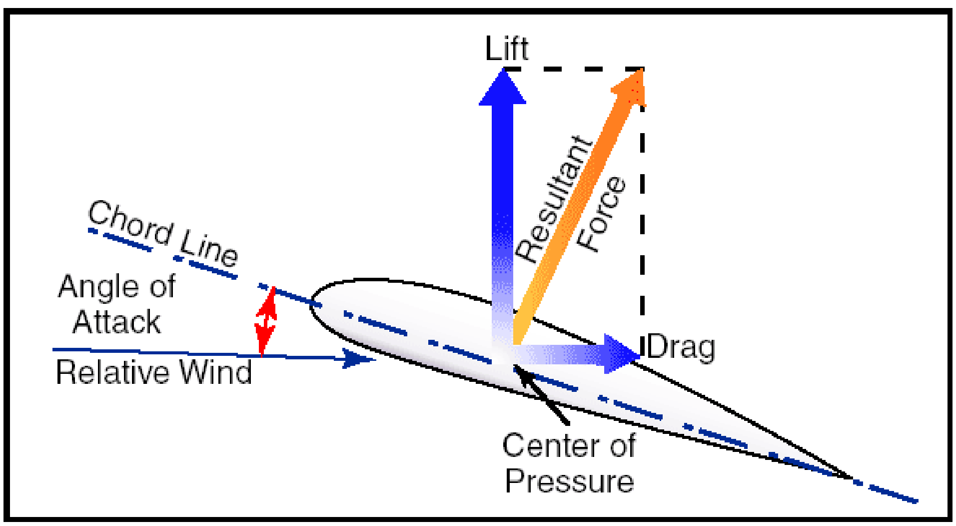
Section 4

Airfoils & Wings

(Chap F5)

Airfoil Review



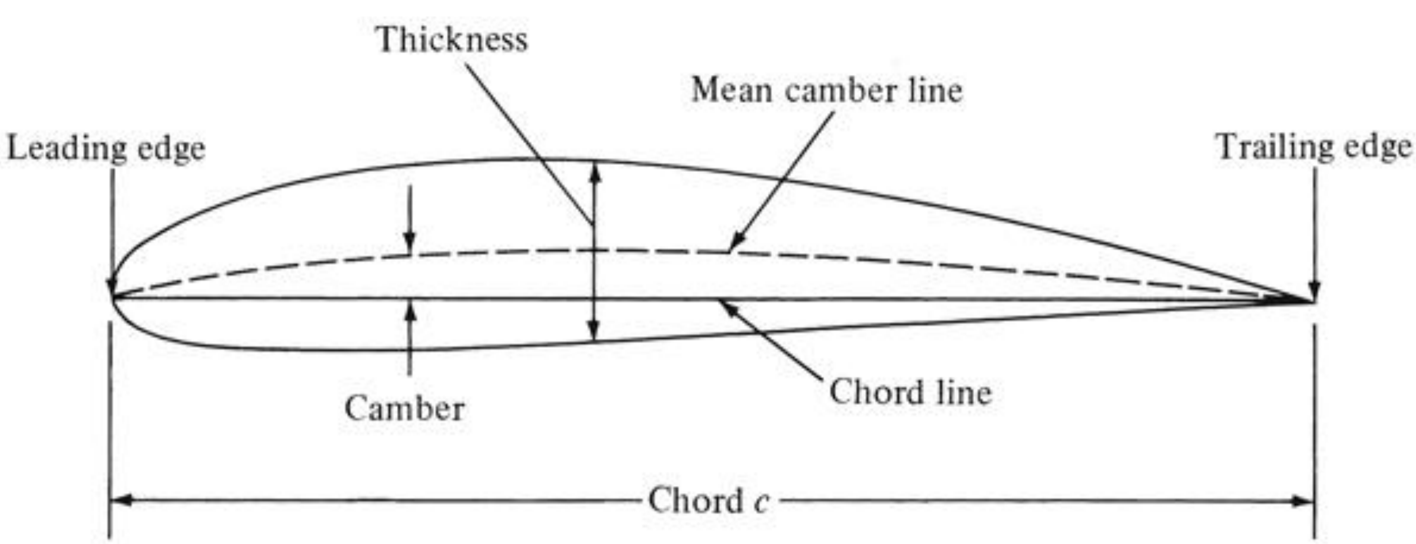


Figure 5.3 Airfoil nomenclature. The shape shown here is a NACA 4415 airfoil.

Aircraft Nomenclature (F5.2):

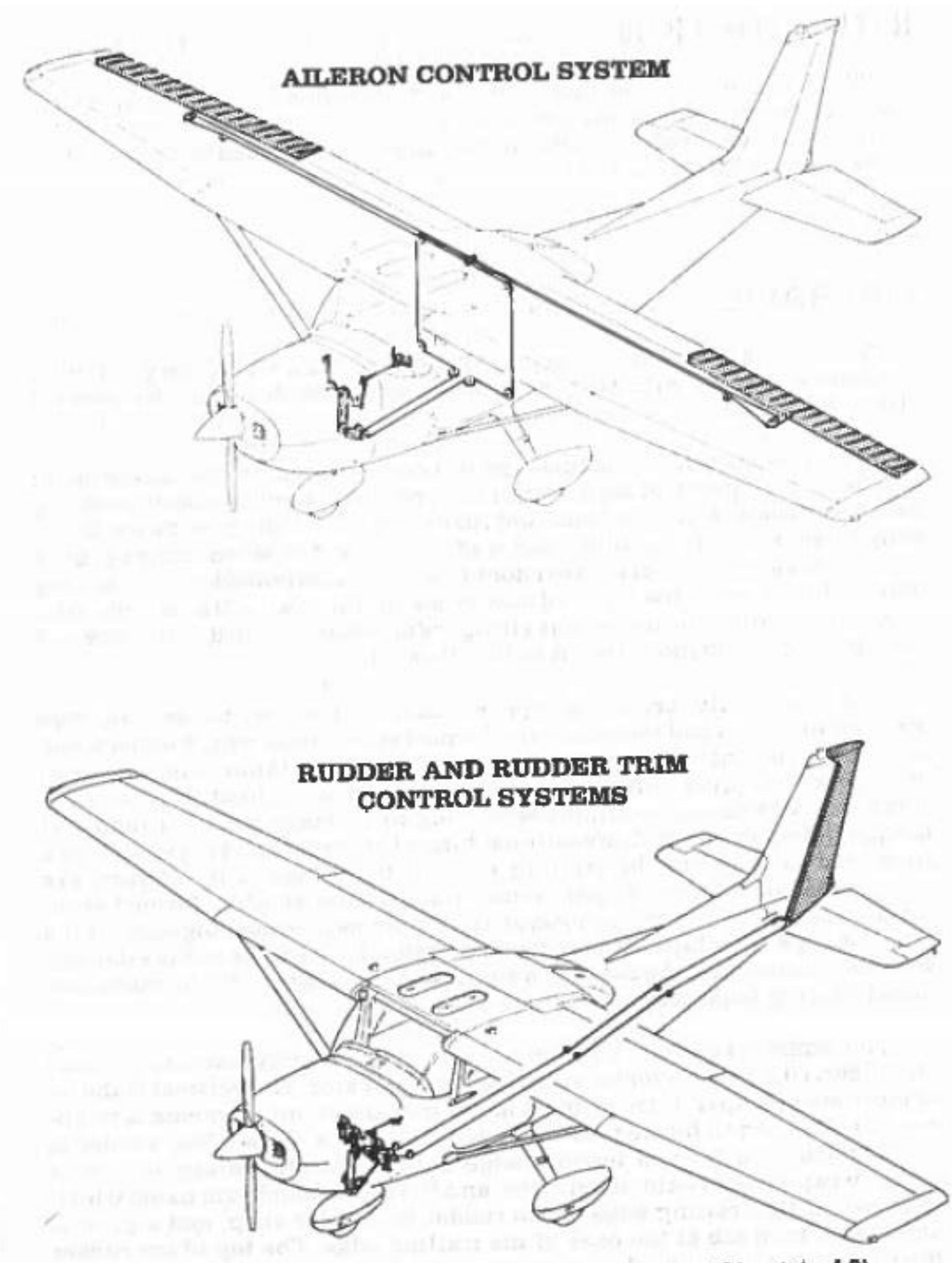
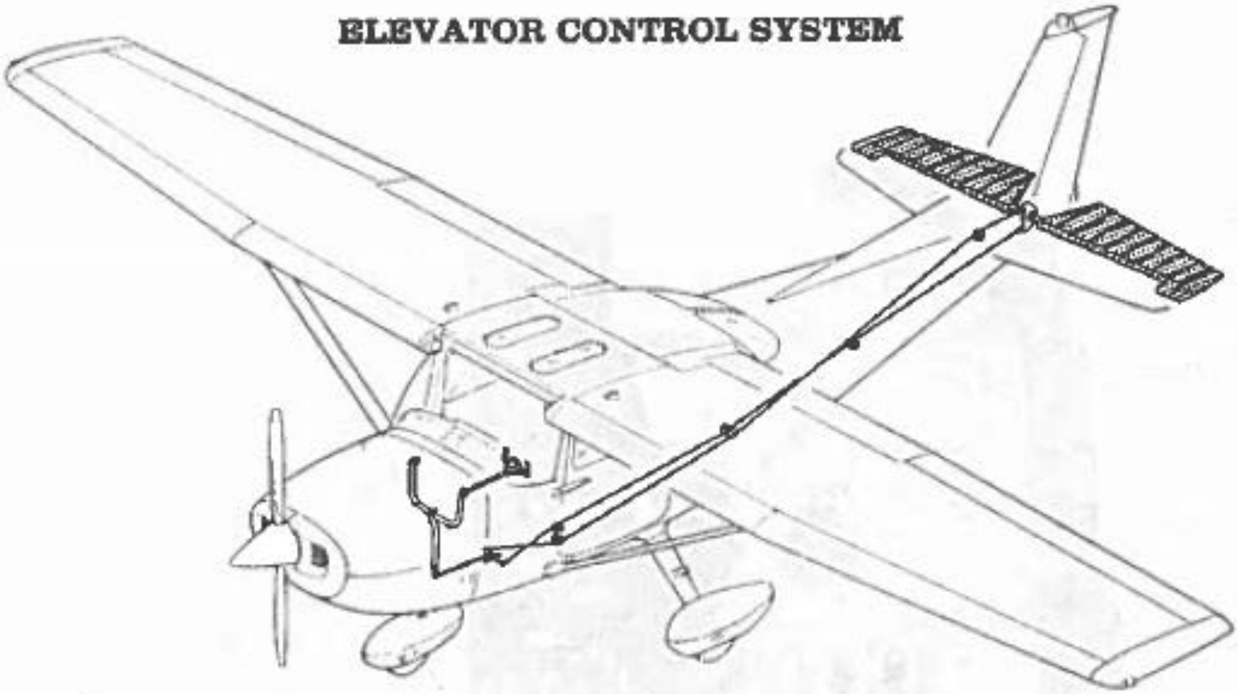


Figure 7-1. Flight Control and Trim Systems (Sheet 1 of 2)



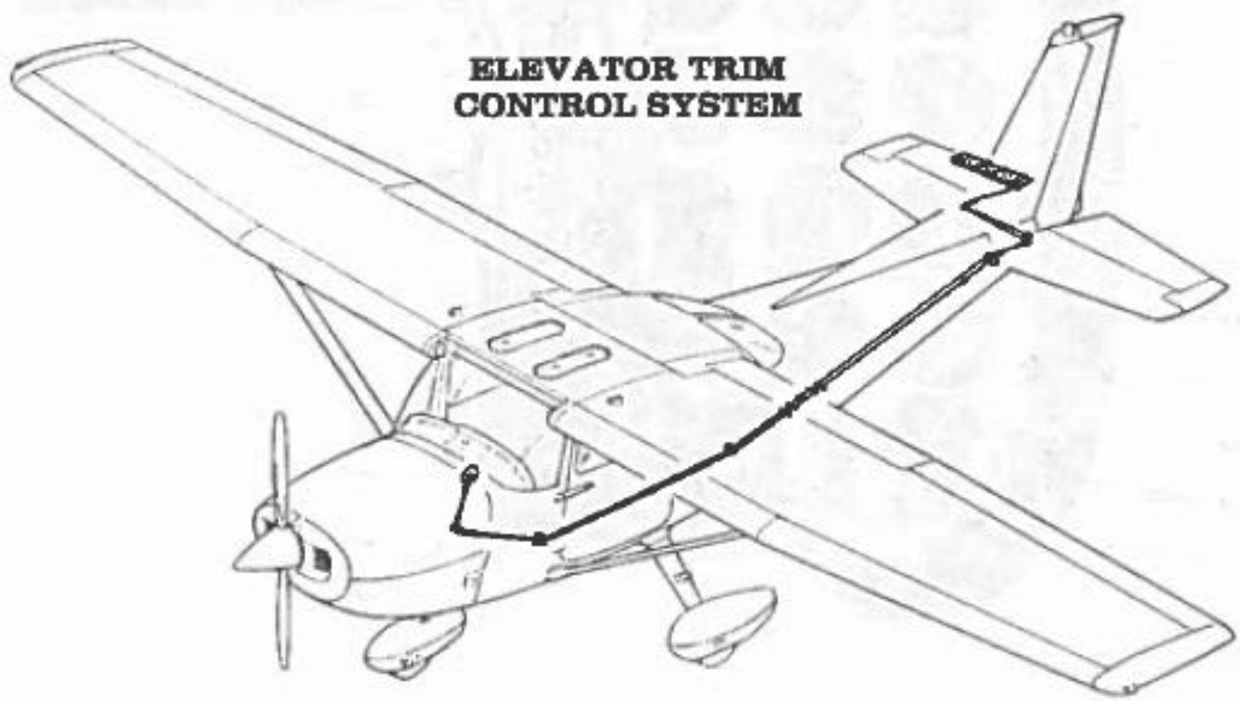
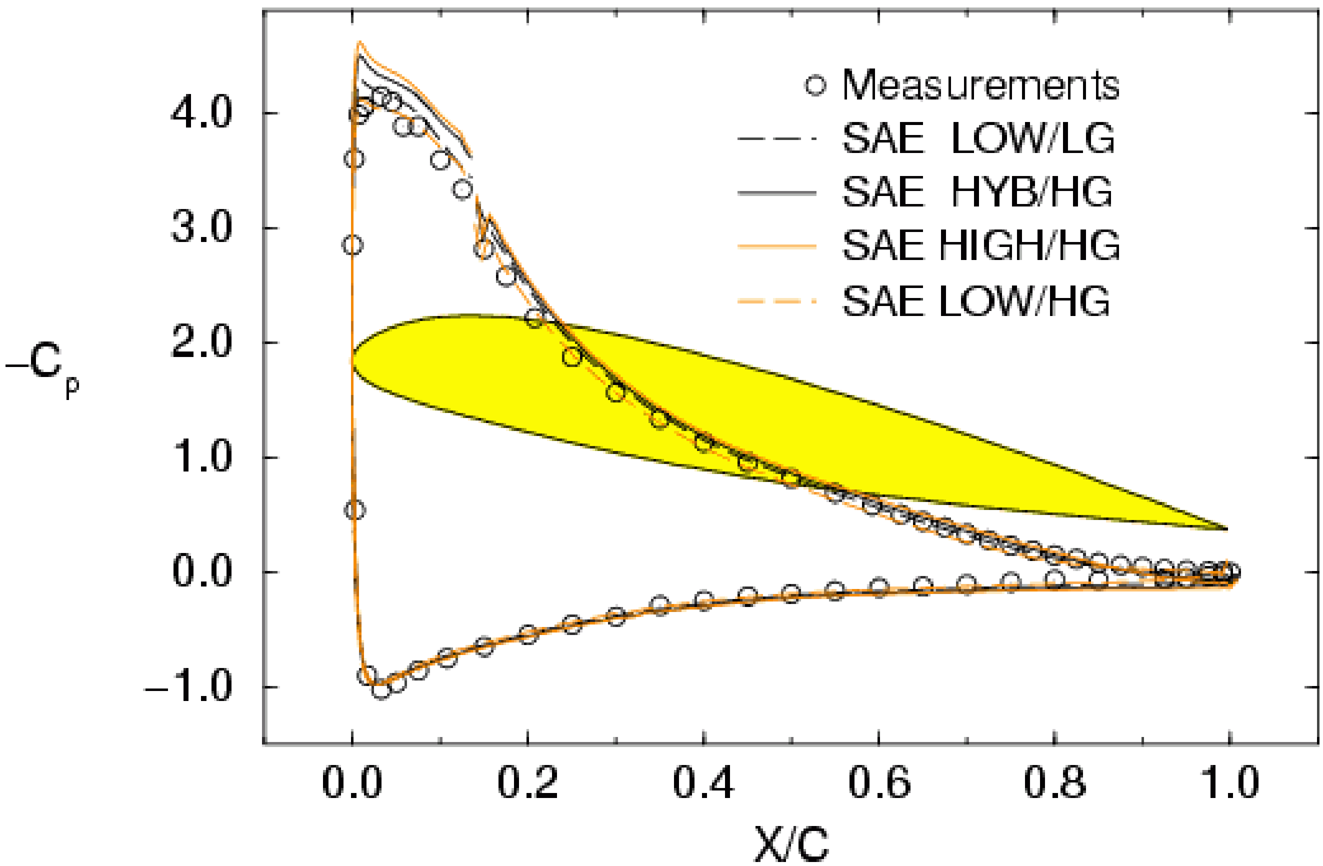


Figure 7-1. Flight Control and Trim Systems (Sheet 2 of 2)

Pressure Distribution on an Airfoil:



Airfoil Data (F5.4): Lift

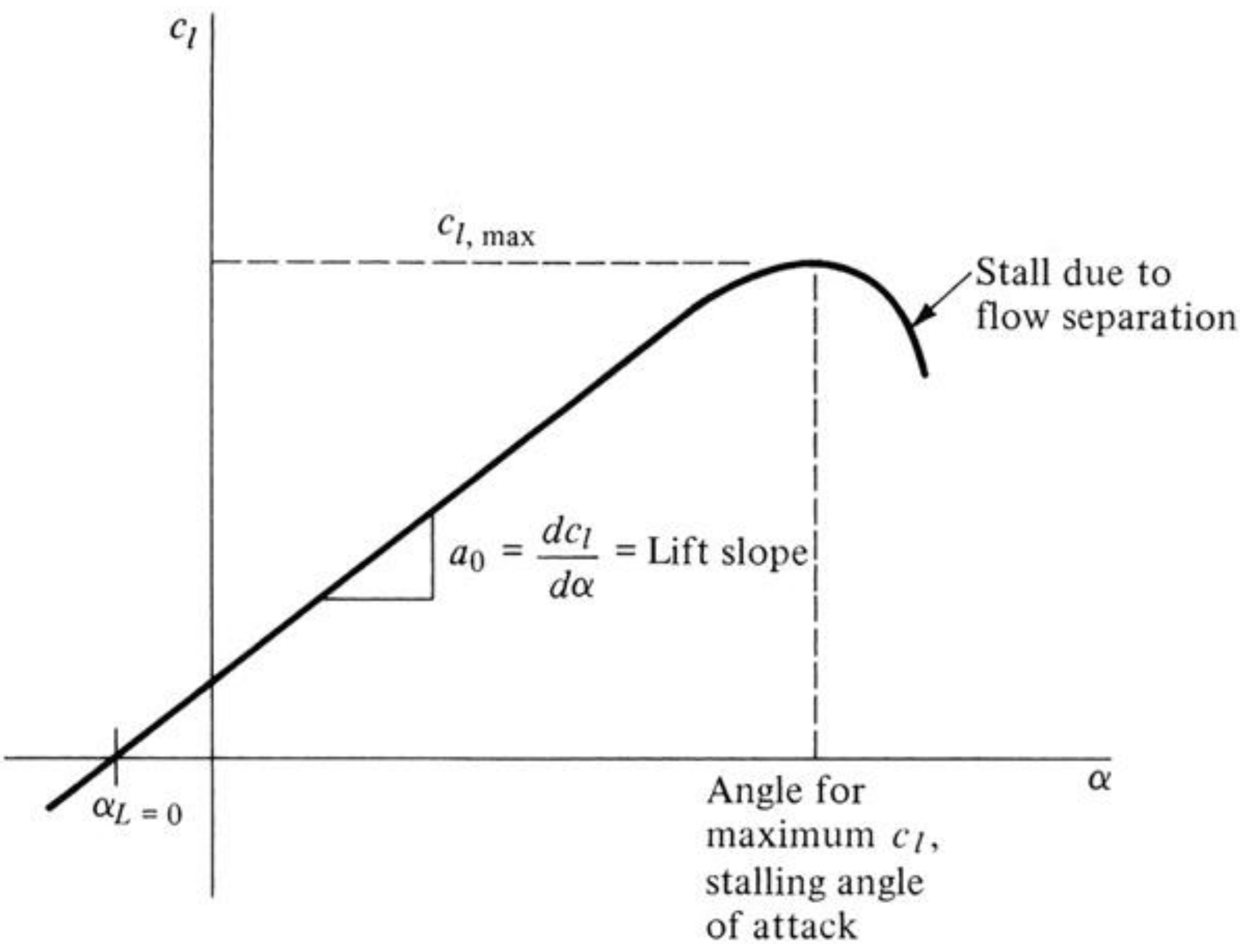


Figure 5.6 Sketch of a typical lift curve.

