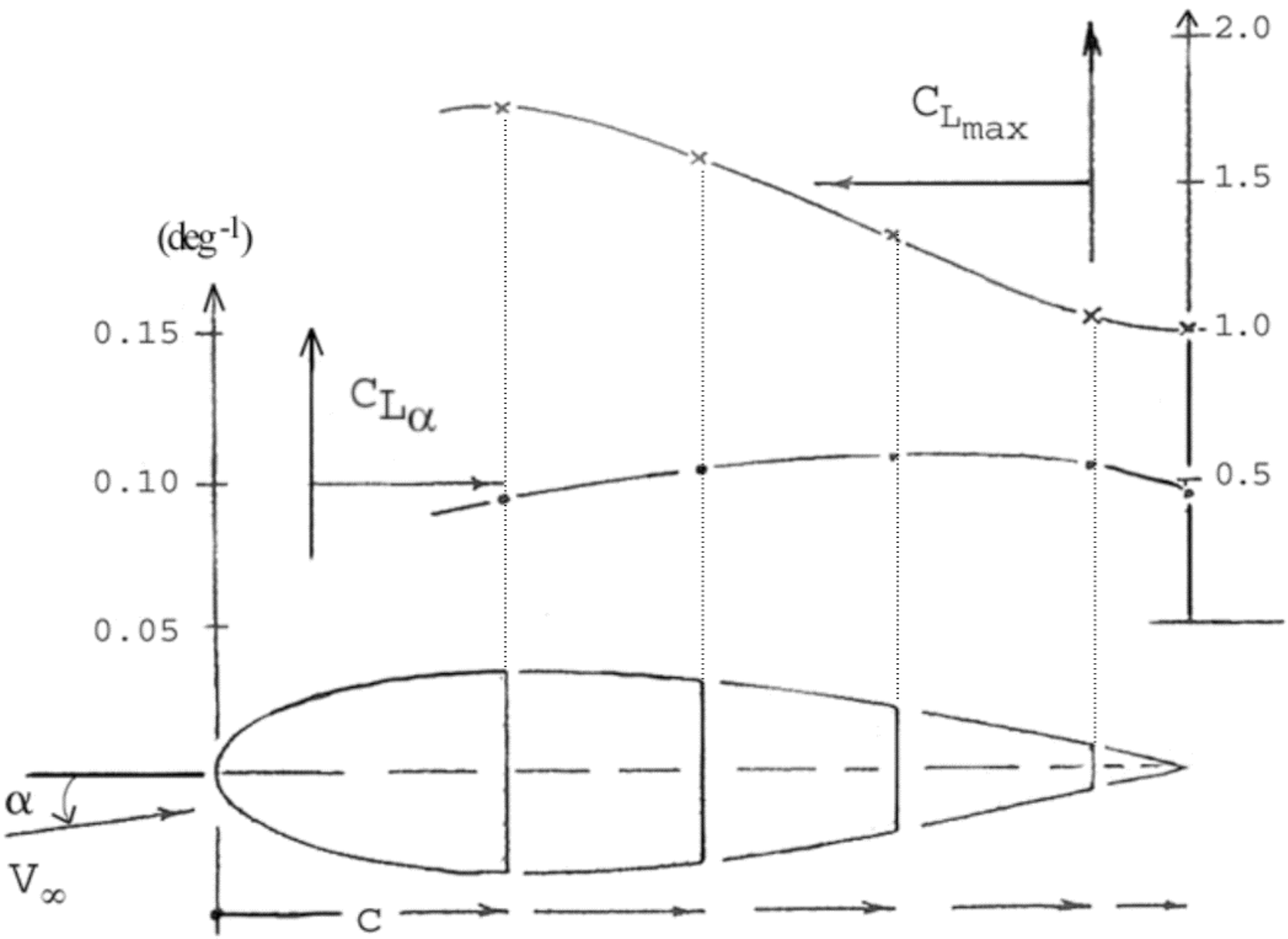
:

Thickness Effect Summary

- Loss in maximum lift due to surface roughness is encountered for airfoils with t/c > approx. 0.26
- At clean surface conditions, maximum lift coefficient peaks at t/c = 0.35 and lift-to-drag ratio peaks at t/c = 0.30
- Results back general view that maximum thickness ratios greater than 26% are deemed to have unacceptable performance characteristics
- One way to improve performance characteristics of thick airfoils is by installing vortex generators on suction surface
- Are there any other options?

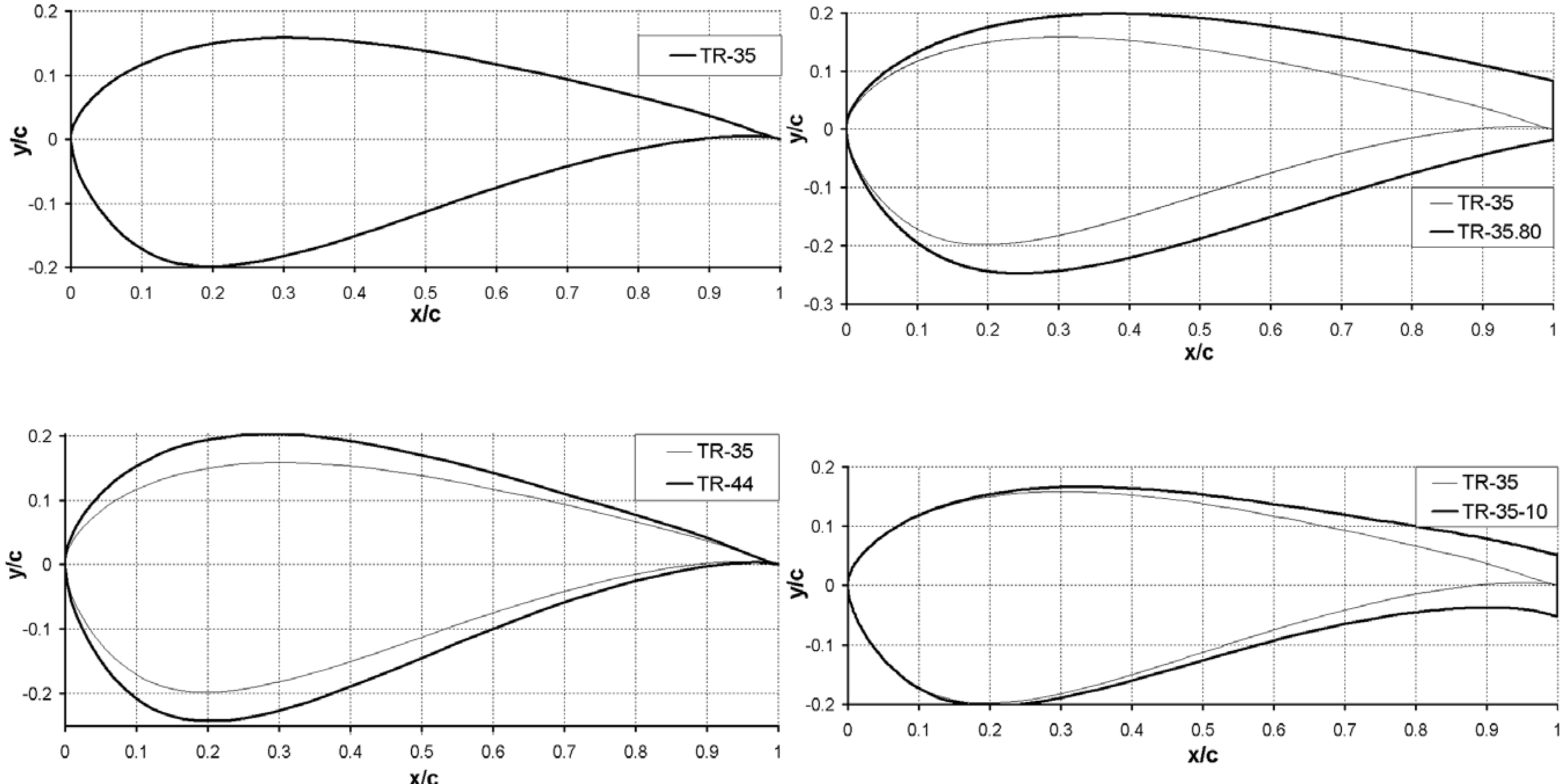
Blunt Trailing-Edge on Gö-490

Hoerner & Borst (1985)