Stall is due to upper-surface boundary-layer separation, caused by adverse pressure gradient

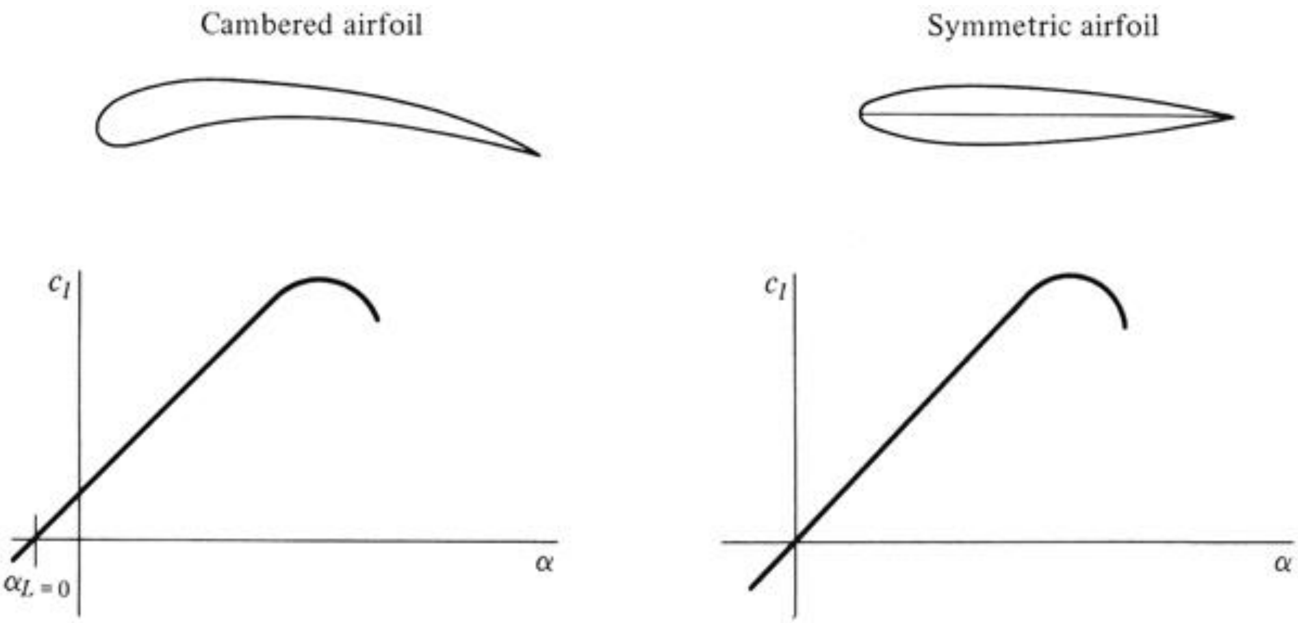


Figure 5.7 Comparison of lift curves for cambered and symmetric airfoils.

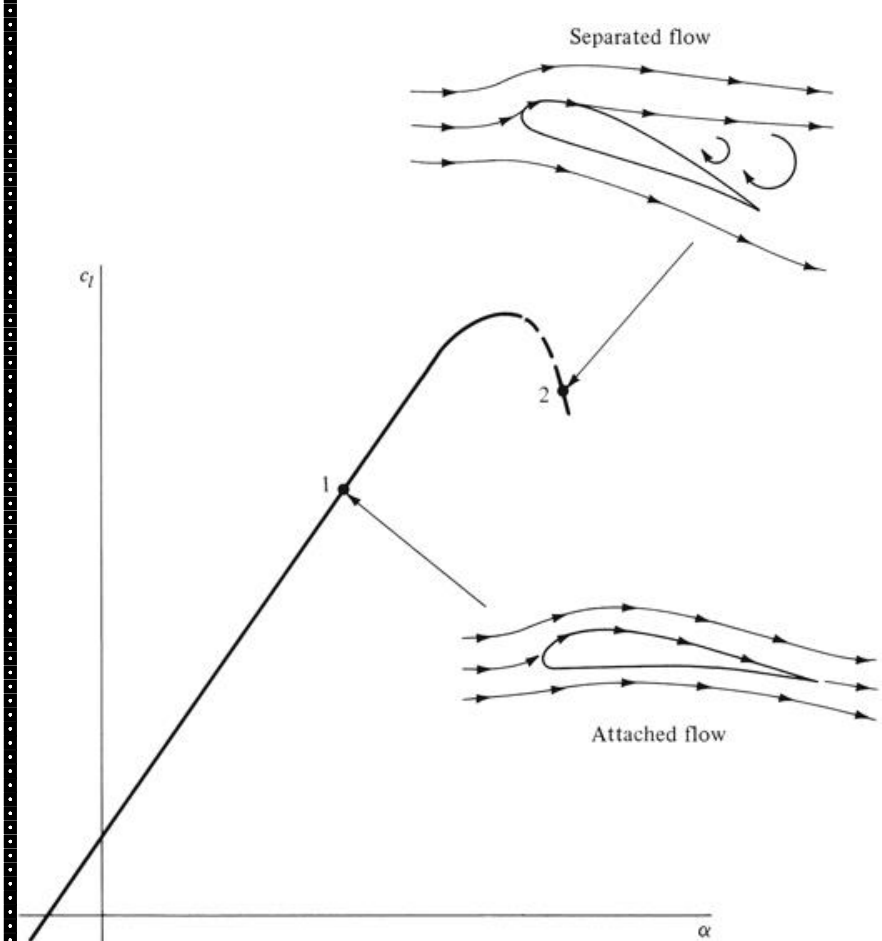


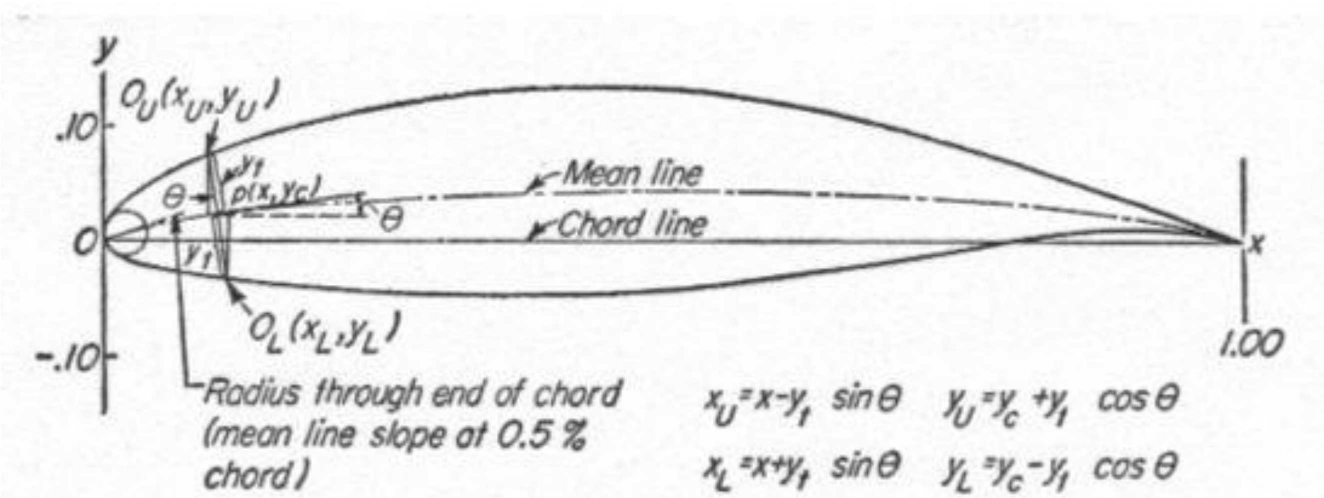
Figure 5.8 Flow mechanism associated with stalling.

NACA Airfoils

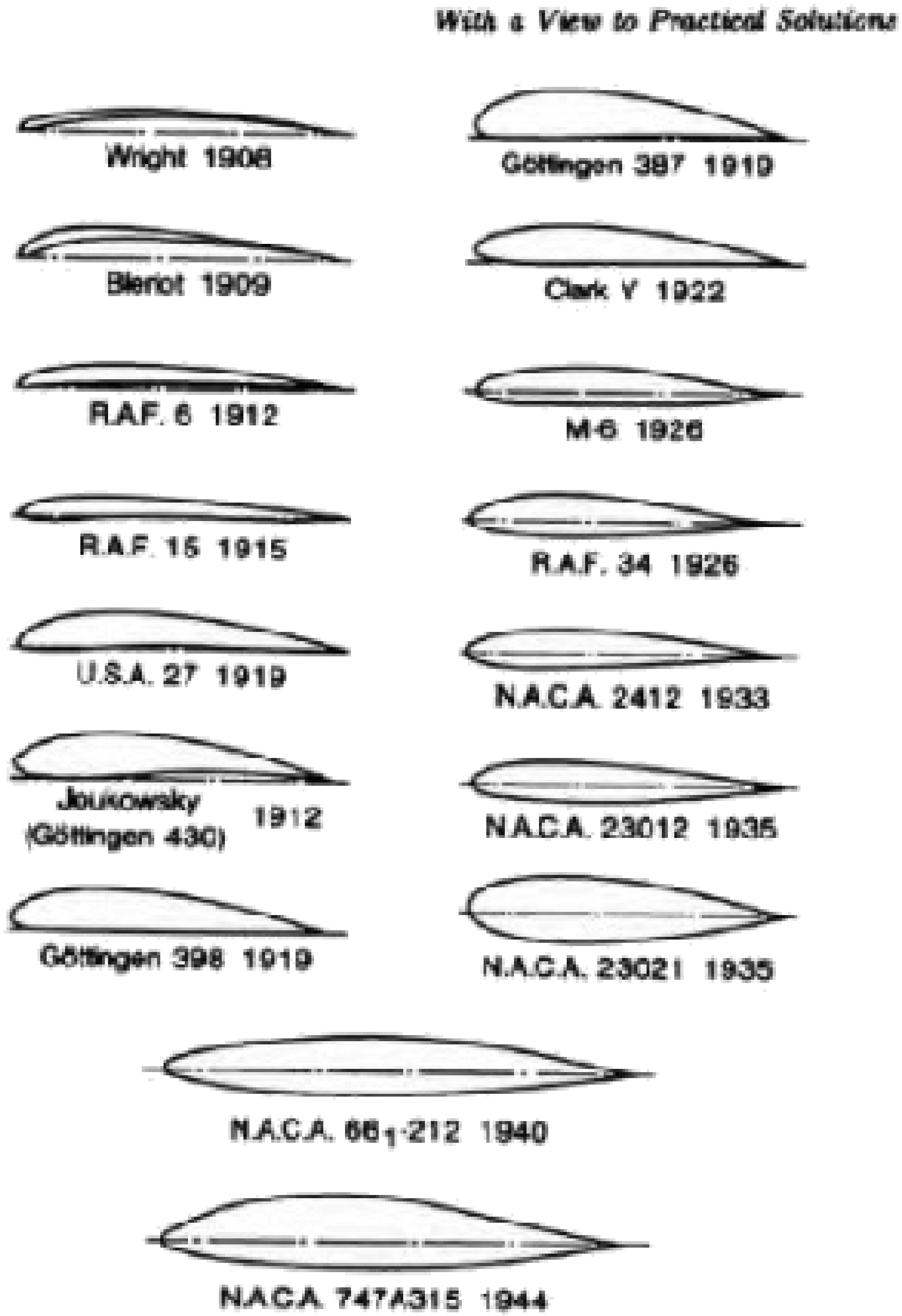
The early NACA airfoil series, the 4-digit, 5-digit, and modified 4-/5-digit, were generated using analytical equations that describe the camber (curvature) of the mean-line (geometric centerline) of the airfoil section as well as the section's thickness distribution along the length of the airfoil. Later families, including the 6-Series, are more complicated shapes derived using theoretical rather than geometrical methods. Before the National Advisory Committee for Aeronautics (NACA) developed these series, airfoil design was rather arbitrary with nothing to guide the designer except past experience with known shapes and experimentation with modifications to those shapes.

This methodology began to change in the early 1930s with the publishing of a NACA report entitled *The Characteristics of 78 Related Airfoil Sections from Tests in the Variable Density Wind Tunnel*. In this landmark report, the authors noted that there were many similarities between the airfoils that were most successful, and the two primary variables that affect those shapes are the slope of the airfoil mean camber line and the thickness distribution above and below this line. They then presented a series of equations incorporating these two variables that could be used to generate an entire family of related airfoil shapes. As airfoil design became more sophisticated, this basic approach was modified to include additional variables, but these two basic geometrical values remained at the heart of all NACA airfoil series, as illustrated below. *(Clarkson College)*

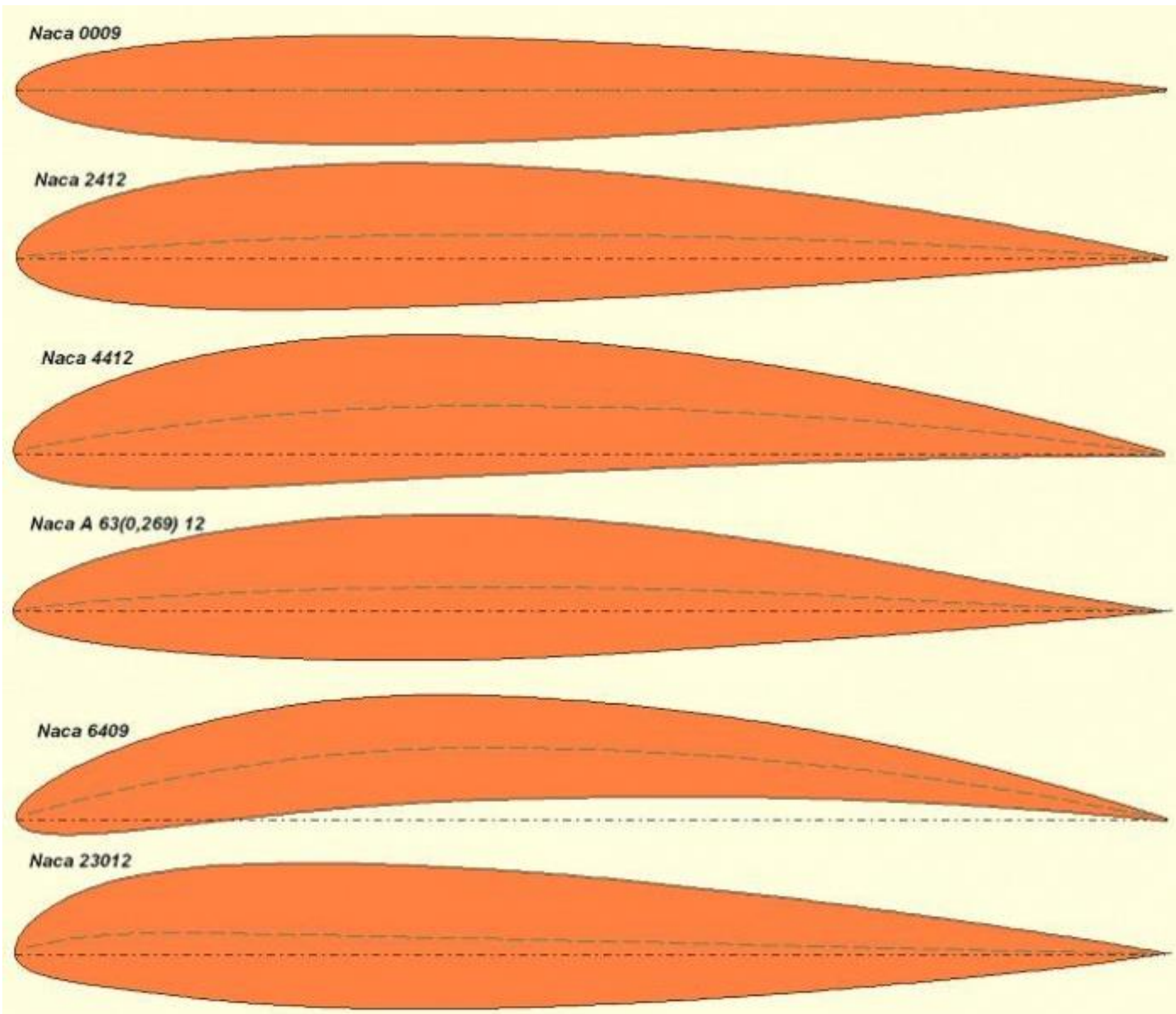
NACA airfoil:



NACA Airfoils



NACA Airfoils:

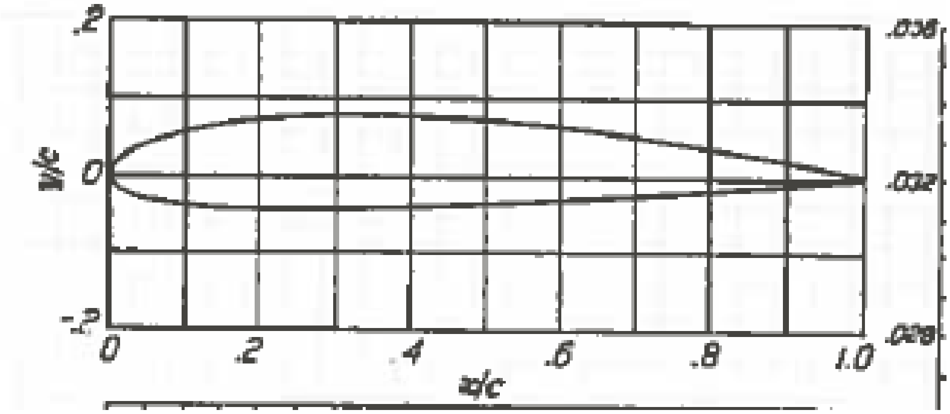


NACA Airfoil Applications:

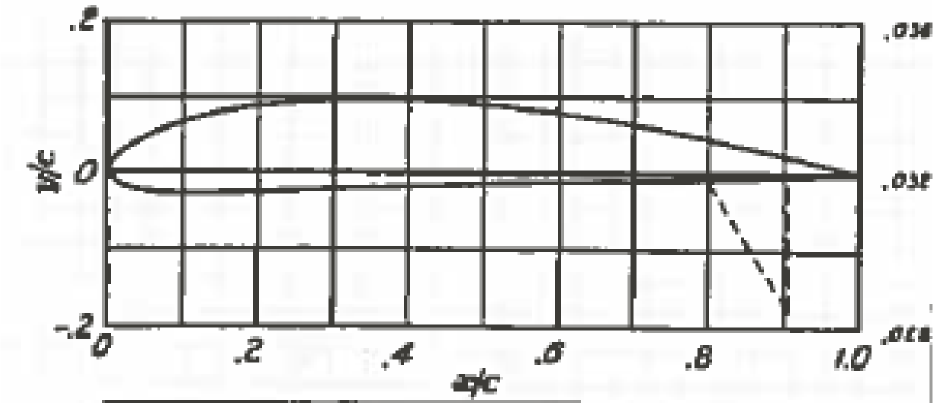
Family	Advantages	Disadvantages	Applications
4-Digit	1. Good stall characteristics 2. Small center of pressure movement across large speed range 3. Roughness has little effect	1. Low maximum lift coefficient 2. Relatively high drag 3. High pitching moment	1. General aviation 2. Horizontal tails ***Symmetrical:*** 3. Supersonic jets 4. Helicopter blades 5. Shrouds 6. Missile/rocket fins
5-Digit	1. Higher maximum lift coefficient 2. Low pitching moment 3. Roughness has little effect	1. Poor stall behavior 2. Relatively high drag	1. General aviation 2. Piston-powered bombers, transports 3. Commuters 4. Business jets
16-Series	1. Avoids low pressure peaks 2. Low drag at high speed	1. Relatively low lift	1. Aircraft propellers 2. Ship propellers
6-Series	1. High maximum lift coefficient 2. Very low drag over a small range of operating conditions 3. Optimized for high speed	1. High drag outside of the optimum range of operating conditions 2. High pitching moment 3. Poor stall behavior 4. Very susceptible to roughness	1. Piston-powered fighters 2. Business jets 3. Jet trainers 4. Supersonic jets
7-Series	1. Very low drag over a small range of operating conditions 2. Low pitching moment	1. Reduced maximum lift coefficient 2. High drag outside of the optimum range of operating conditions 3. Poor stall behavior 4. Very susceptible to roughness	Seldom used
8-Series	Unknown	Unknown	Very seldom used

NACA Airfoil Examples: Lift Data

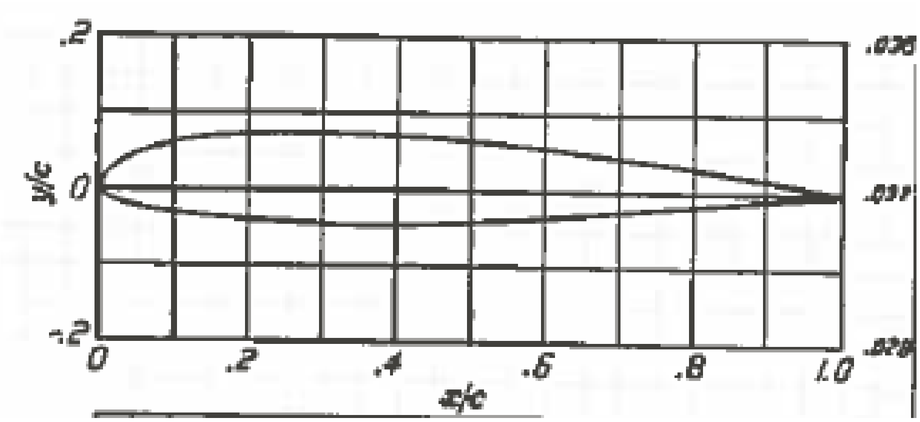
NACA 2412:



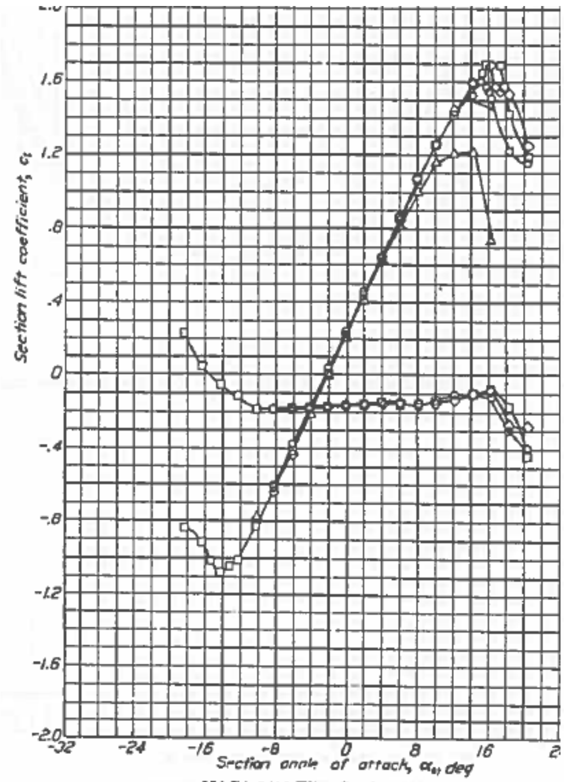
NACA 4412:



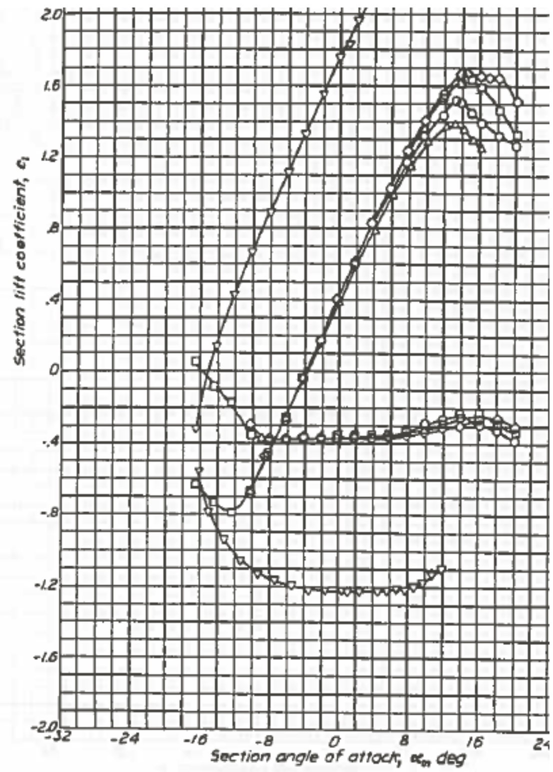
NACA 23012:



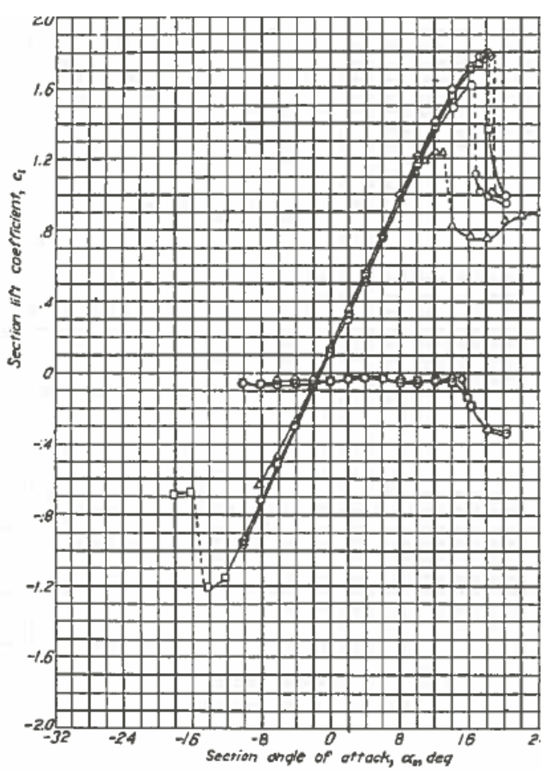
NACA Airfoil Examples: Coeff. Of Lift Data



NACA 2412 Wing Section



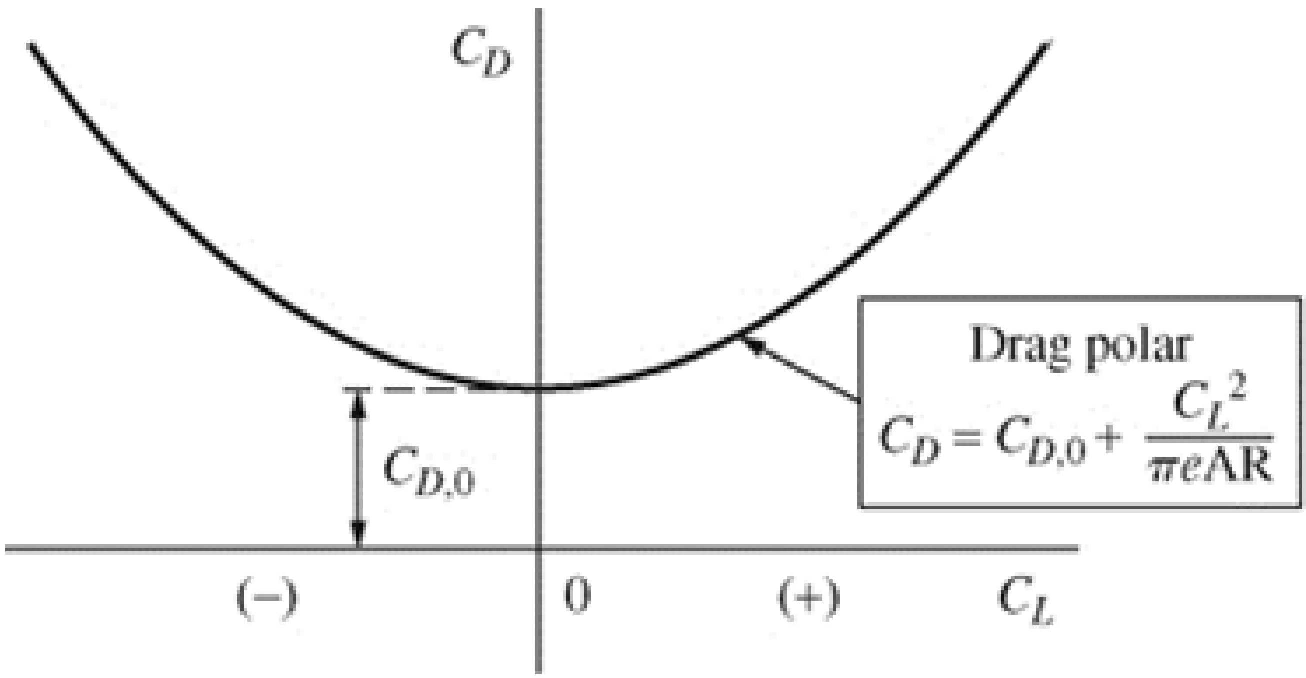
NACA 4412 Wing Section



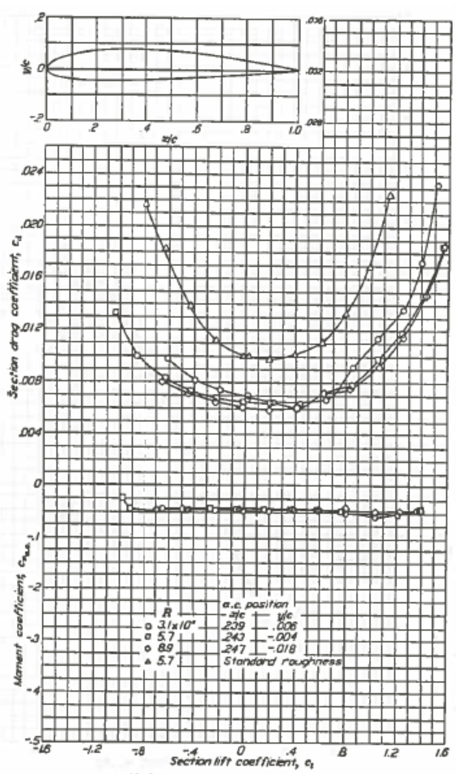
NACA 23012 Wing Section

Airfoil Data (F5.4): Drag

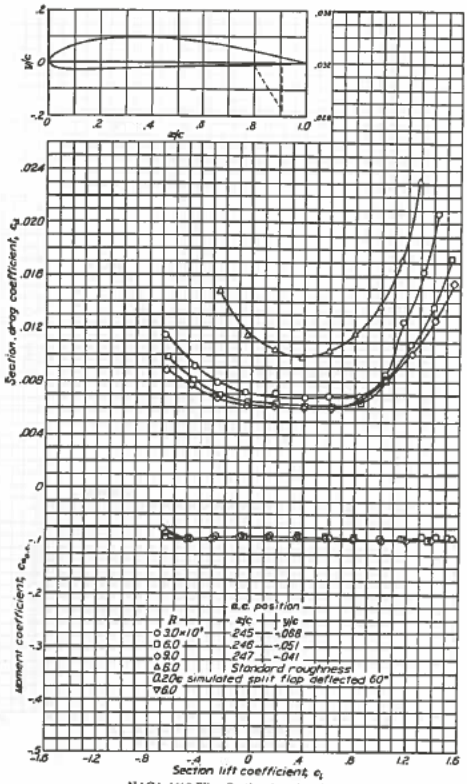
Drag "Polar" (F6.1)



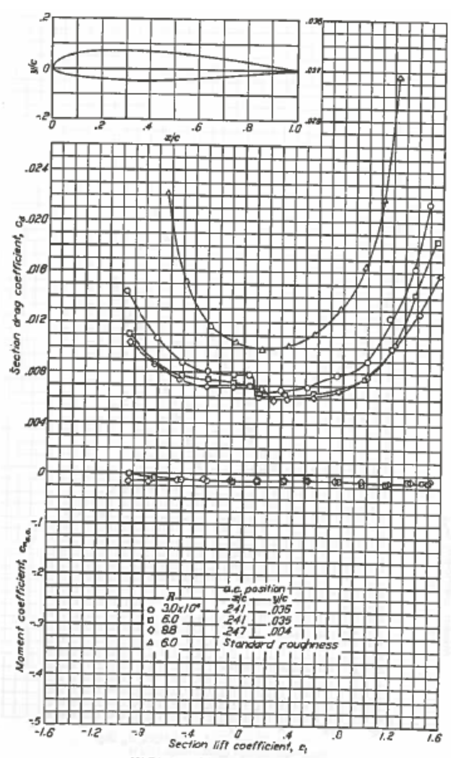
NACA Airfoil Examples: Coeff of Drag Data



NACA 2412 Wing Section (*continued*)