<

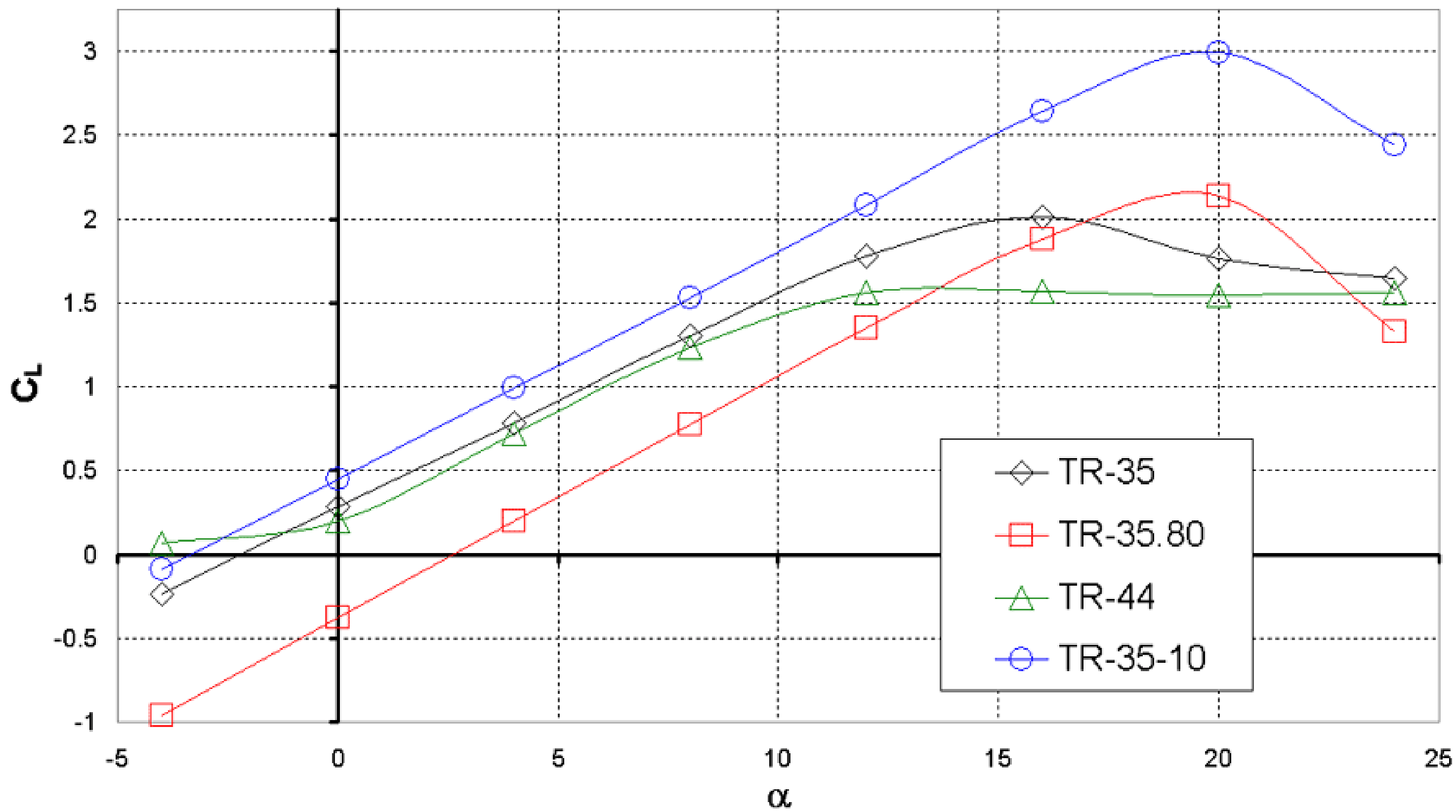
TR Series Airfoils



- TR-35 is baseline sharp-trailing edge, cambered airfoil with t/c = 35%
- TR-35.80 is TR-35 truncated at x/c = 0.80 resulting in t/c = 44%, t_{TE}/c = 10%
- TR-44 is sharp-trailing edge, cambered airfoil with t/c = 44%
- TR-35-10 is blunt trailing-edge airfoil with t/c = 35%, t_{TE}/c = 10%

Effect of Trailing-Edge Modification on Lift

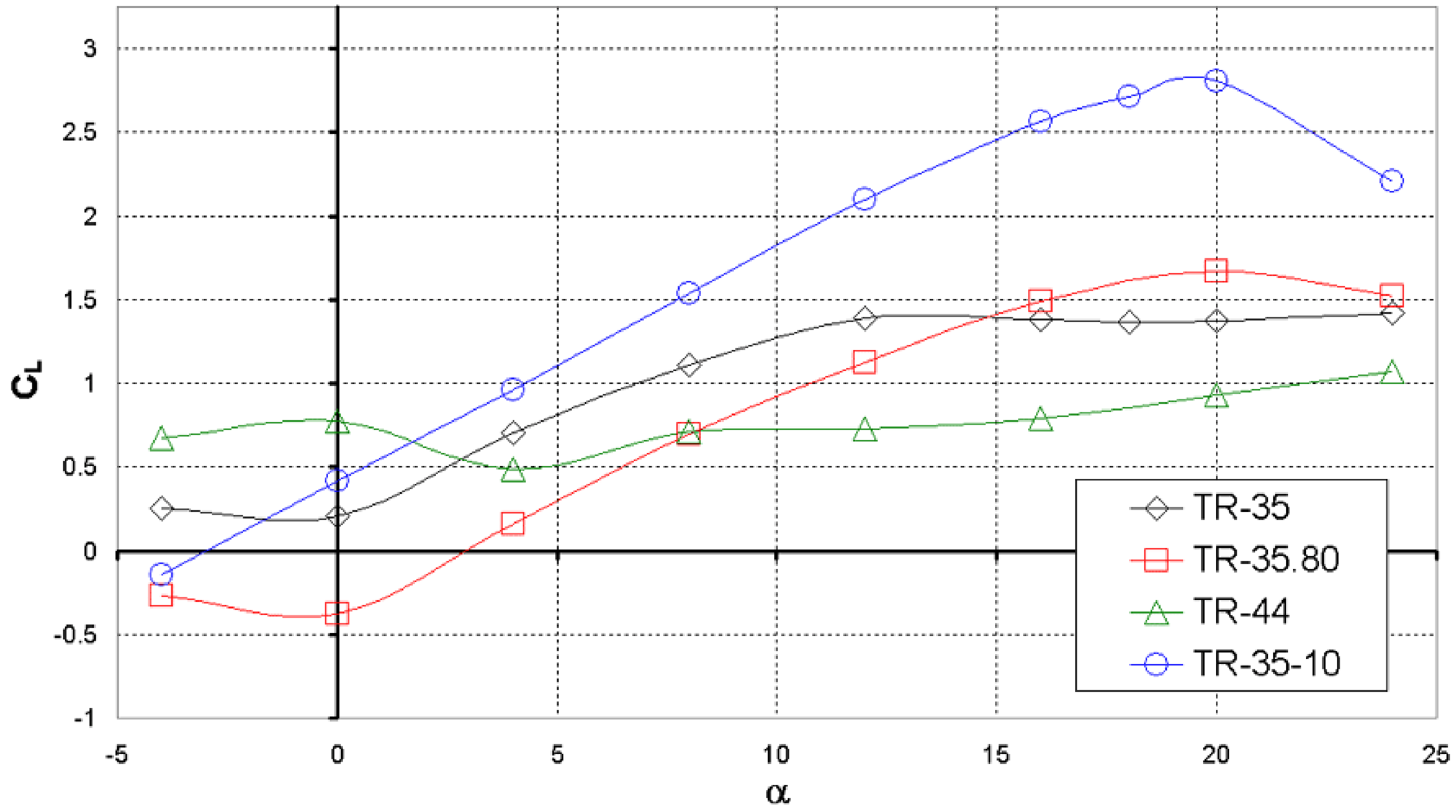
Re = 4.5 x 10^6, Clean, ARC2D



- **Truncating cambered airfoil (TR-35 → TR-35.80) results in loss of camber and, hence, loss in lift**
- **TR-35.80 has significantly higher maximum lift than TR-44**
- **TR-35-10 shows superior lift performance over entire angle-of-attack range**

Effect of Trailing-Edge Modification on Lift

Re = 4.5 x 10^6, Soiled, ARC2D

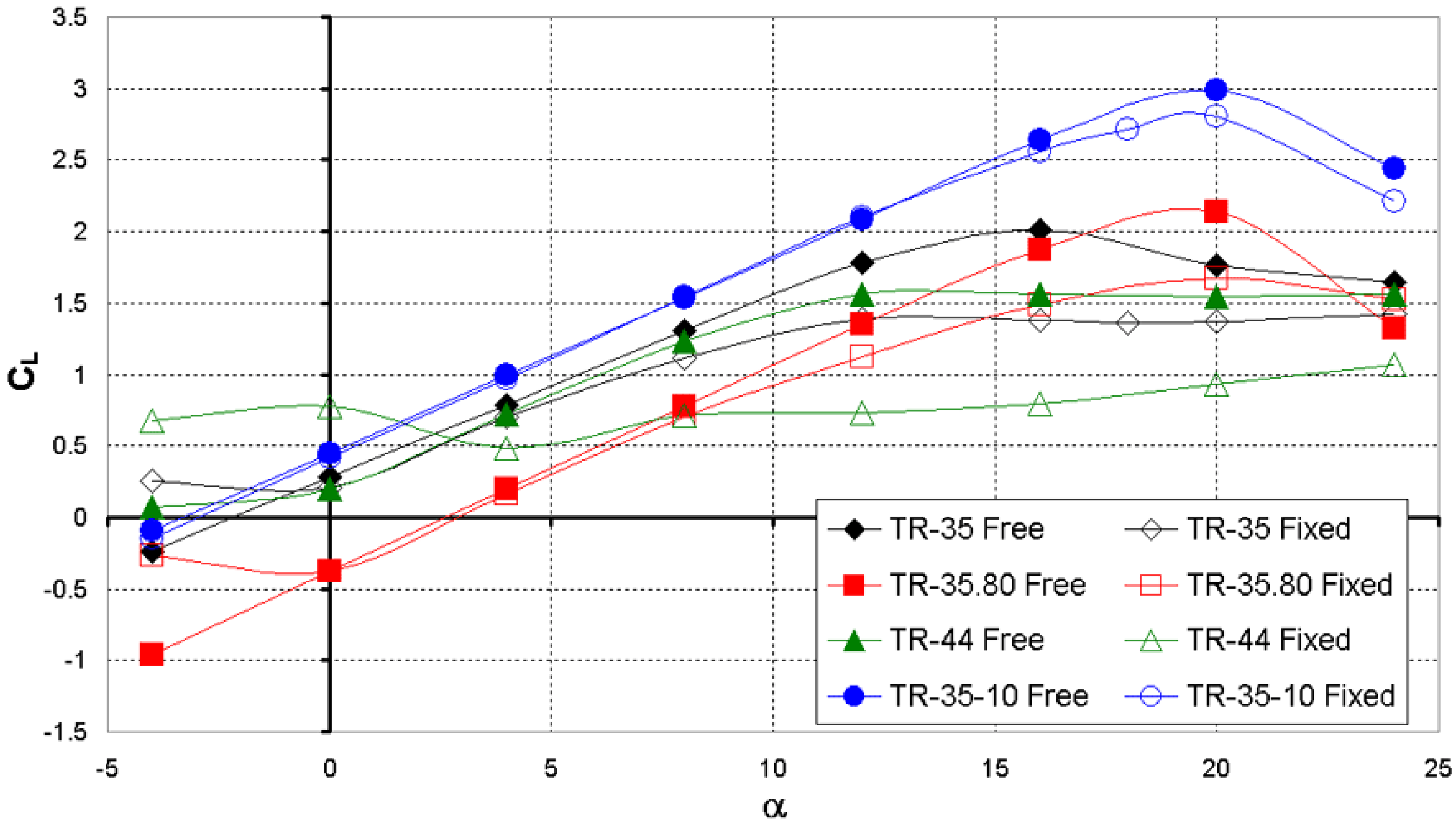


- Boundary layer transition due to leading-edge soiling on thick blades leads to premature flow separation and as a result loss in lift and increase in drag
- Blunt trailing edge causes a delay in flow separation and mitigating the loss in lift

UCDAVIS

Effect of Soiling on Lift

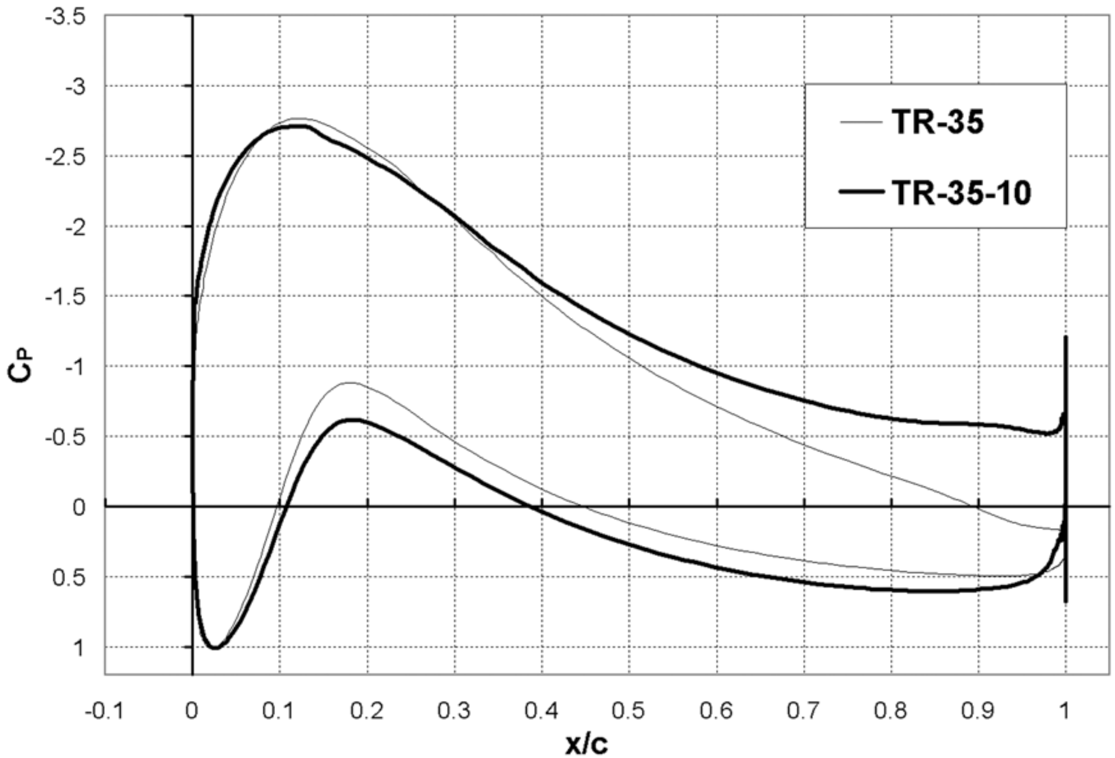
Re = 4.5 x 10^6, ARC2D



- **Lift performance of TR-35-10 is hardly affected by soiling**
- **Other airfoils nearly incapable of generating lift at soiled conditions**

Effect of Blunt Trailing Edge Modification on Pressure Distribution

Re = 4.5 x 10^6, α = 8˚, Clean



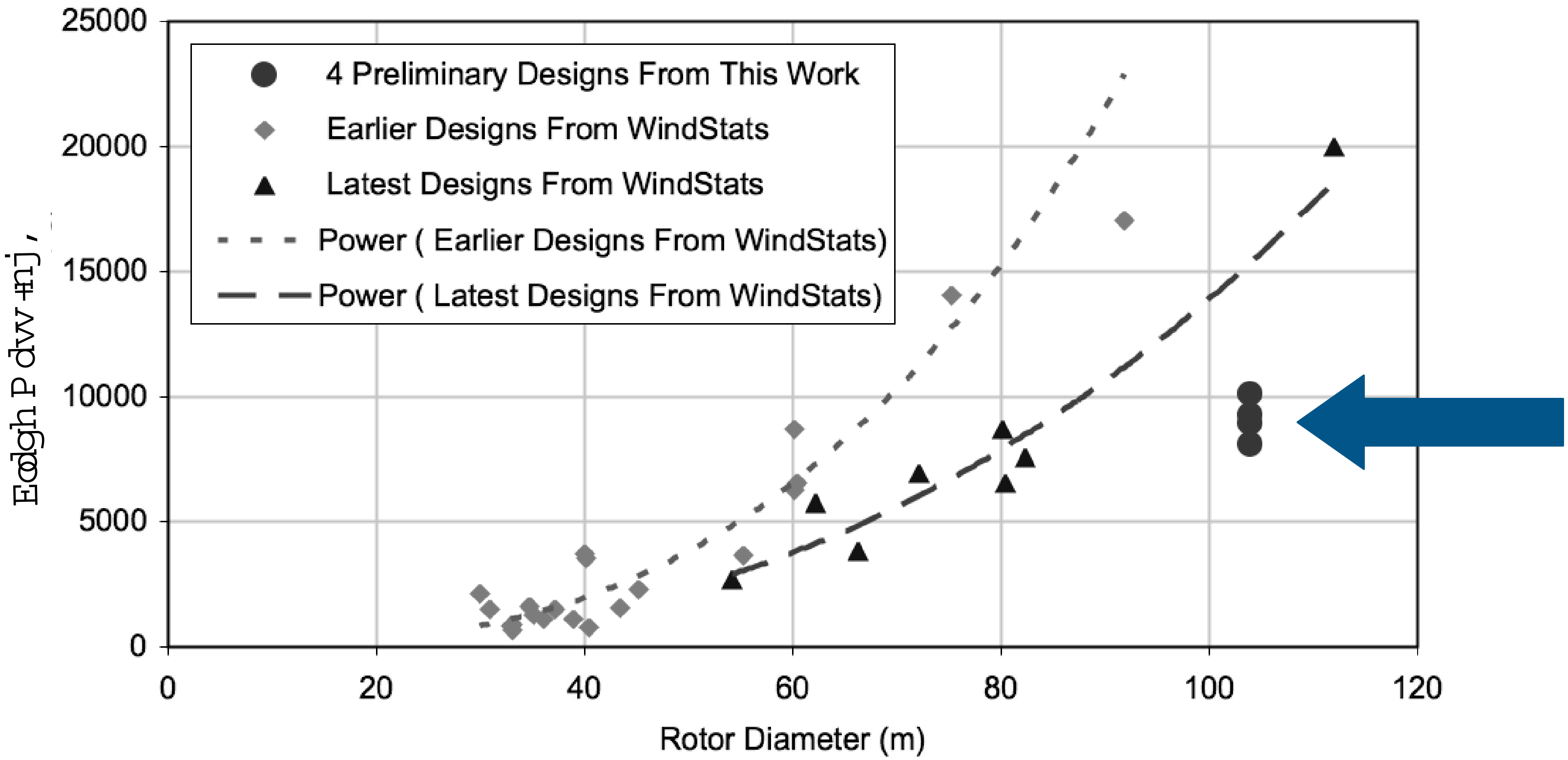
- Time-averaged pressure distributions of the TR-35 and TR-35-10 airfoils
- Blunt trailing edge reduces the adverse pressure gradient on the upper surface by utilizing the wake for off-surface pressure recovery
- The reduced pressure gradient mitigates flow separation thereby providing enhanced aerodynamic performance