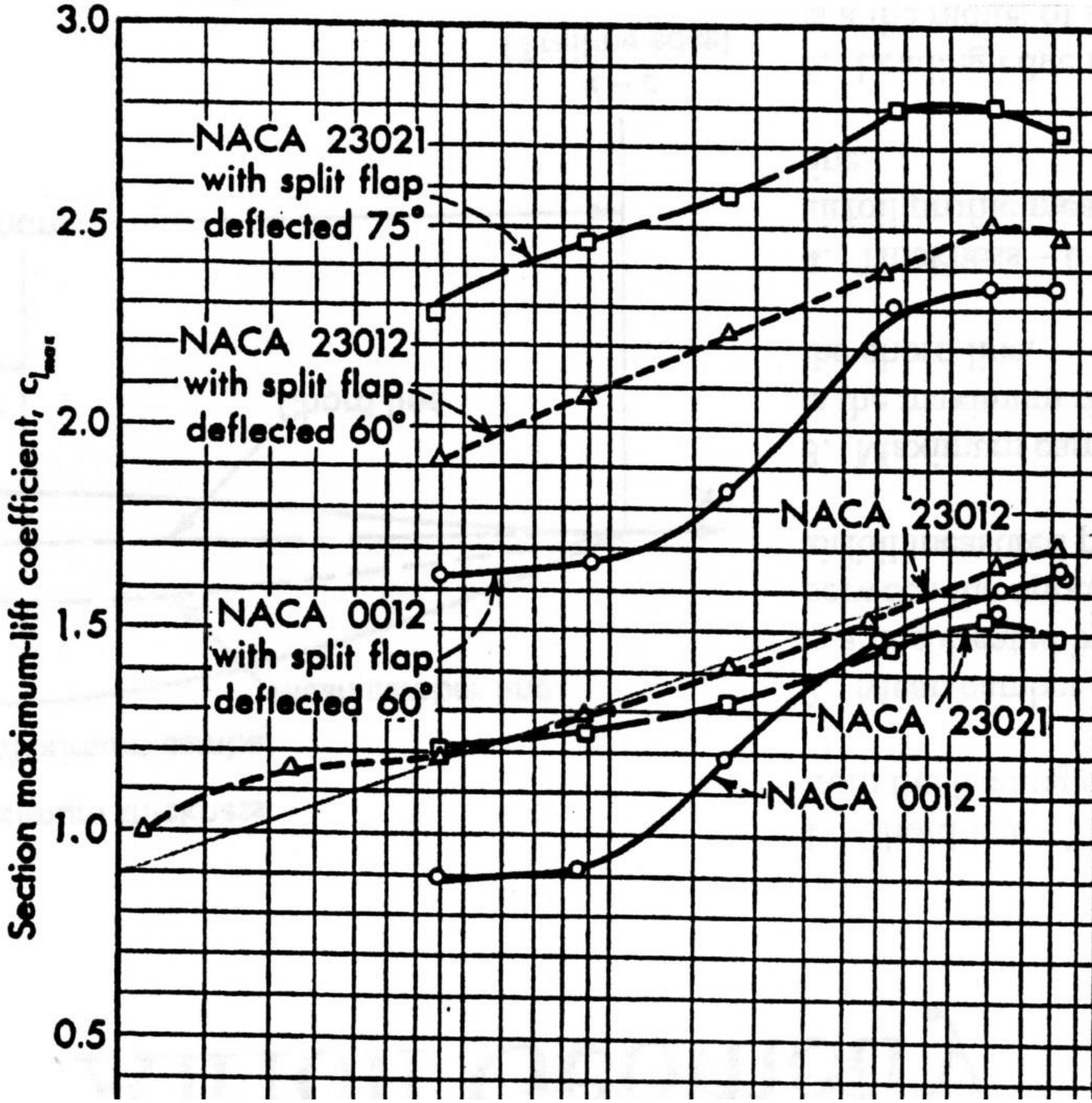


NACA 4412 Wing Section (*continued*)

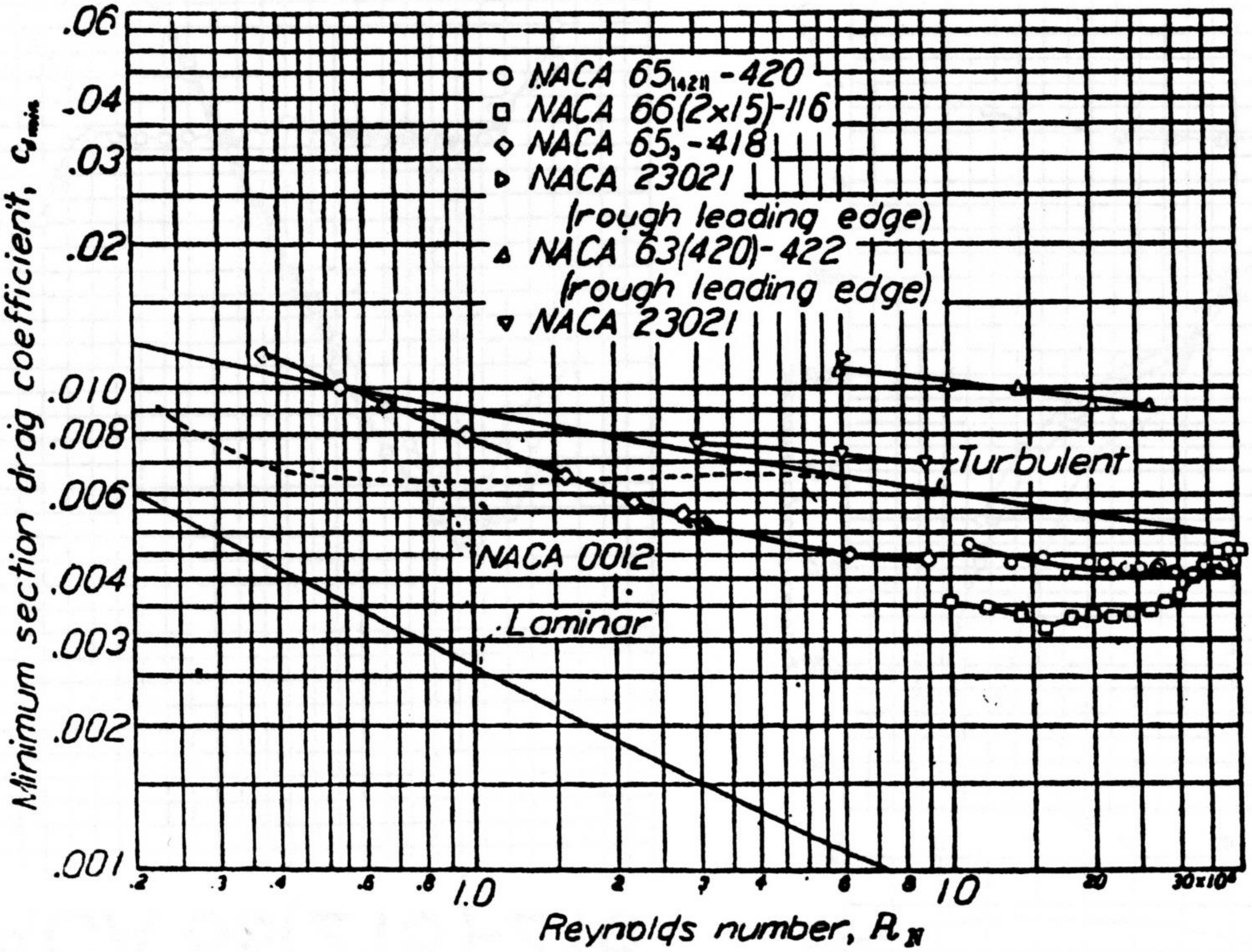


NACA 23012 Wing Section (*continued*)

Maximum Lift Coefficient



Maximum Drag Coefficient



Laminar vs Turbulent Boundary Layer:

What Affects Transition Location Re_x?

"Drag Bucket"

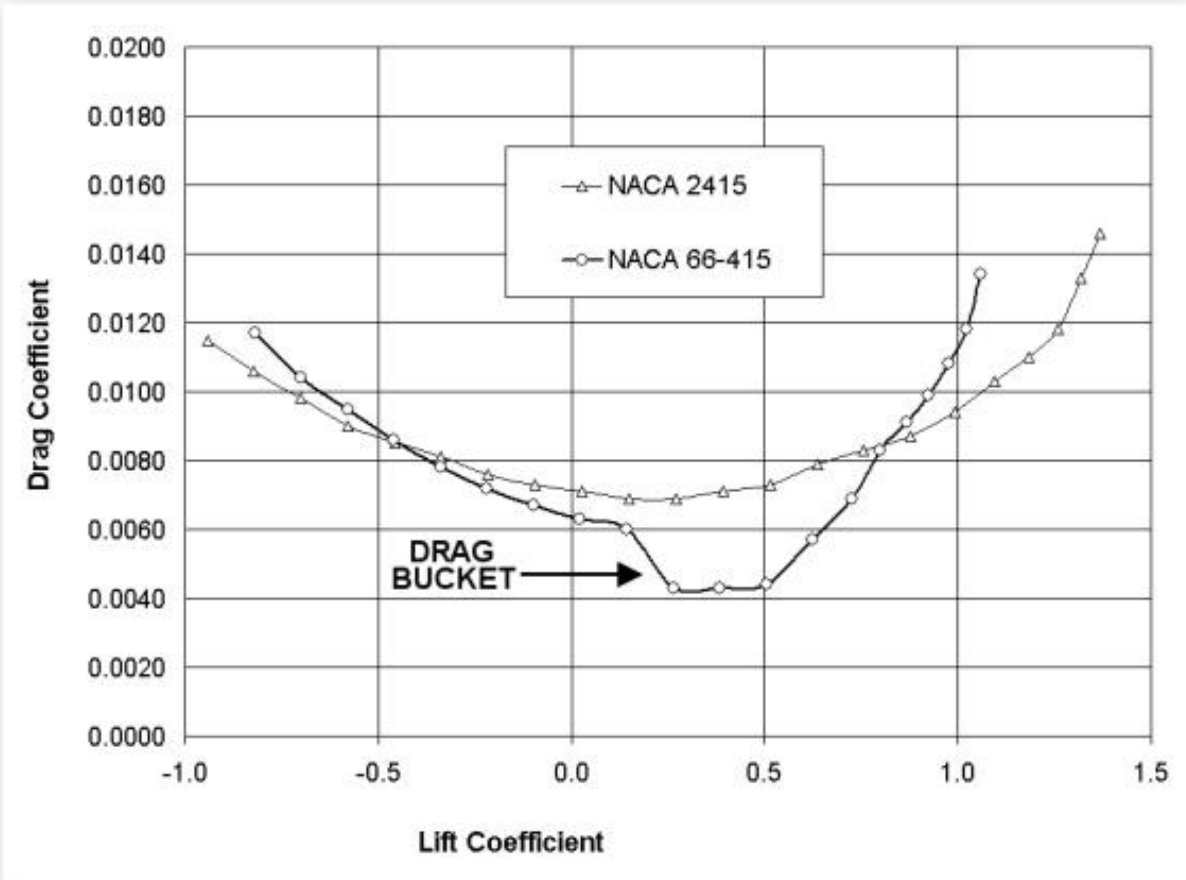
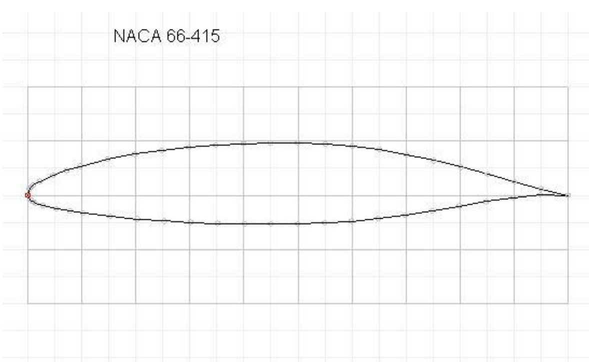
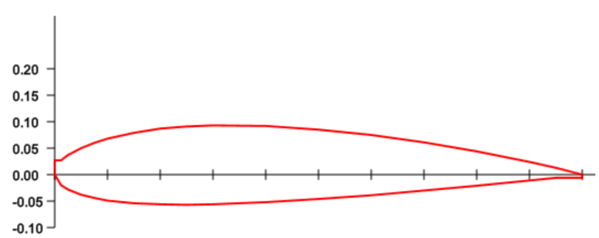


FIGURE 3: Laminar airfoil and non-laminar airfoil drag polar chart comparisons.





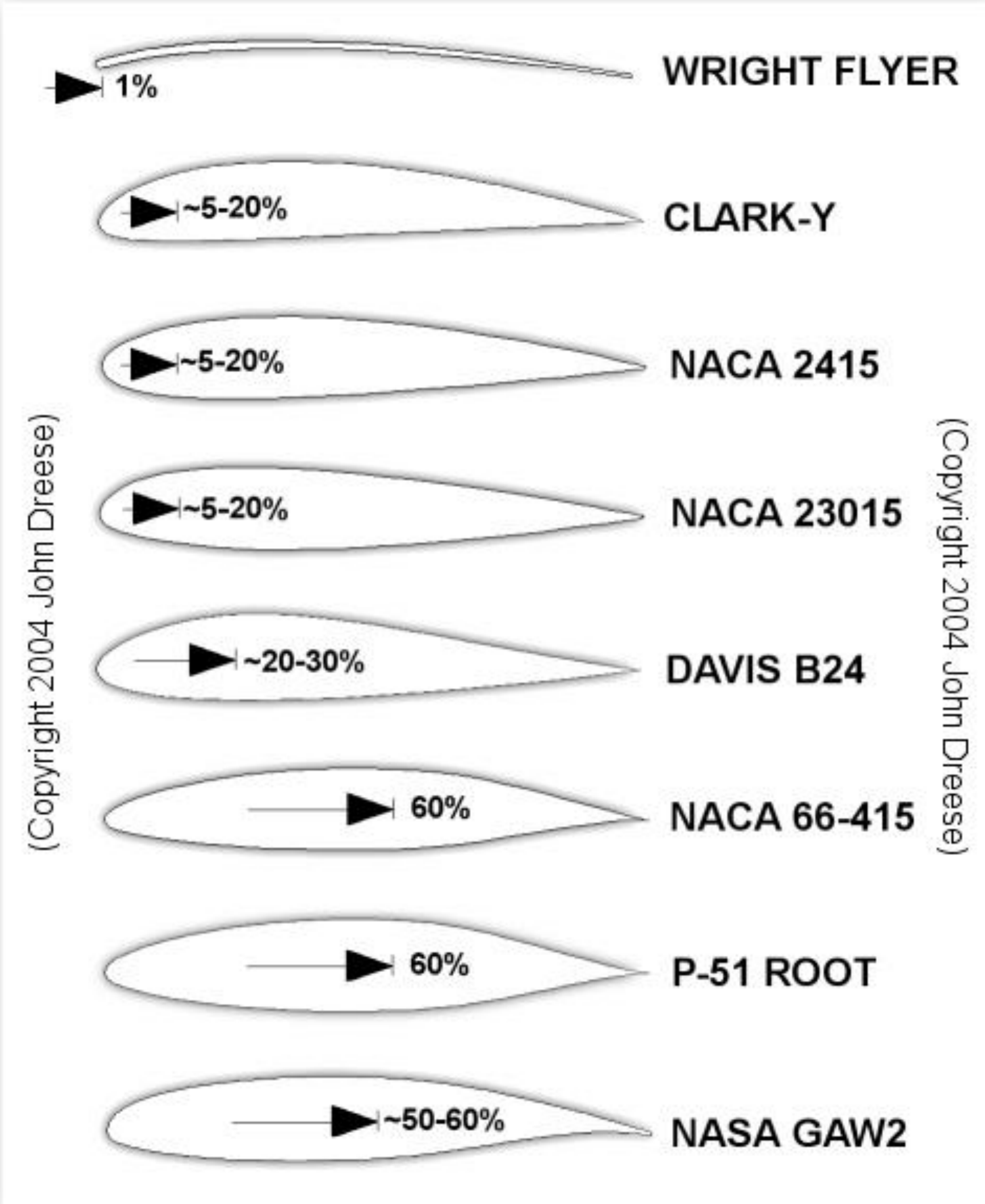


FIGURE 2: Extent of laminar flow on some famous airfoils.

Moment on an Airfoil:

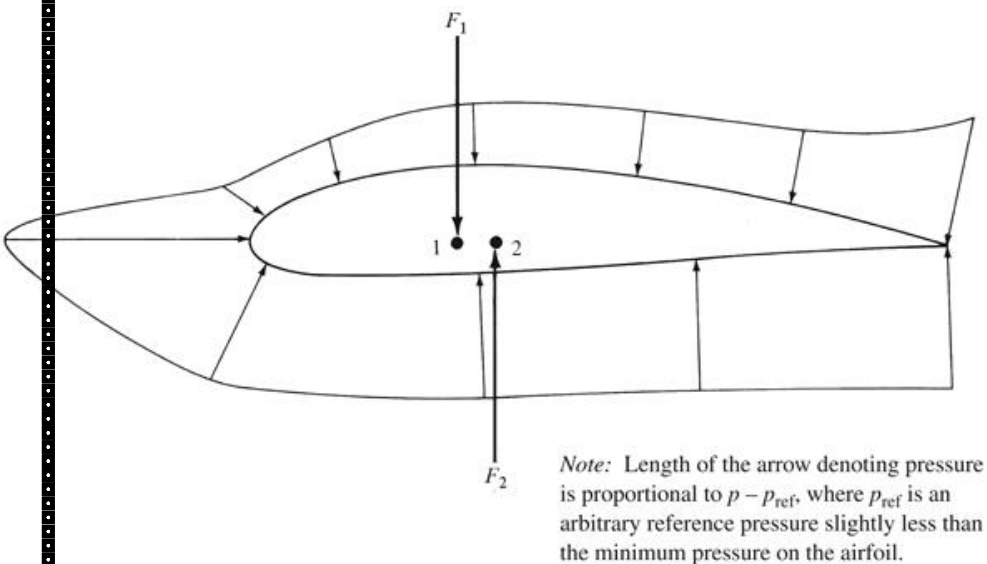


Figure 5.5 The physical origin of moments on an airfoil.