UCDAVIS

Passive Flow/Load Control Conclusions

- Passive control is used extensively in the design of wind turbine blades
- One example of flow control for the blade root region of large wind turbine blades is the blunt trailing edge (or flatback) airfoil concept
- The incorporation of a blunt trailing edge for thick airfoils is beneficial for following reasons:
  - Improves aerodynamic lift performance (C_{Lmax}, $C_{L\alpha}$, reduced sensitivity to transition)
  - Allows for very thick sections shapes to be used ($t/c >> 30\%$) $\rightarrow$ lower stress levels in structure
  - Reduced chord for given maximum thickness can mitigate large blade transportation constraints
- Trailing edge may need to be treated for reduction of base drag, flow unsteadiness and noise
- Truncation of cambered section shapes is not a good idea because it leads to changes in camber and maximum thickness-to-chord ratio resulting in reduced lift performance

Blade System Design Study (BSDS) - Phase I (TPI Composites, Inc.)



- **Use of high thickness flatback airfoils in the inner blade, combined with the use of IEC Class III design loads, results in a large reduction blade primary structure for given power output performance**
- **Resulting blade designs are significantly lighter than the latest designs in the marketplace**

Active Flow/Load Control

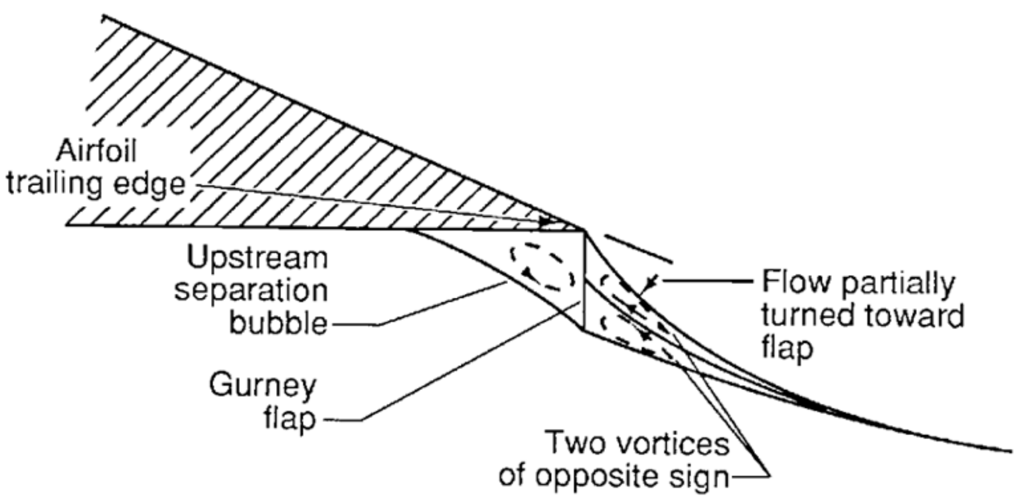
- Blade load variations due to wind gusts, direction changes, large scale turbulence
- Actively control the loading on blade/turbine by modifying:
  - Blade incidence angle
  - Flow velocity
  - Blade size
  - Blade aerodynamic characteristics through:
    - Changes in section shape
    - Surface blowing/suction
    - Other flow control techniques

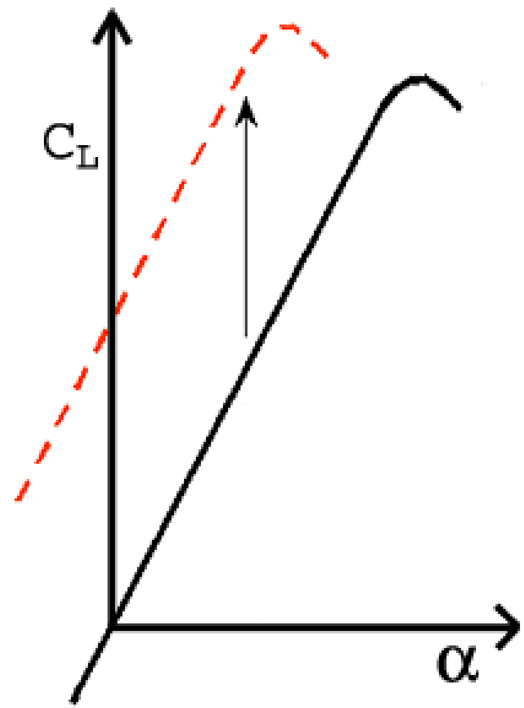
- Active load control:
  - May remove fundamental design constraints for large benefits
  - These large benefits are feasible if active control technology is considered from the onset
- Active load control is already used in wind turbine design. E.g.:
  - Yaw control
  - Blade pitch control
  - Blade aileron

UCDAVIS

Gurney Flap (Passive)

- Gurney flap (Liebeck, 1978)
  - Significant increases in C_L
  - Relatively small increases in C_D
  - Properly sized Gurney flaps ⇨ increases in L/D

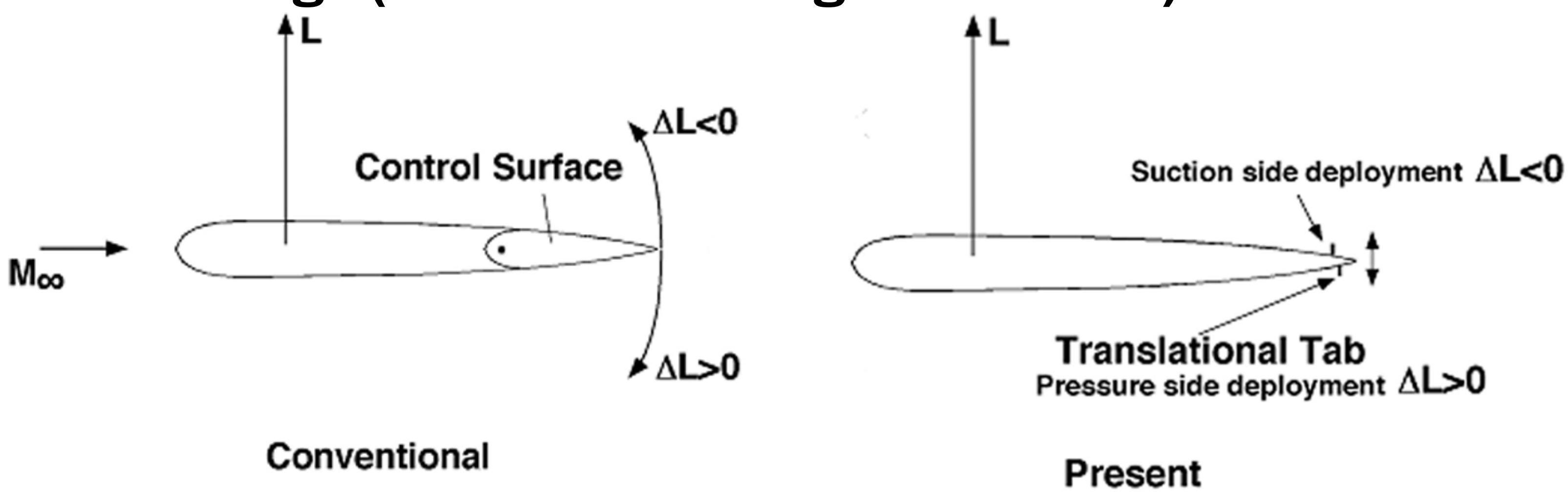




Microtab Concept

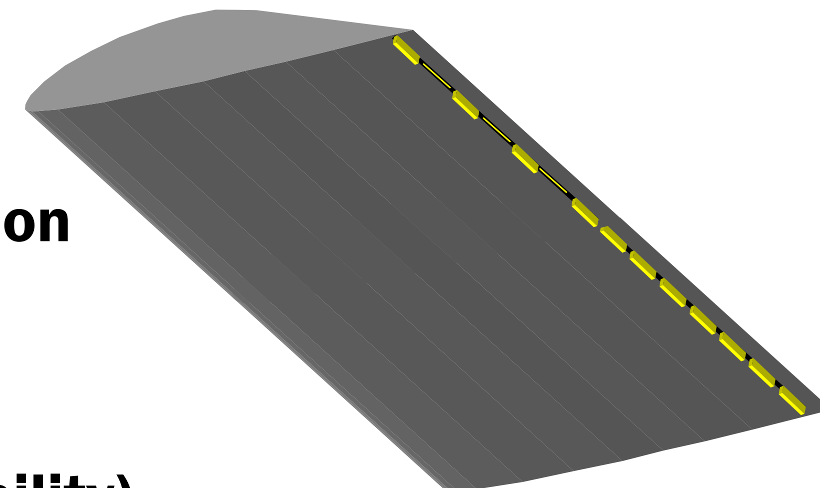
Yen Nakafuji & van Dam (2000)

- Generate *macro-scale* changes in aerodynamic loading using *micro-scale* devices?
- Trailing edge region is most effective for load control
- Micro-Electro-Mechanical (MEM) devices are ideal for trailing edge implementation due to their small sizes
- Devices are retractable and controllable
- Does not require significant changes to conventional lifting surface design (i.e. manufacturing or materials)

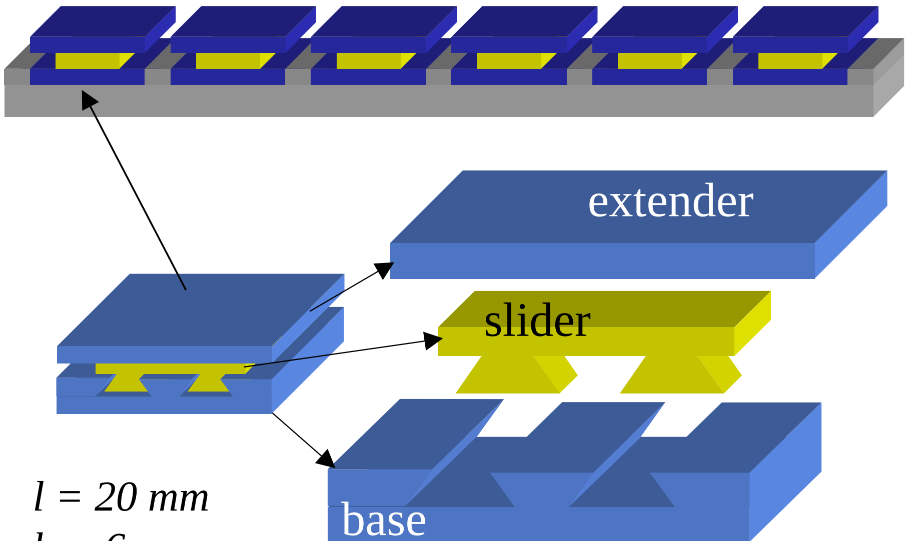


MEMS Microtab Characteristics

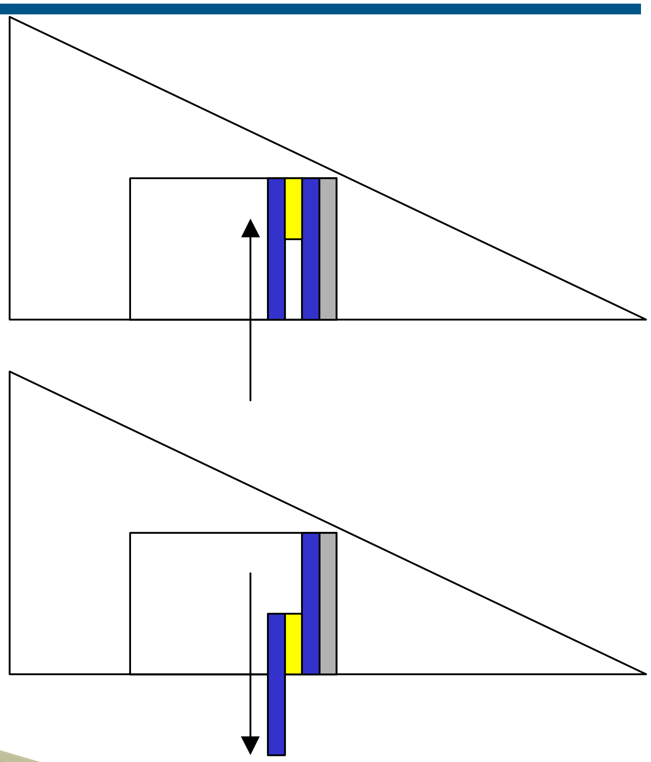
- Small, simple, fast response
- Retractable and controllable
- Lightweight, inexpensive
- Two-position “ON-OFF” actuation
- Low power consumption
- No hinge moments
- Expansion possibilities (scalability)
- Do not require significant changes to conventional lifting surface design (i.e. manufacturing or materials)