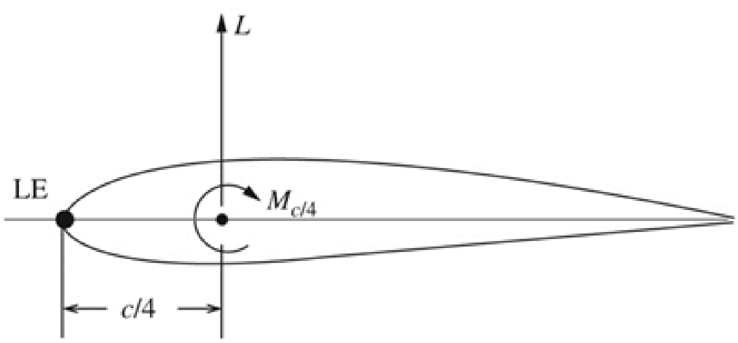
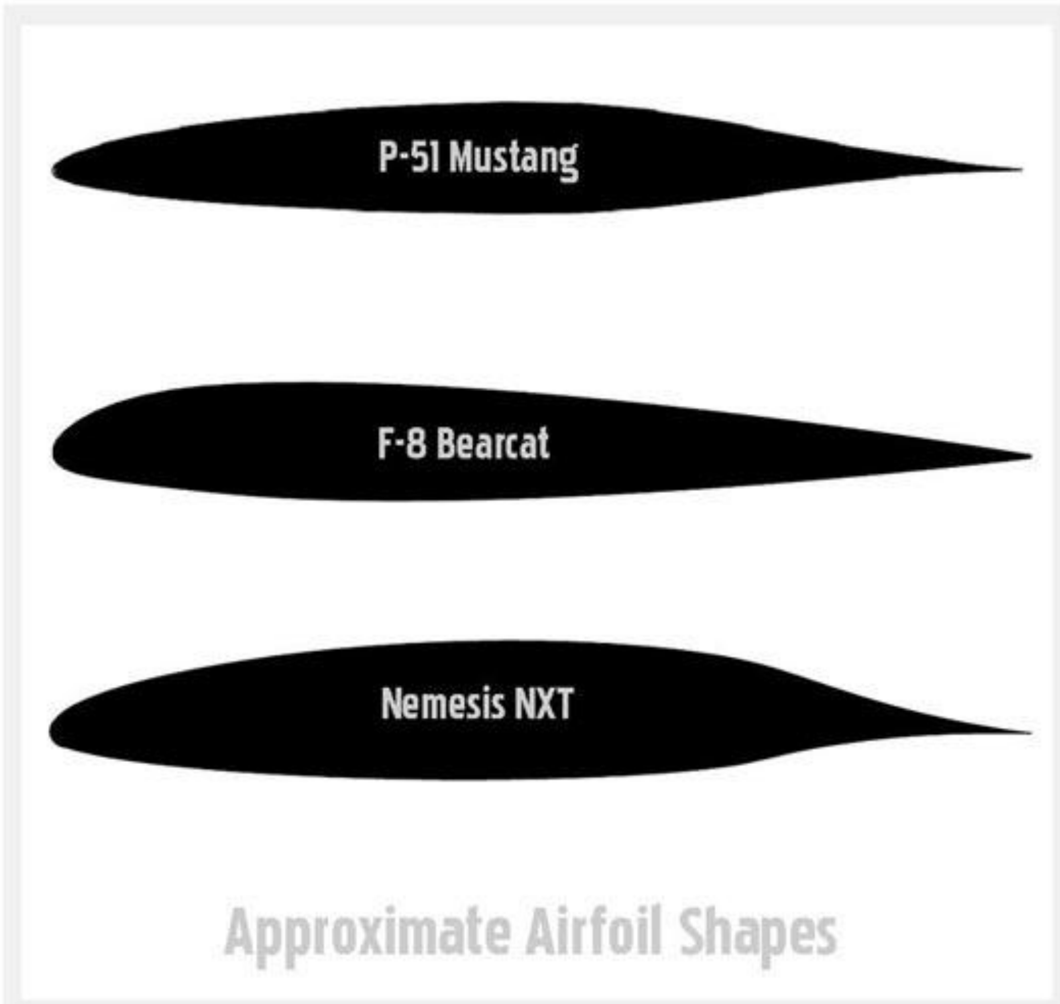


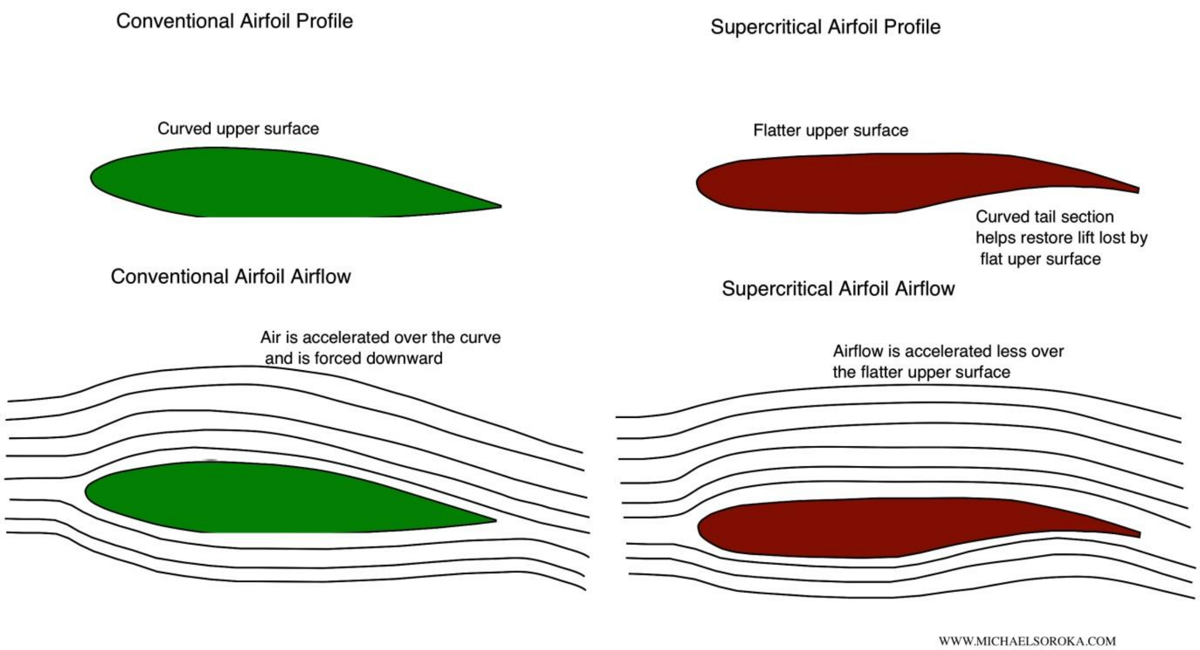
Figure 5.11 Sketch of lift and moments on an airfoil.

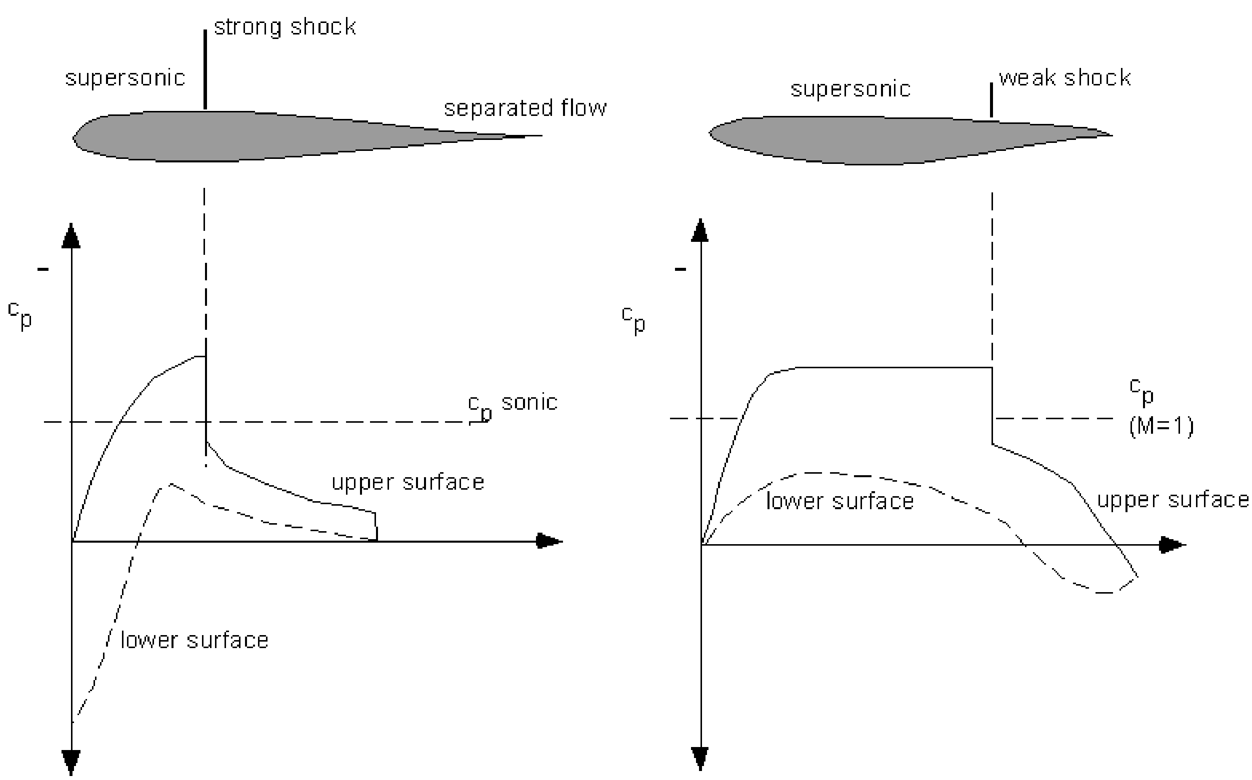
Modern Airfoils:



(UICU Airfoil Site)

“Supercritical” Airfoils:





From Bertin & Smith, 2nd Edition, p. 366

Rotorcraft Airfoils: "Practical Helicopter Aerodynamics" by R. W. Prouty

Figure 6-1—Rotor Airfoils

Old Airfoils	Comments	Where Used
	Symmetrical, 12% thick	Sikorsky S-51 Vertol CH-46A,47A
	Symmetrical, 15% thick	Bell 47 Hiller 12E Hughes 300,500
	Developed from symmetrical, 10% thick airfoil by drooping nose	Vertol CH-46, 47

Modern Airfoils		
	Slightly cambered	Sikorsky S-76 UH-60
	Wortmann rotor airfoil	Bell 214
	Modification of laminar-flow airfoil	Vertol YUH-61
	Modification of laminar-flow airfoil	Hughes AH-64

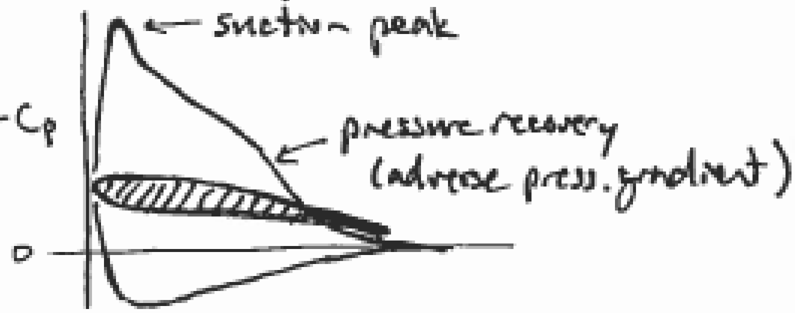
Future Airfoils	
	Developed using transonic aerodynamic analysis
	Developed using supercritical design techniques

2-D Airfoil Summary/Review: Lift (Drag later)

- Lift force = change in downward momentum flow induced by wing

  = net ΔP between upper and lower surfaces

- C_p distribution: $-C_p$



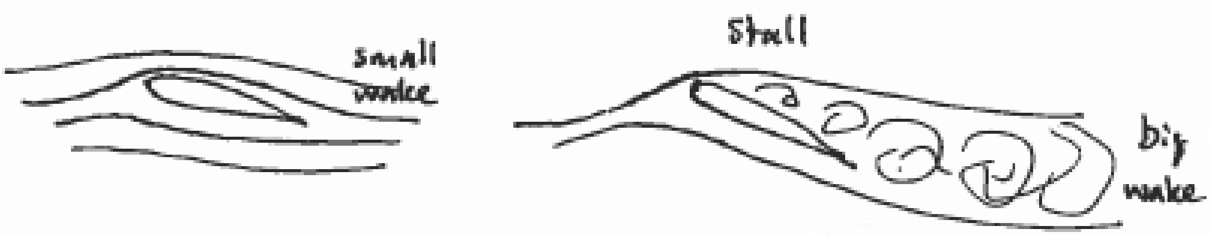
- In general: more camber = more lift for constant α

  more lift = more drag

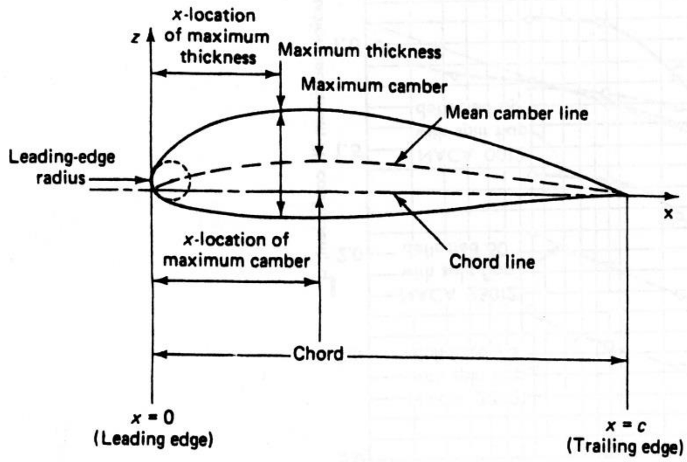
- c_ℓ increases with α, with constant $\frac{dc_\ell}{d\alpha}$, limited by stall

- Stall is due to boundary-layer separation on the upper surface

- $c_{\ell_{max}}$ can be dramatically increased by high-lift devices



Airfoil Geometry Review



1. Chord line - The chord line is a line drawn from the leading edge to the trailing edge.

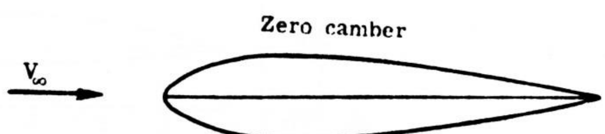
2. Mean camber line – The mean camber line is a line created by the locus of points midway between the upper and lower surfaces of the airfoil measured perpendicular to the chord line.

3. Maximum camber – The maximum camber is the maximum rise of the camber line from the chord line.

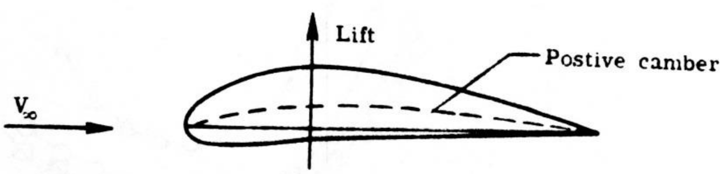
4. Thickness – t - The thickness is the height of airfoil profile measured perpendicular to the chord line.

5. Leading edge radius – The leading edge radius is a the radius of a circle that is tangent to the upper and lower surfaces with its center located on a line drawn tangent to the mean line at the leading edge.

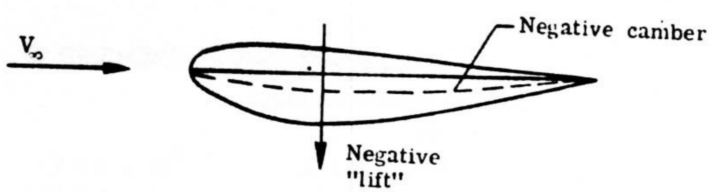
From *Airplane Aerodynamics* by Dommash, Sherby and Connolly
Aerodynamics for Engineers by Bertin and Smith



Symmetric airfoil -- Camber line = Chord line, no lift at $\alpha = 0^o$. Angle of zero lift is also 0, i.e. $\alpha_{L=0} = 0^o$.



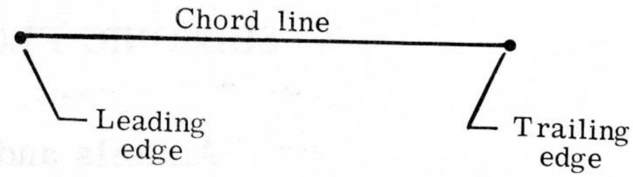
Asymmetric airfoil -- Camber line above chord line: Positive lift at $\alpha = 0^o$. $\alpha_{L=0} < 0^o$



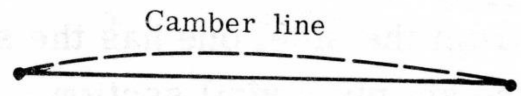
Asymmetric airfoil -- Camber line below chord line: Negative "lift" at $\alpha = 0^o$. $\alpha_{L=0} > 0^o$

How to Build an Airfoil

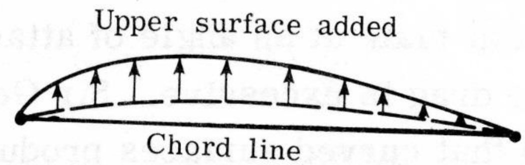
1. Set up leading edge and trailing edge and construct chord line between them.



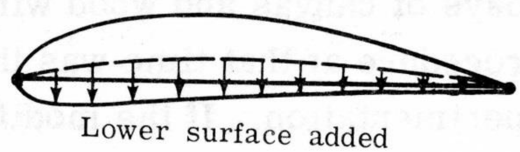
2. Add curvature with camber line.



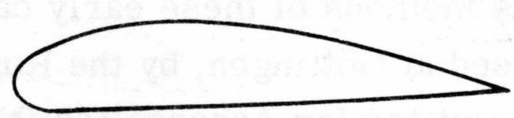
3. Wrap thickness about camber line to form upper surface.



Wrap same thickness about camber line to form lower surface.



4. Final airfoil shape.



- **What are some of the geometric factors that influence the aerodynamic performance of an airfoil?**
  - Thickness to chord ratio, t/c
    - Location of max t/c
  - Nose radius
  - Camber
    - Maximum camber
    - Location of max camber

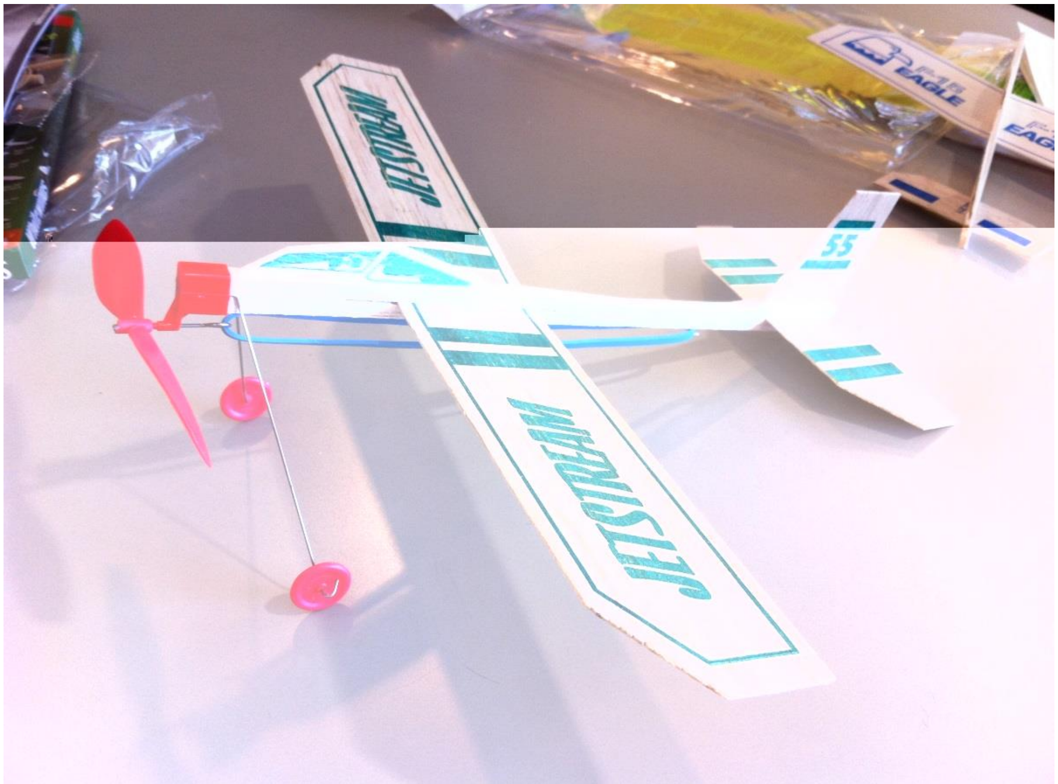
- **What is the influence of thickness?**
- Influence of t/c on lift coefficient
  - C_{lmax} increases with increasing t/c up to t/c in the order of 13-15% at t/c > 15% begins to C_{lmax} decrease.
- Influence of t/c on drag coefficient
  - C_{dmin} increases with increasing t/c

- **What is the major effect of the leading edge radius on airfoil performance?**
  - Effects airfoil stall characteristics
    - Small leading edge radius has a sharp stall break
    - Large leading edge radius has a gentle stall break

- **What is the influence of camber on the aerodynamic characteristics?**
- Increasing camber increases zero lift angle of attack.
- Camber can be used to get a low drag coefficient at the designed lift coefficient.
- The maximum lift coefficient of moderately cambered airfoil sections increase with increasing camber.
- Camber can affect the stall behavior.
  - For airfoil sections that have the maximum camber far forward the stall is very abrupt

- **Recap: Aerodynamic coefficients are a function of:**
  - Geometry
  - Angle of attack
  - Reynolds number

Why Wings Lift:



Finite Wings (F5.13):

Difference between 2-D (airfoil) flow and 3-D (wing) flow is driven by what happens at the wingtips:

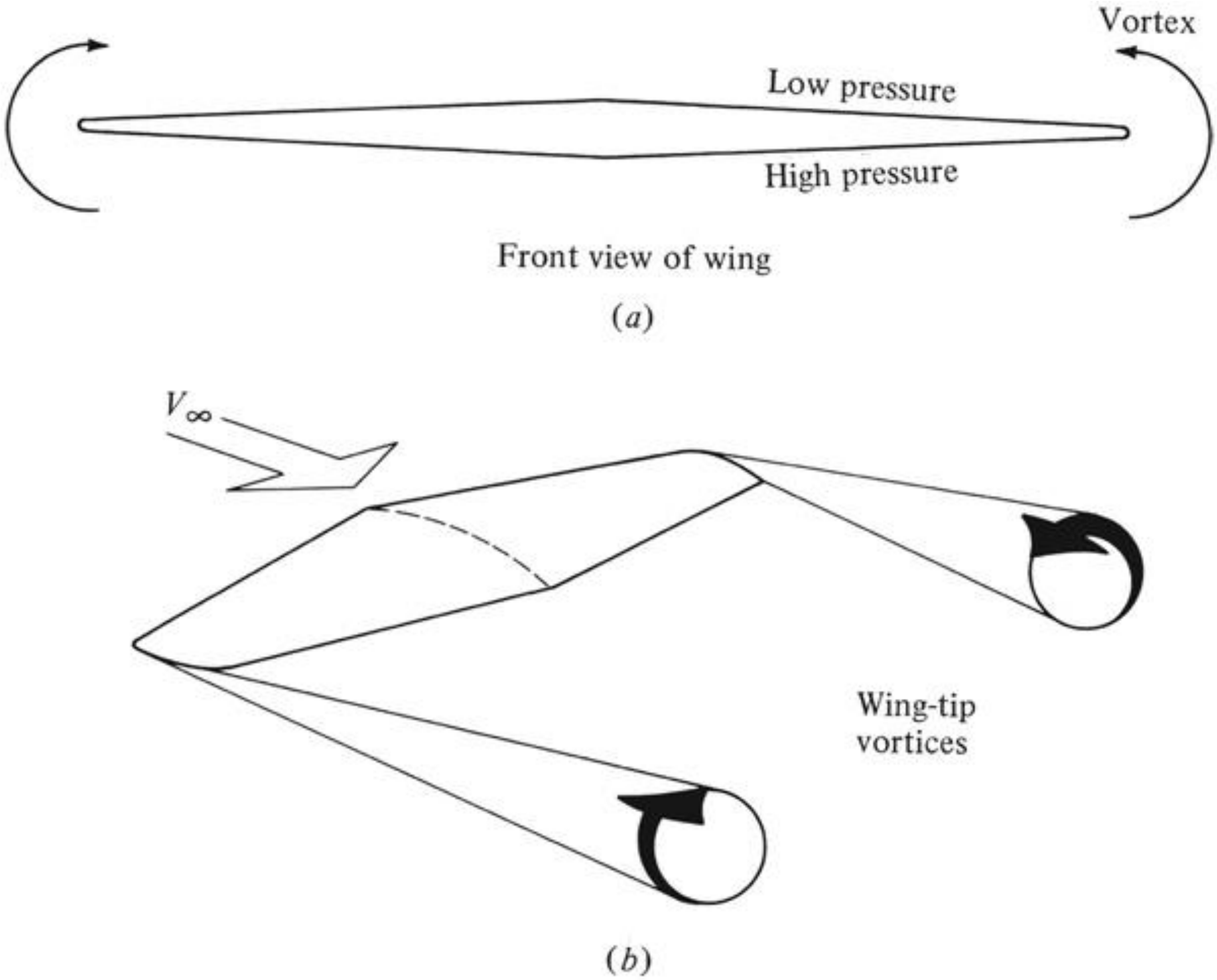
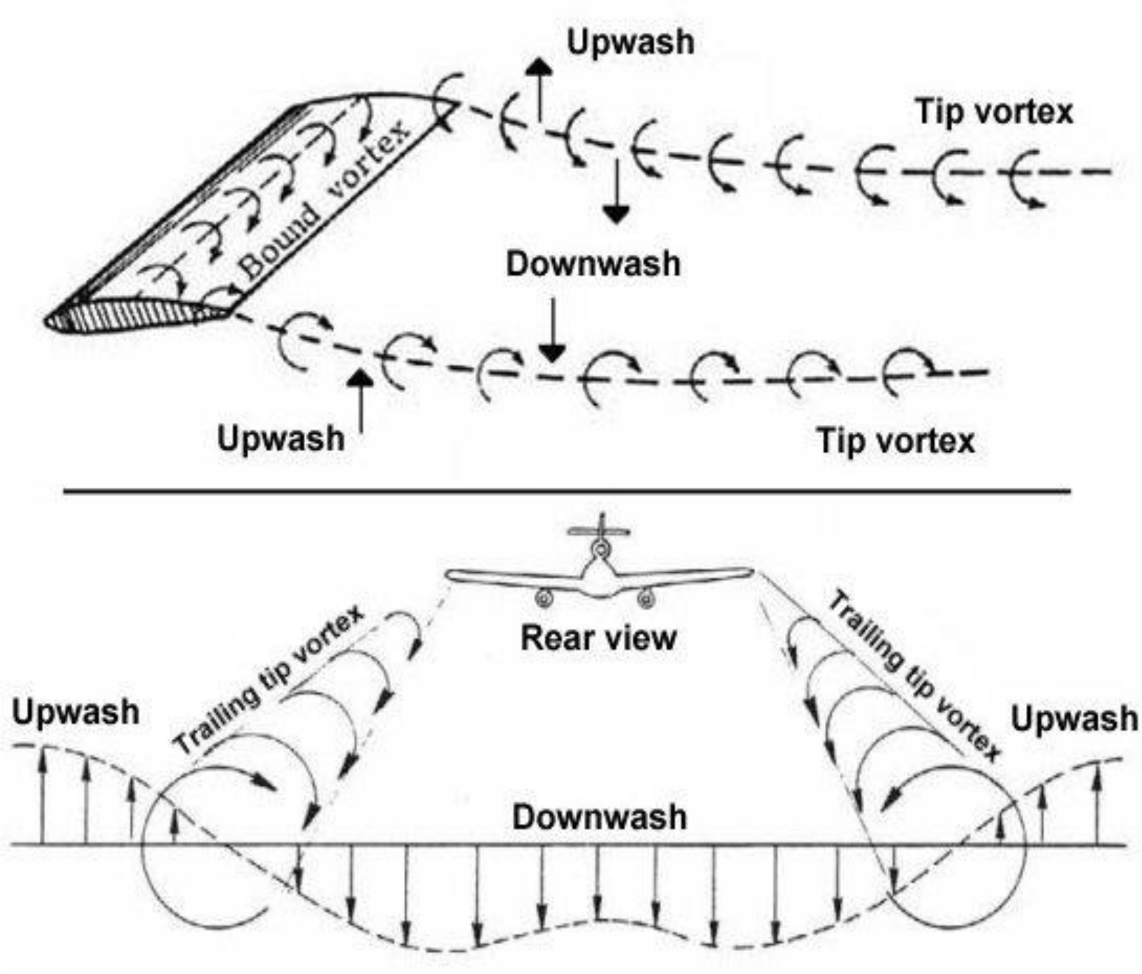


Figure 5.43 Origin of wing-tip vortices on a finite wing.



Downwash produced by both lifting wing and tip vortices

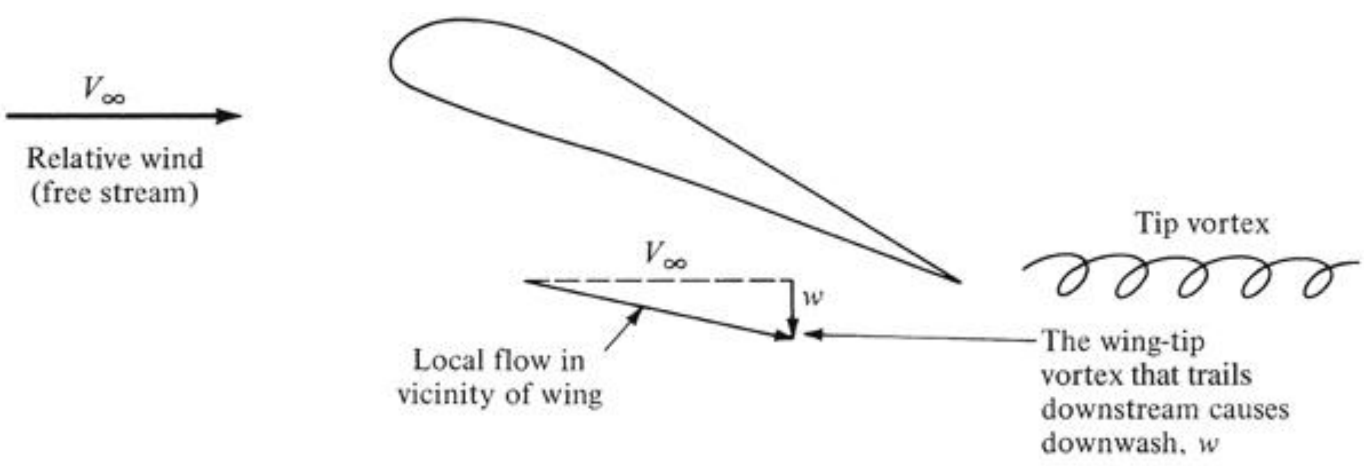


Figure 5.45 The origin of downwash.

Consequences of Downwash:

- Effective angle of attack is reduced

- Drag increase: "*drag due to lift*"
  Equivalent Interpretations:
  1) wingtip vortices alter flowfield to increase pressure and friction drag at the wingtip
  2) Lift vector tilted back, increasing drag component
  3) Wingtip vortices leave behind kinetic energy that came from aircraft

For 3-D wings (vs 2-D airfoils):

- Spanwise downwash results in reduced lift
- Wingtip vortices result in increased drag

Calculation of Induced Drag (F5.14)

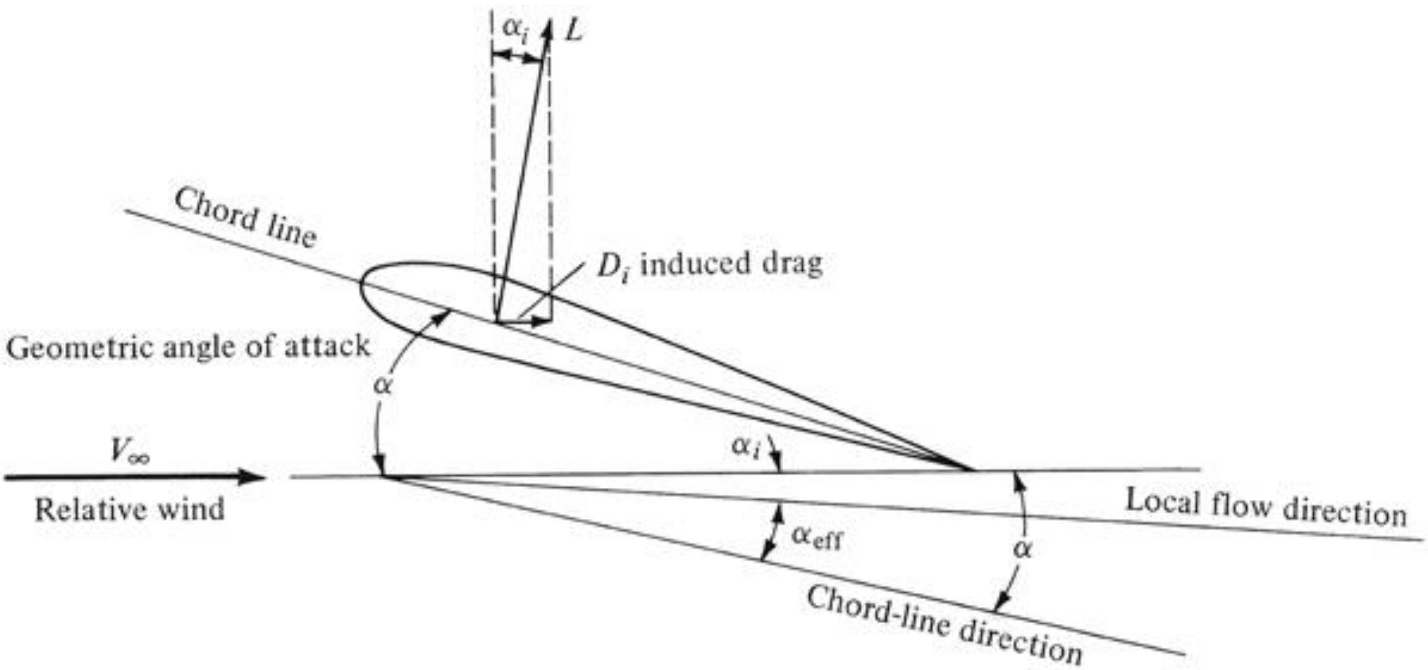


Figure 5.47 The origin of induced drag.

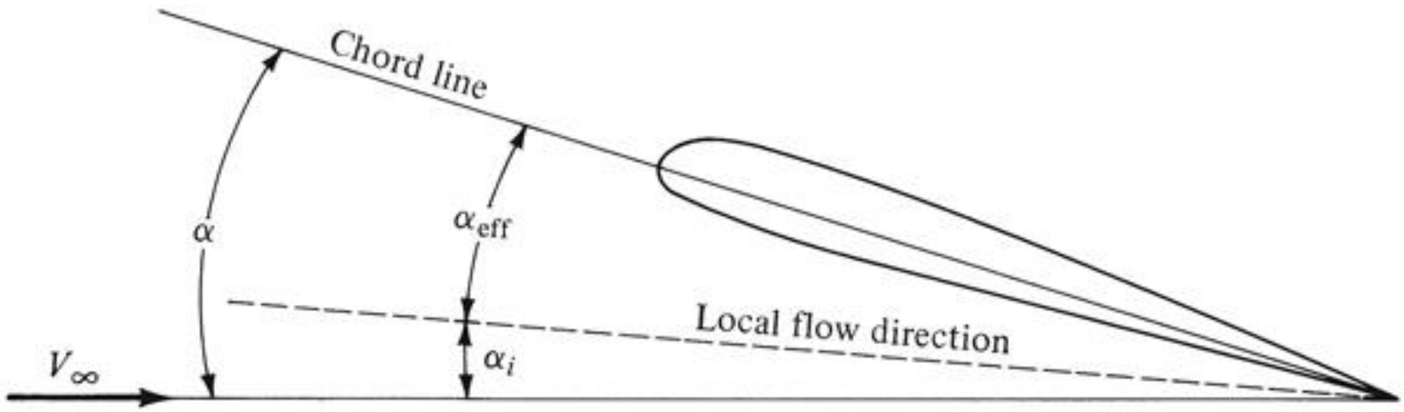


Figure 5.50 Relation between the geometric, effective, and induced angles of attack.

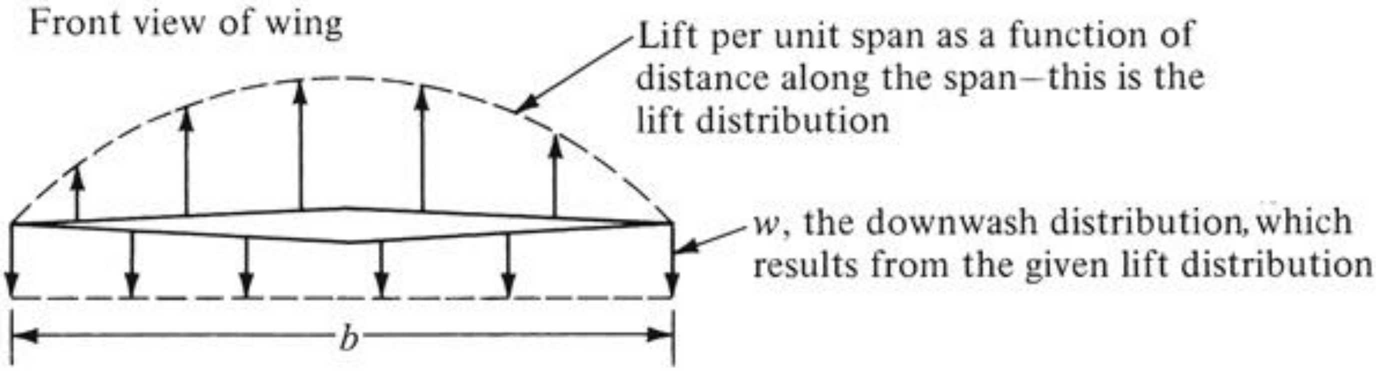


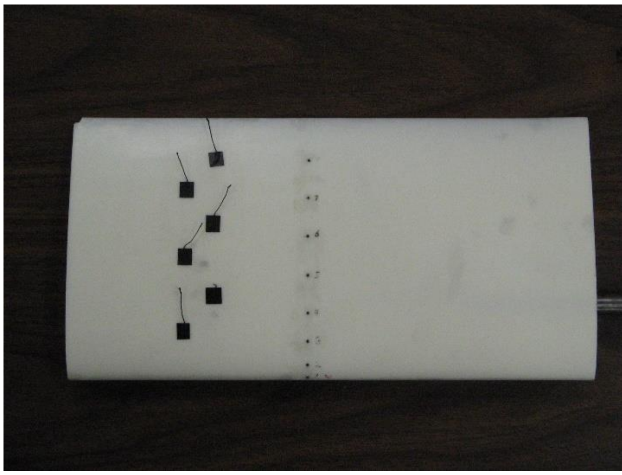
Figure 5.48 Lift distribution and downwash distribution.