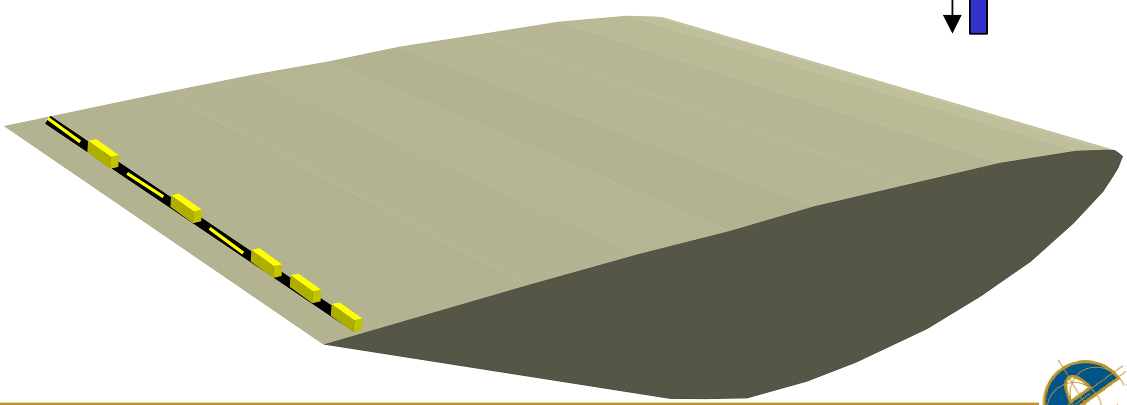


Microtab Assembly & Motion



l = 20 mm
h = 6 mm
w = 1.2 mm





Previous Testing & Results

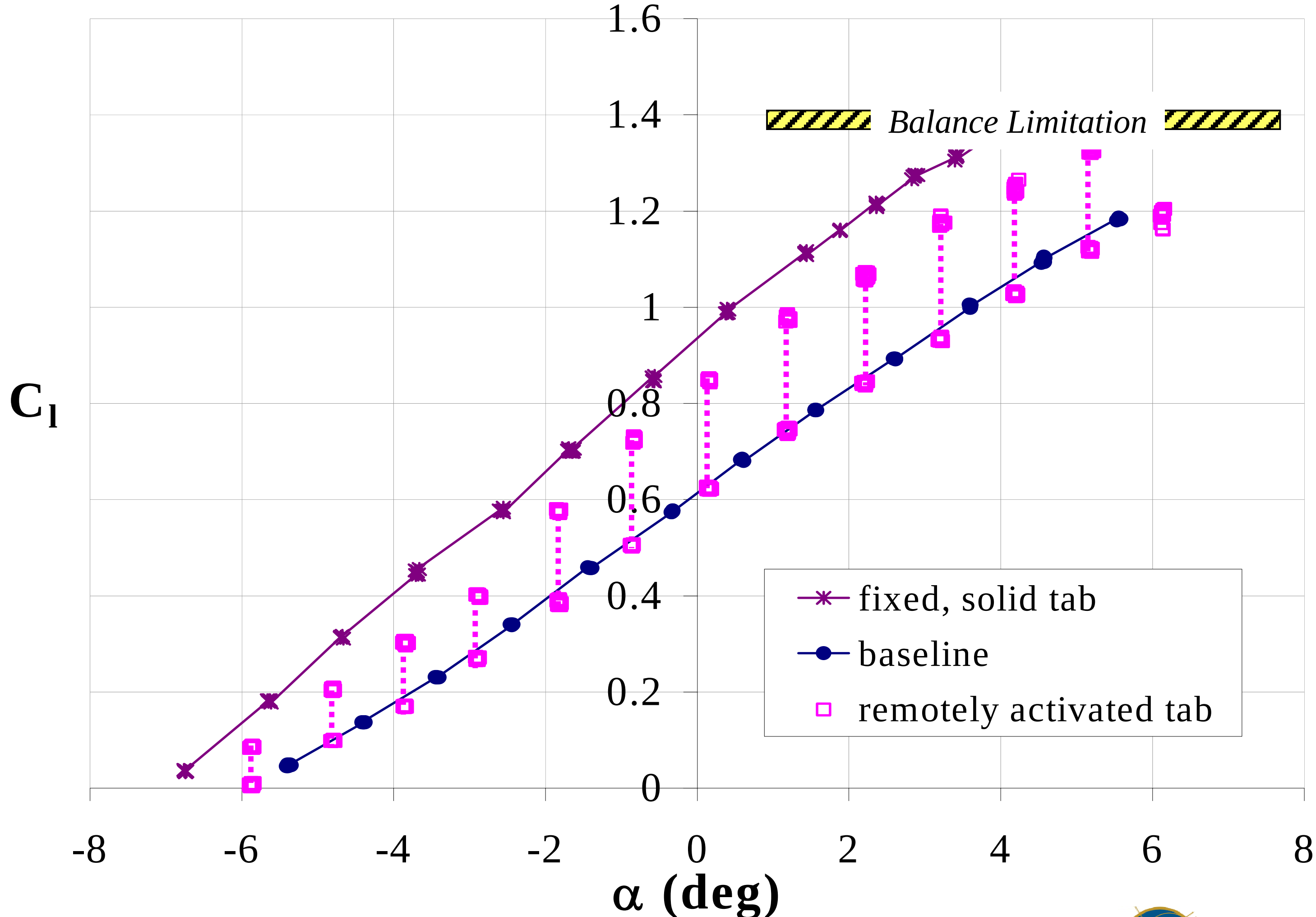
Fixed Solid Tab Model

Integrated Microtab Model

UCDAVIS

Retractable Tab Results

Experimental: GU(25)-5(11)8, Re=1.0×10^6, 1%c tabs, 5%c from TE



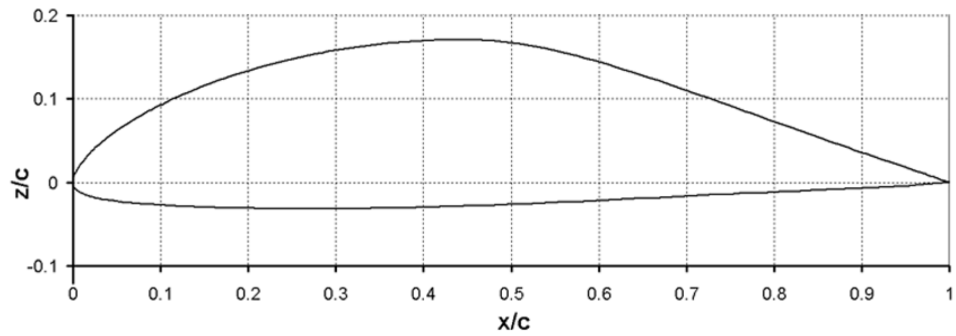
Continued Research Using Computational Fluid Dynamics (CFD)

- Experimental testing is expensive and time consuming. The UC Davis wind tunnel is limited to:
  - Low-speed subsonic conditions
  - Maximum Reynolds number $\approx 1 \times 10^6$
- Advantages of CFD:
  - Relatively fast and inexpensive to study a large number of geometric variations
  - Provides detailed insight to the flow-field phenomena
  - Provides better overall flexibility

Test Airfoil

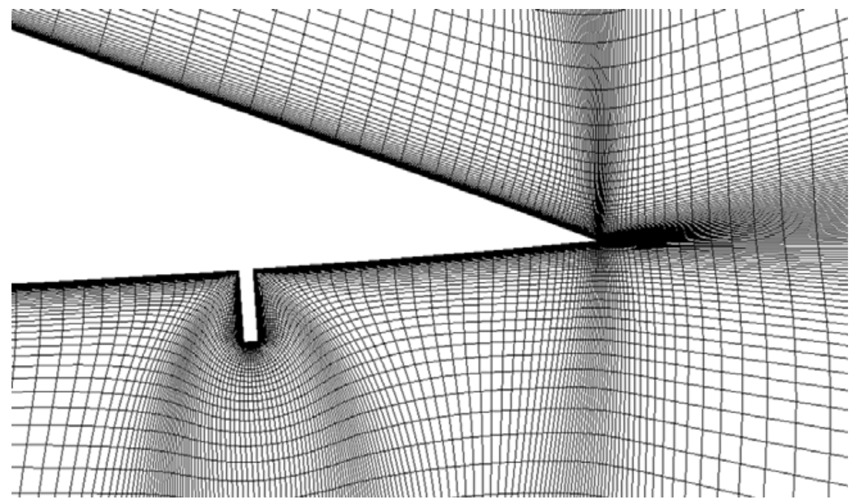
GU-25-5(11)-8

- High-lift airfoil
- Thick upper surface
- Nearly flat lower surface
- Large trailing edge volume



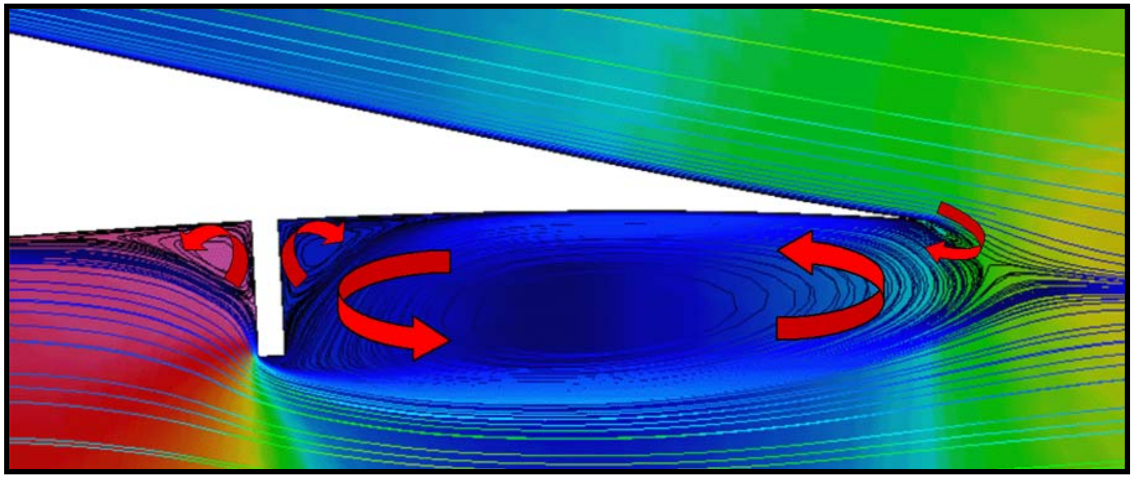
GU25_LTL=95 (C-grid)

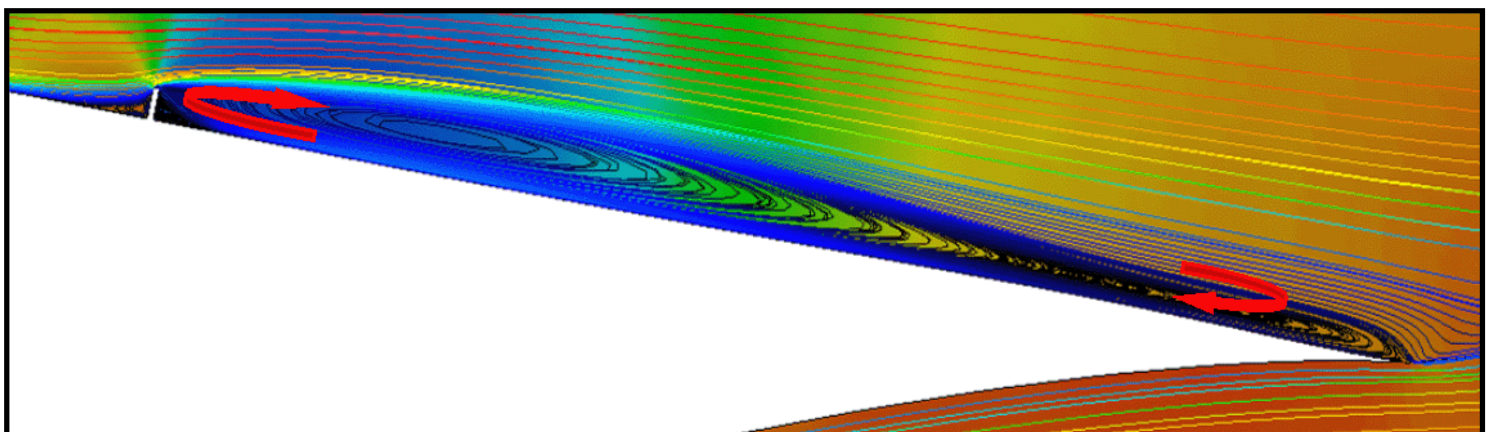
- Farfield at 50c
- (450-496)$\times$(124)
- 75 points on wake-cut (150 total)



Microtab Effect on Flow Development

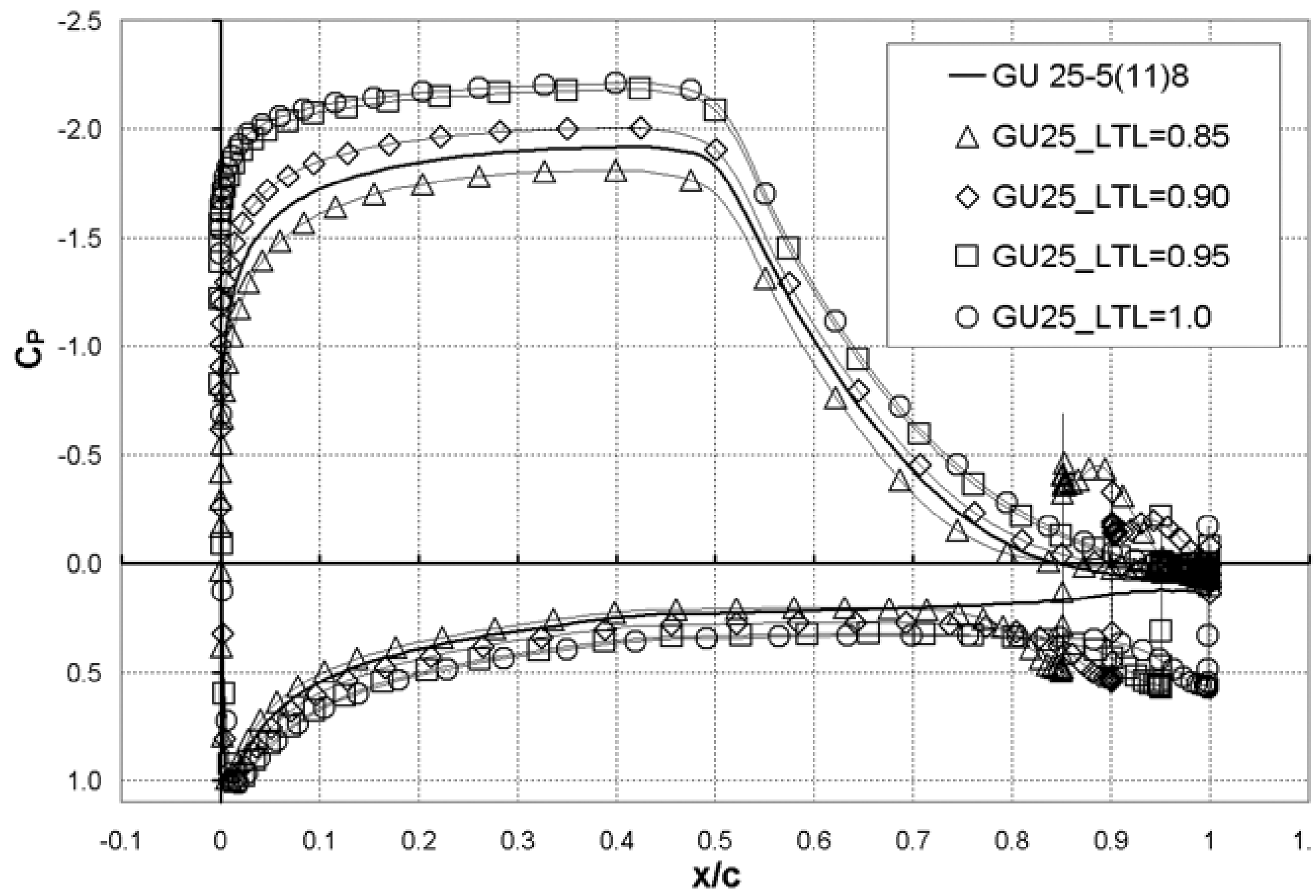
- **Changes in the Kutta condition lead to an effective increase/decrease in camber**





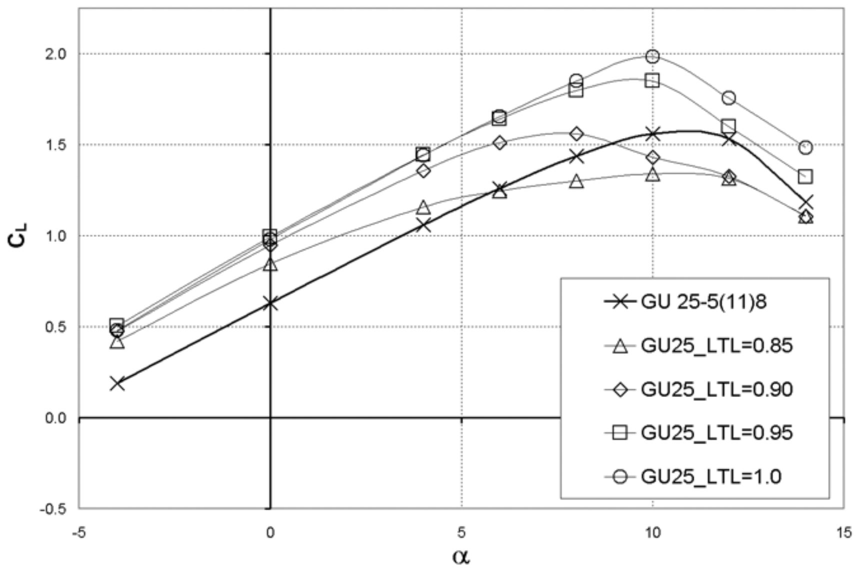
Effect of Lower Surface Tab on Surface Pressure Distribution

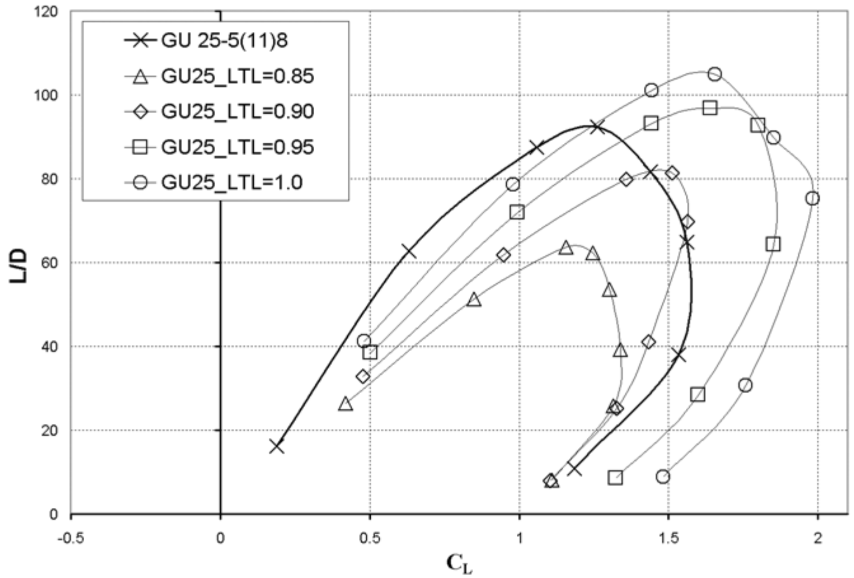
a = 8˚, Re=1.0×10^6, M_∞=0.2, x_{tr}=0.455