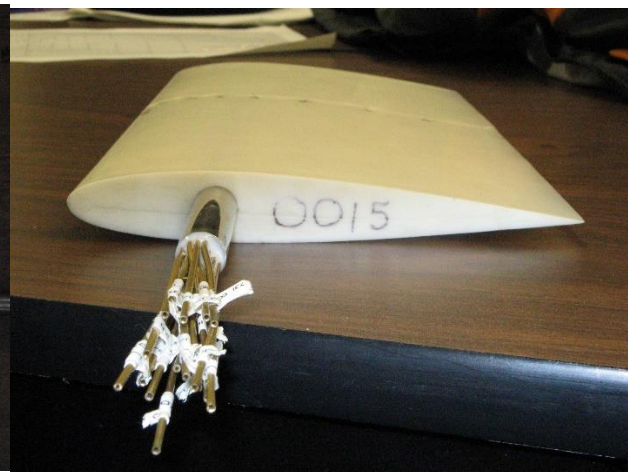
Drag due to Lift (Induced Drag):

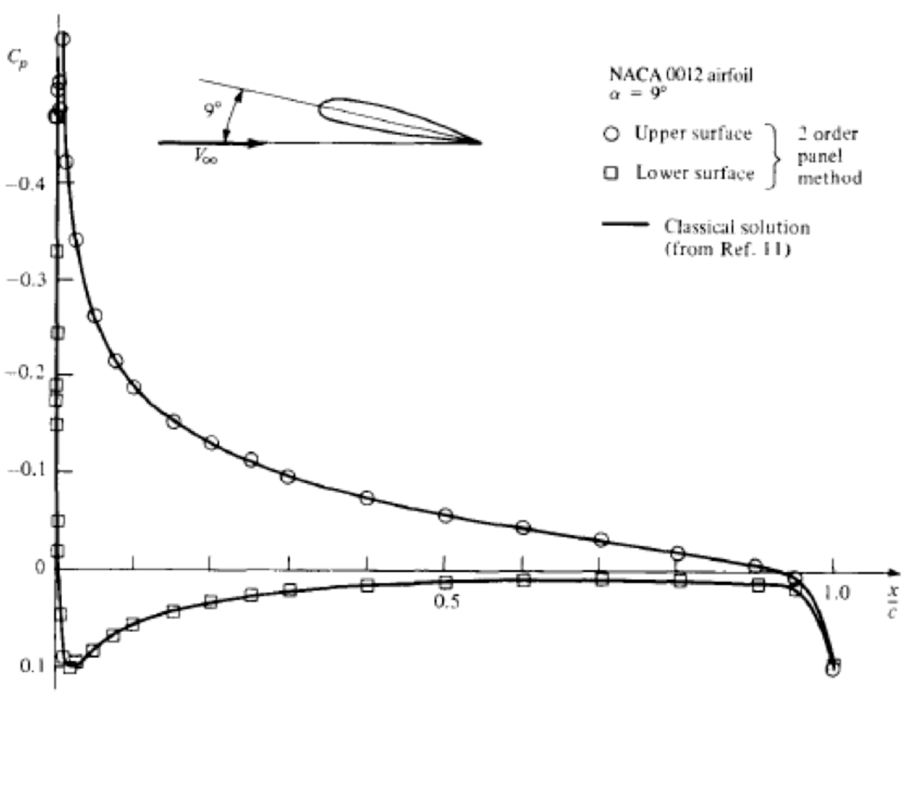
Review of Lift

Experimental Techniques for Surface Pressures

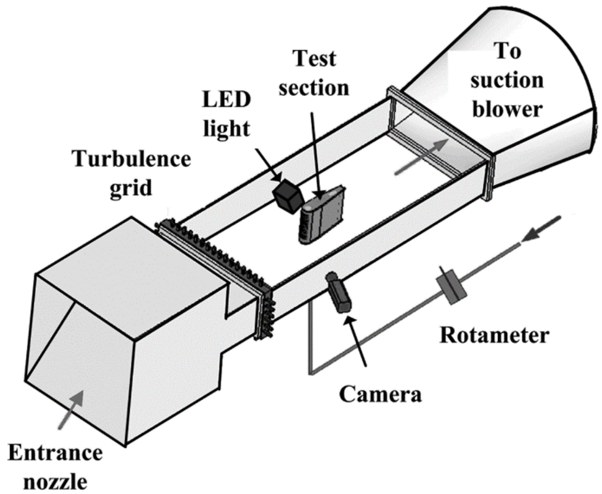
Pressure Taps:

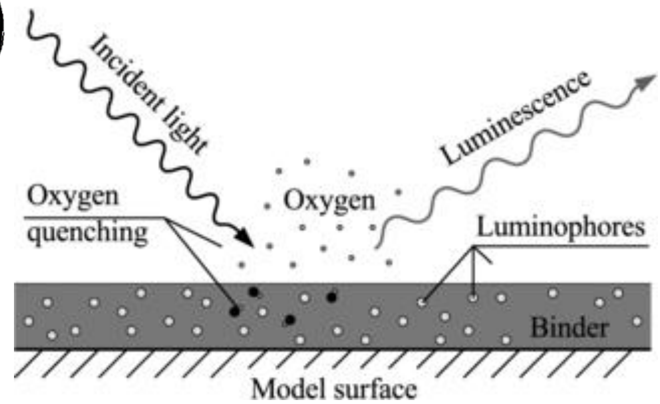


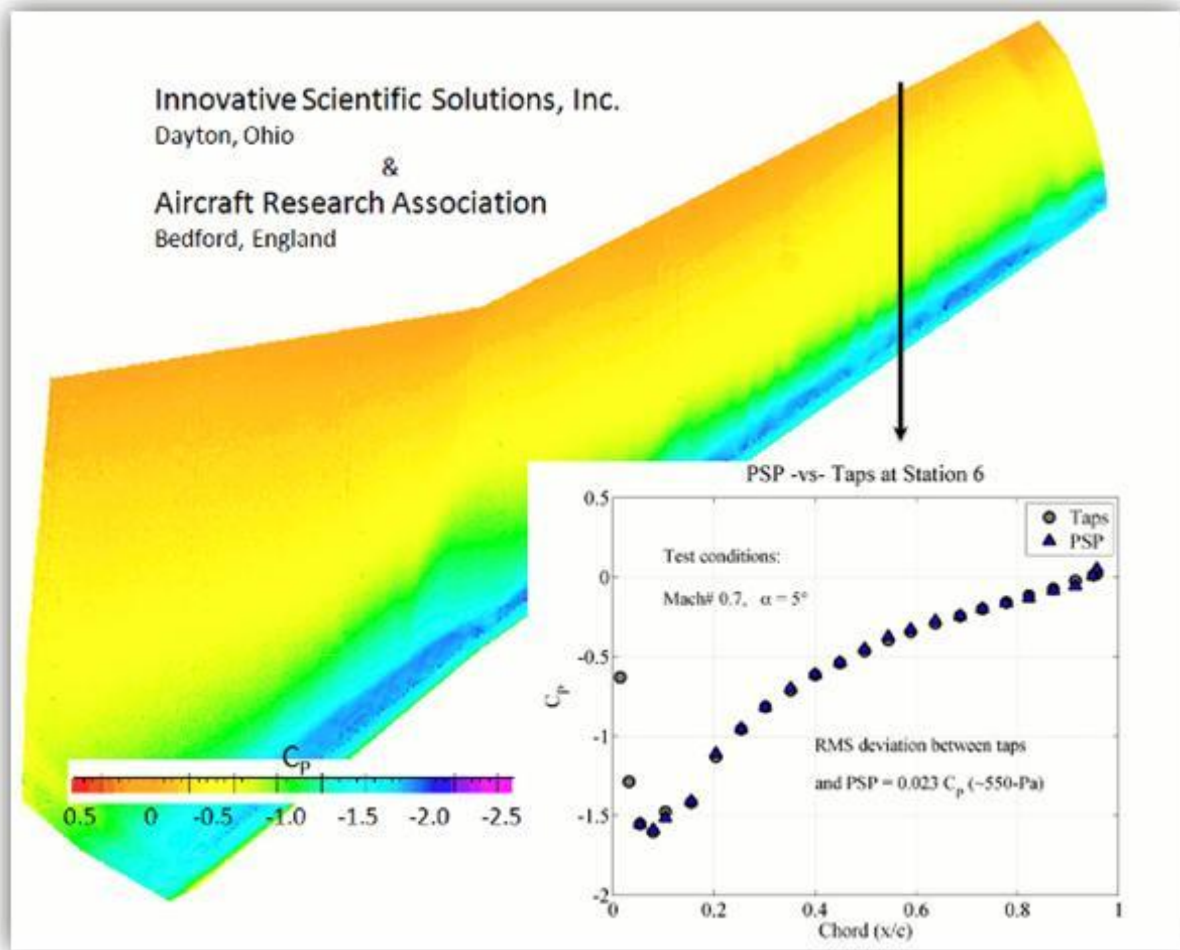




Pressure-Sensitive Paint:







High-Lift Devices Increase C_L (and C_D)

High-Lift Devices: Flaps and Slats (F5.17)

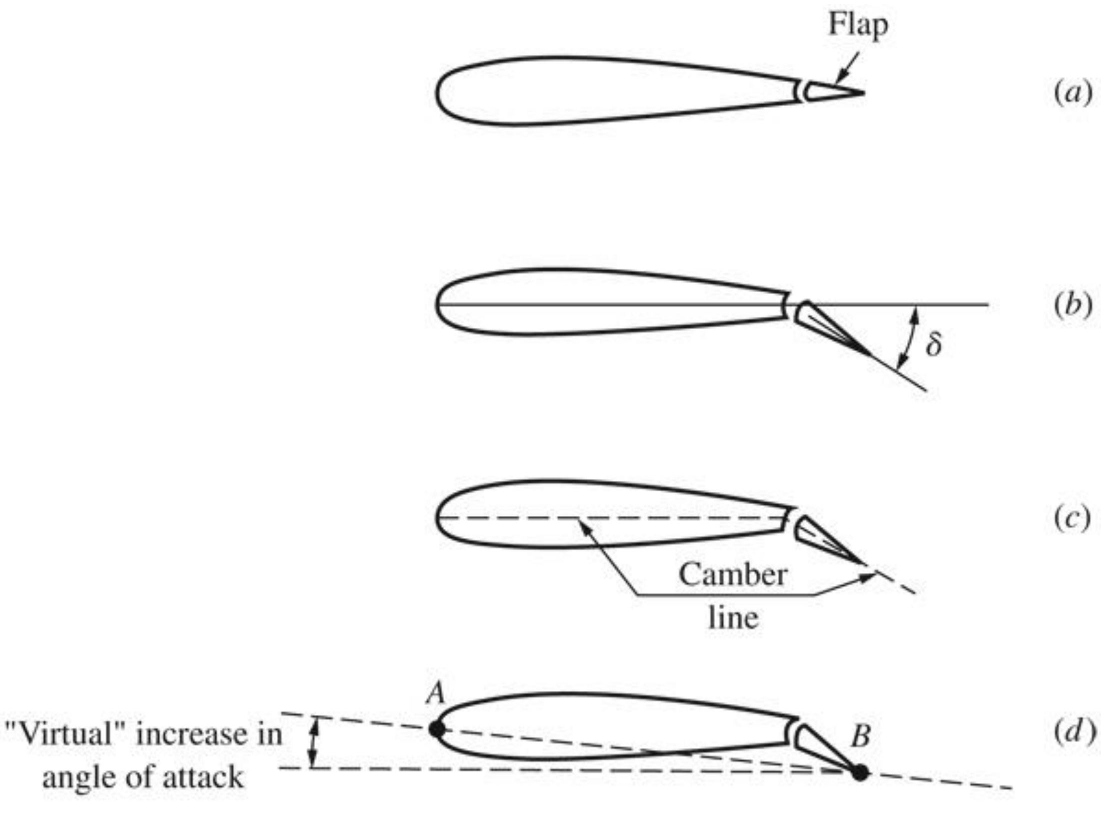


Figure 5.67 When a plain flap is deflected, the increase in lift is due to an effective increase in camber and a virtual increase in angle of attack.

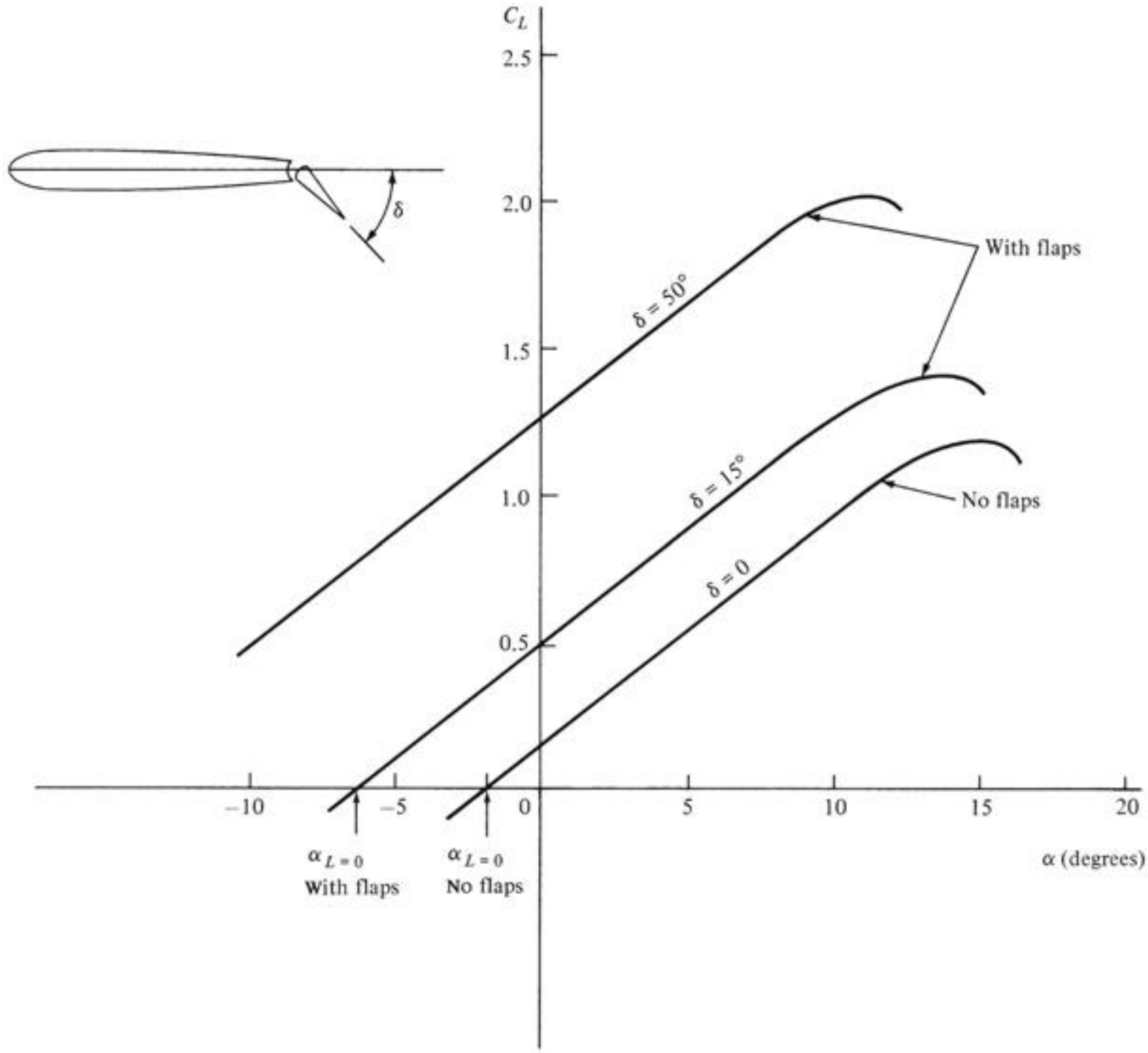


Figure 5.68 Illustration of the effect of flaps on the lift curve. The numbers shown are typical of a modern medium-range jet transport.