Effect of Lower Surface Tab on Lift and L/D

$Re=1.0\times10^6$, $M_\infty=0.2$, $x_{tr}=0.455$



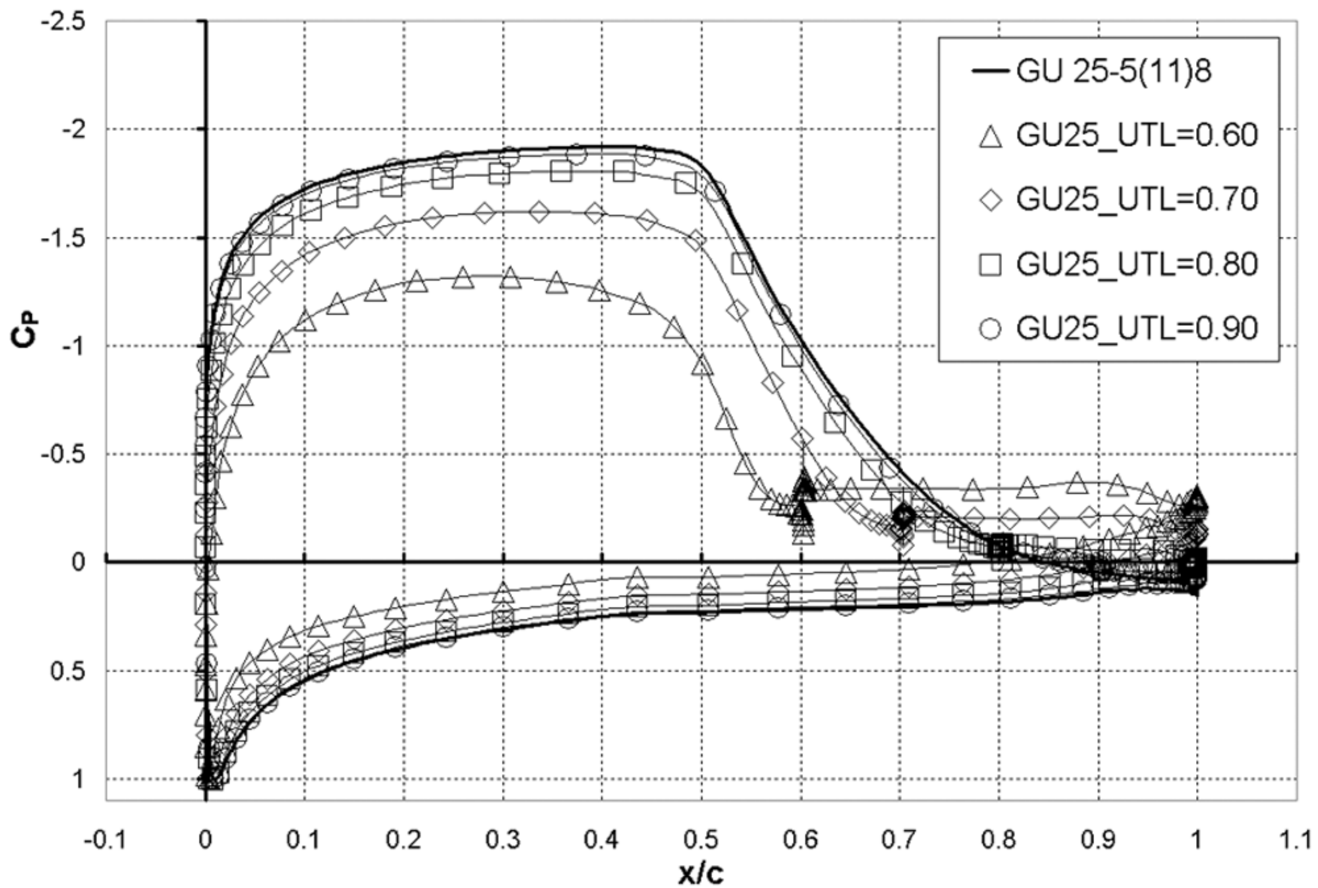


- **Forward location (up to 0.10c forward of trailing edge) has little impact on tab effectiveness for GU airfoil**
- **Tab has fixed height of 0.01c (not optimized)**
  - **Its deployment increases lift at fixed angle of attack**
  - **Its deployment decreases L/D at low lift conditions**
  - **Its deployment increases L/D at high lift conditions**

UCDAVIS

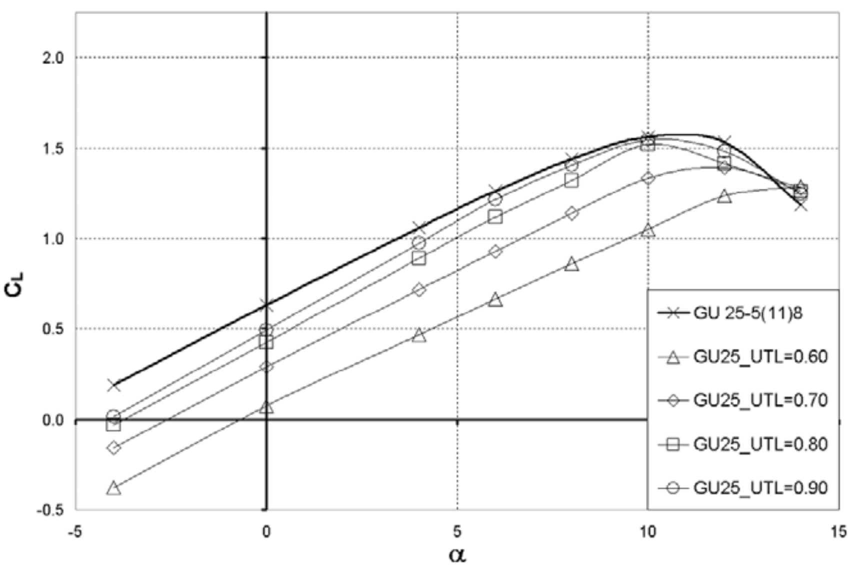
Effect of Upper Surface Tab on Surface Pressure Distribution

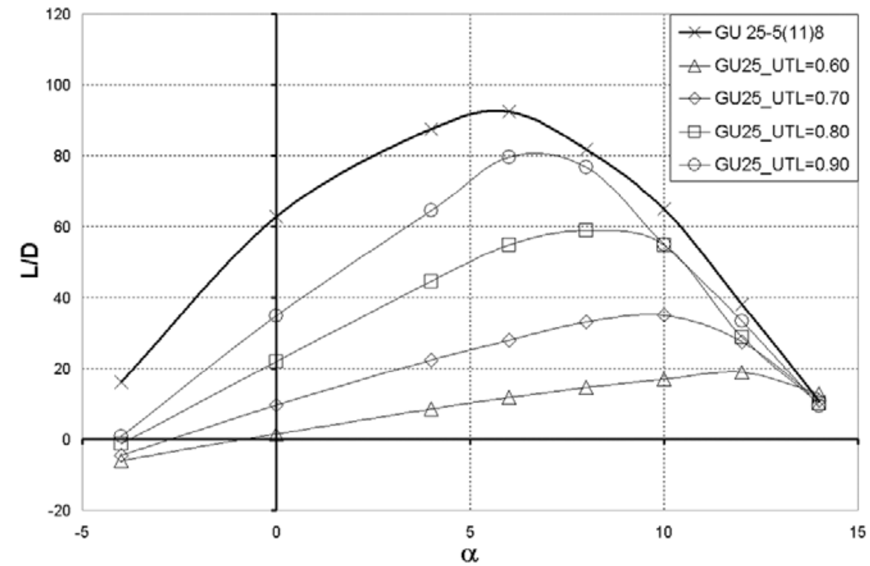
a = 8˚, Re=1.0×10⁶, M_∞=0.2, x_{tr}=0.455



Effect of Upper Surface Tab on Lift and L/D

$Re=1.0\times10^6$, $M_\infty=0.2$, $x_{tr}=0.455$





- Forward location has significant impact on tab load mitigation effectiveness for GU airfoil
- More forward location (onset of pressure recovery) is more effective
- Tab has fixed height of 0.01c (not optimized)
  - Its deployment decreases lift at fixed angle of attack
  - Its deployment decreases L/D (drop in lift and increase in drag)

Active Flow/Load Control Conclusions

- Active flow/load control has been used in the design of wind turbine blades (active pitch, ailerons)
- A new form of active control for large wind turbine blades is the microtab concept
- Microtabs are an effective means of fast load control (load enhancement and mitigation)
- Microtabs remain effective when located forward from the trailing edge
- Focus of work presented is on a flow control actuator. Compete active load control system requires:
  - Sensors
  - Actuators
  - Control algorithm

UCDAVIS

Additional Issues in Blade Aerodynamics

- Computational tools that are:
  - Accurate
  - Less restrictive (provide more design and analysis freedom)
  - Fast
- Aero-acoustics
  - Example 1: Quiet blade tip design
    - Allow higher blade tip speeds for given noise level
    - Higher tip speeds allow for smaller blade chords for given torque
    - Smaller blade chords allow for reduced blade mass
  - Example 2: Rotor-tower flow interactions
    - Critical issue for downwind rotors
- Blade stall prediction
  - Critical issue for stall controlled turbines

UCDAVIS

Acknowledgments

- UC Davis
  - Kevin Standish
  - Eddie Mayda
  - Jonathan Baker
  - Lorena Moreno
  - et al
- Dora Yen Nakafuji, LLNL
- Kevin Jackson, Dynamic Design Engineering, Inc.
- Mike Zuteck, MDZ Consulting
- Derek Berry, TPI Composites, Inc.
- Wind Energy Technology Group, Sandia National Laboratories
- California Energy Commission

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.