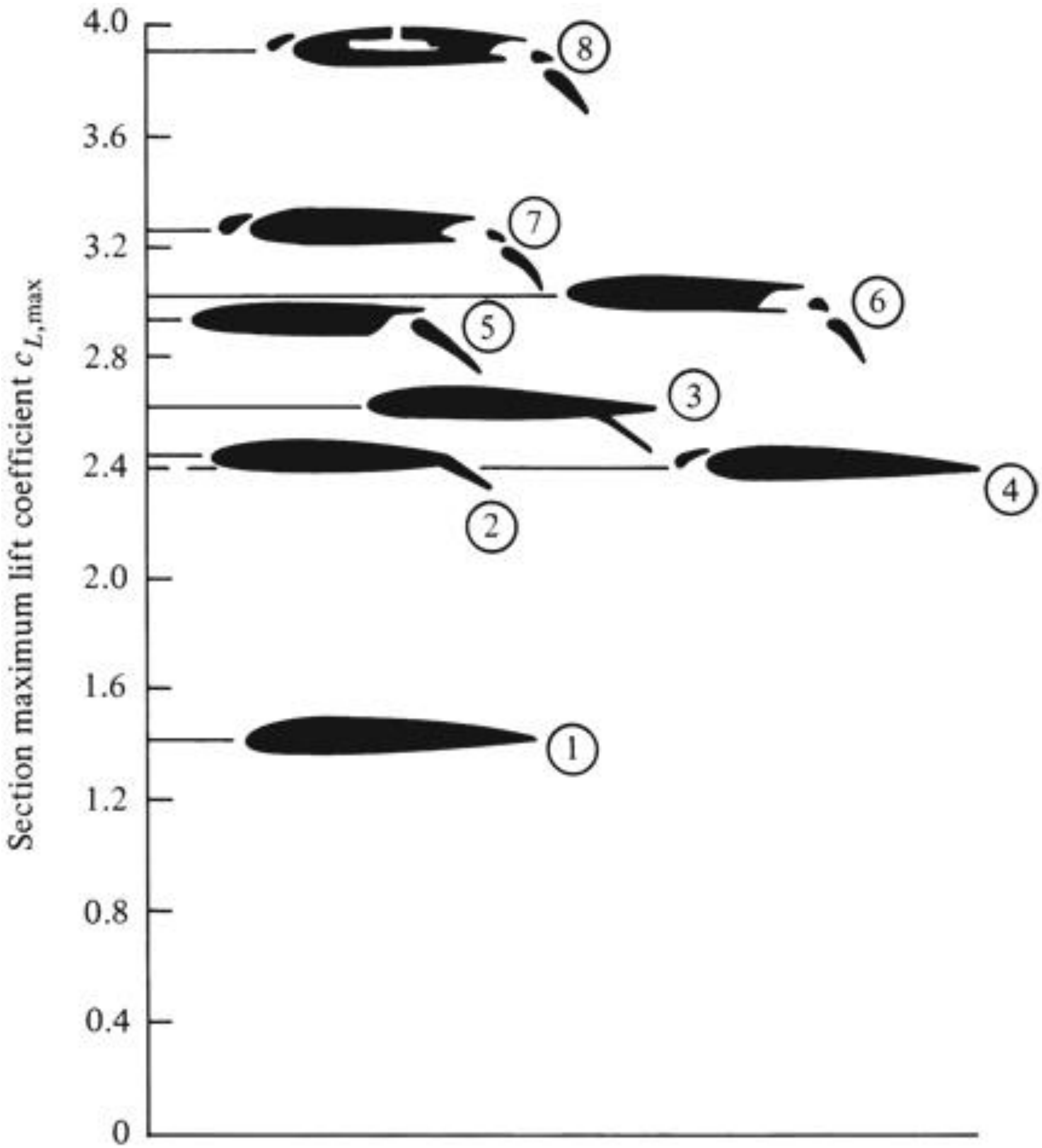


Figure 5.69 Typical values of airfoil maximum lift coefficient for various types of high-lift devices: (1) airfoil only, (2) plain flap, (3) split flap, (4) leading-edge slat, (5) single-slotted flap, (6) double-slotted flap, (7) double-slotted flap in combination with a leading-edge slat, (8) addition of boundary-layer suction at the top of the airfoil. (Source: *From Loftin, NASA SP 468, 1985.*)

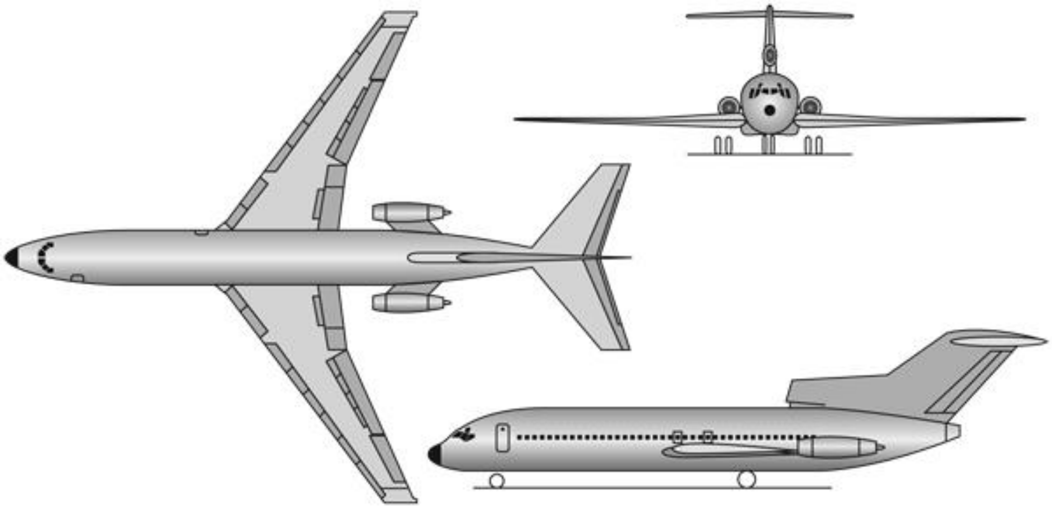


Figure 5.70 Three-view of the Boeing 727 three-engine commercial jet transport.

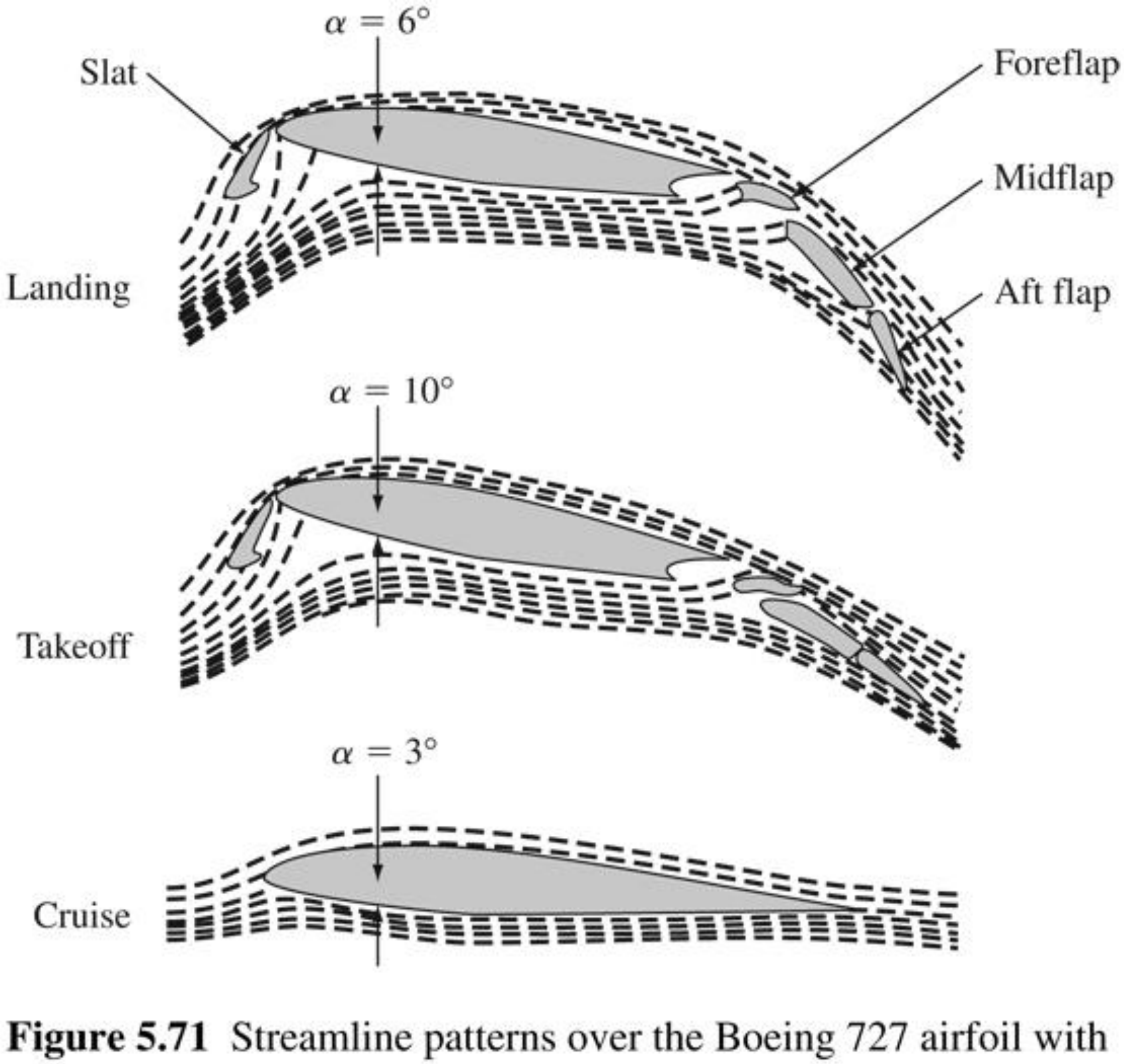


Figure 5.71 Streamline patterns over the Boeing 727 airfoil with and without high-lift devices deployed, comparing the cases for landing, takeoff, and cruise.
(Source: *AIAA, with permission.*)

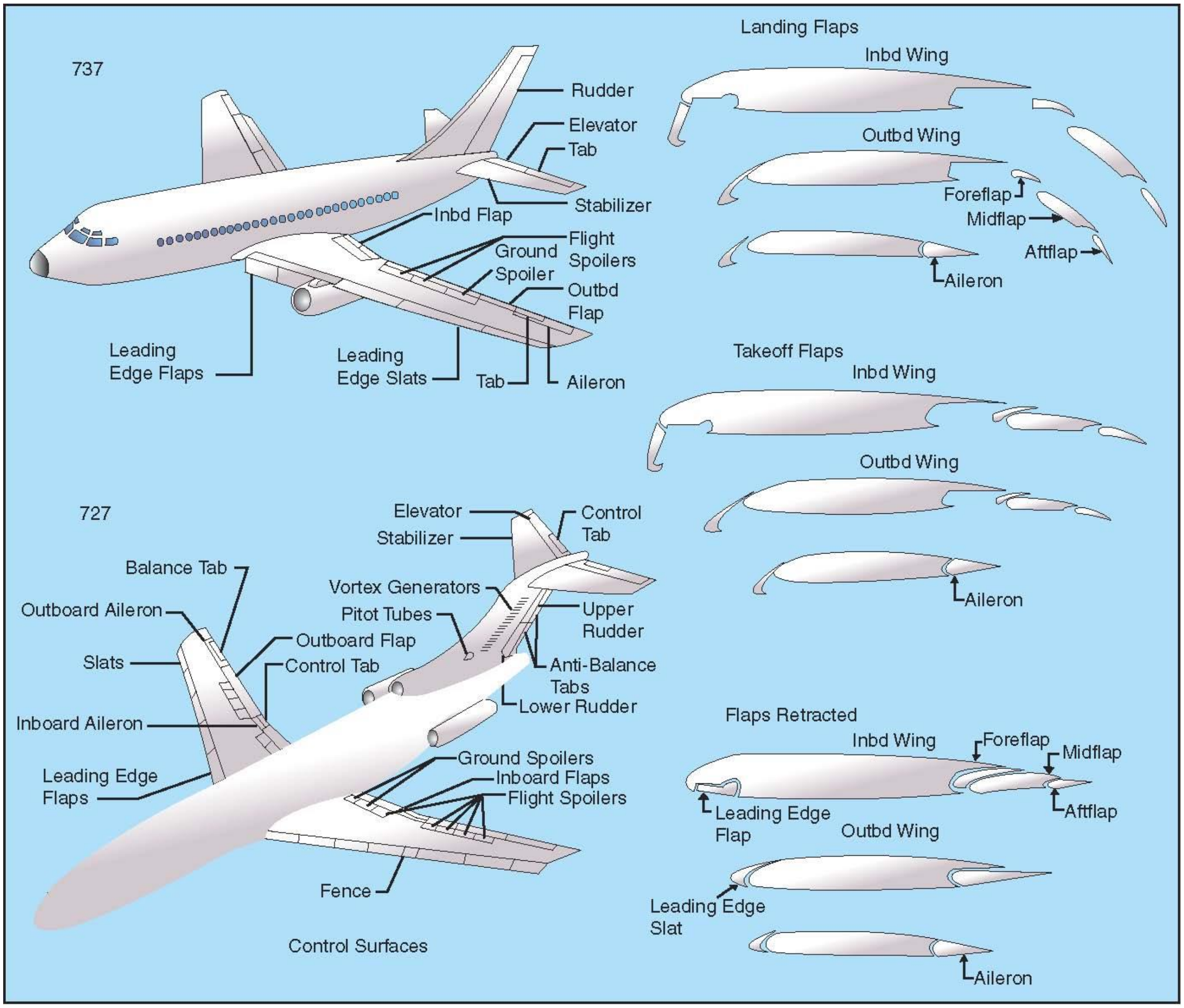
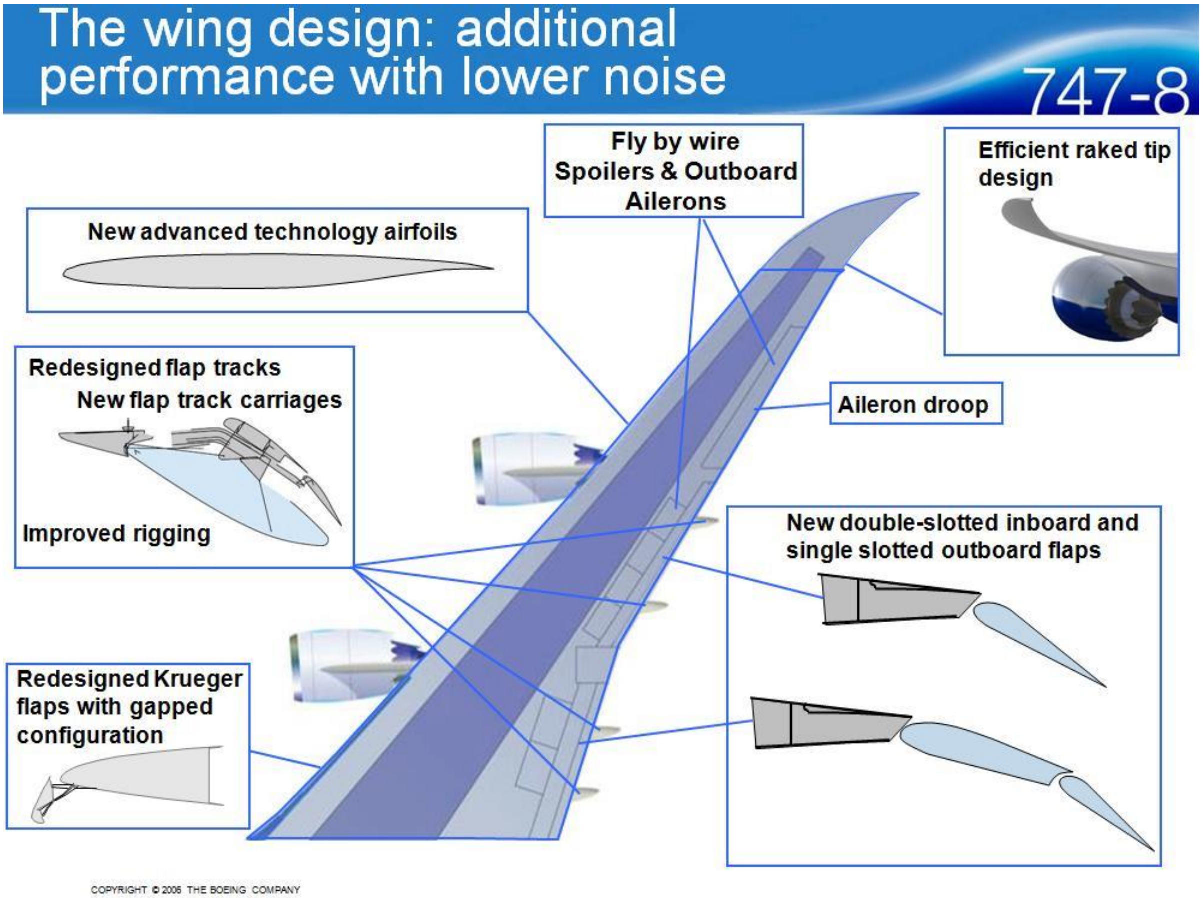


Figure 3-47. Control surfaces.


The wing design: additional performance with lower noise
747-8
Fly by wire Spoilers & Outboard Ailerons
Efficient raked tip design
New advanced technology airfoils
Redesigned flap tracks
New flap track carriages
Improved rigging
Aileron droop
New double-slotted inboard and single slotted outboard flaps
Redesigned Krueger flaps with gapped configuration
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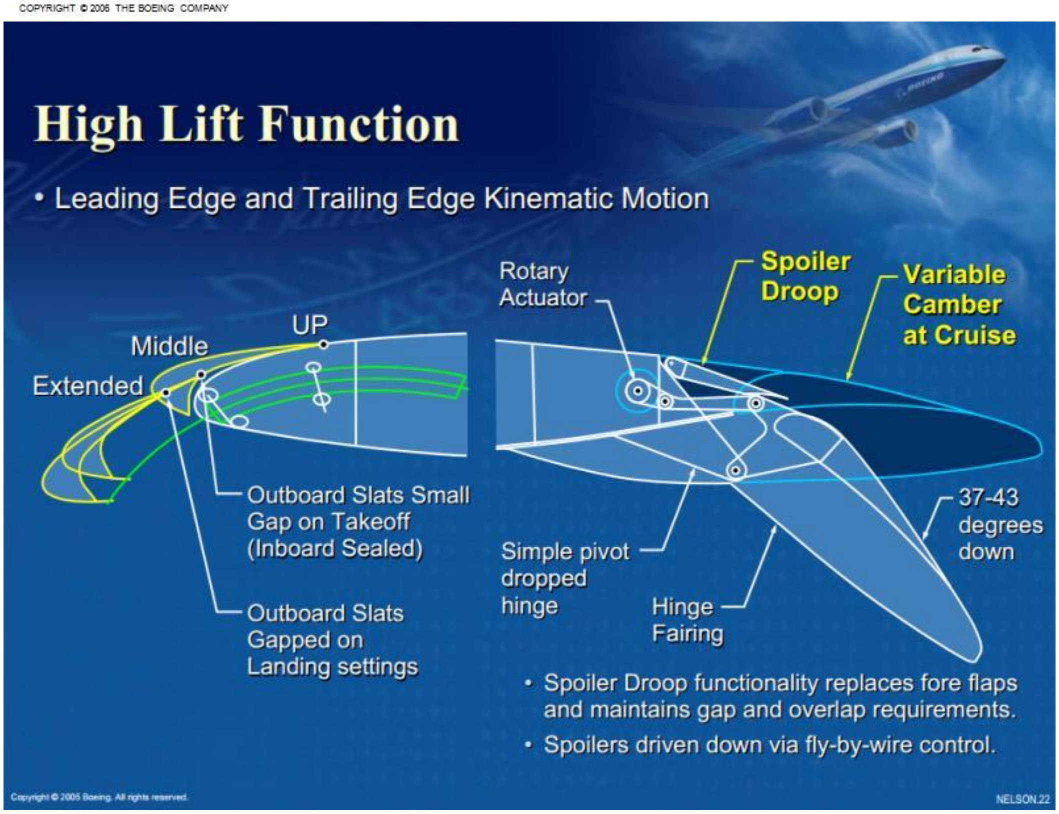
High Lift Function
• Leading Edge and Trailing Edge Kinematic Motion
UP
Middle
Extended
Outboard Slats Small Gap on Takeoff (Inboard Sealed)
Outboard Slats Gapped on Landing settings
Rotary Actuator
Spoiler Droop
Variable Camber at Cruise
37-43 degrees down
Simple pivot dropped hinge
Hinge Fairing
• Spoiler Droop functionality replaces fore flaps and maintains gap and overlap requirements.
• Spoilers driven down via fly-by-wire control.
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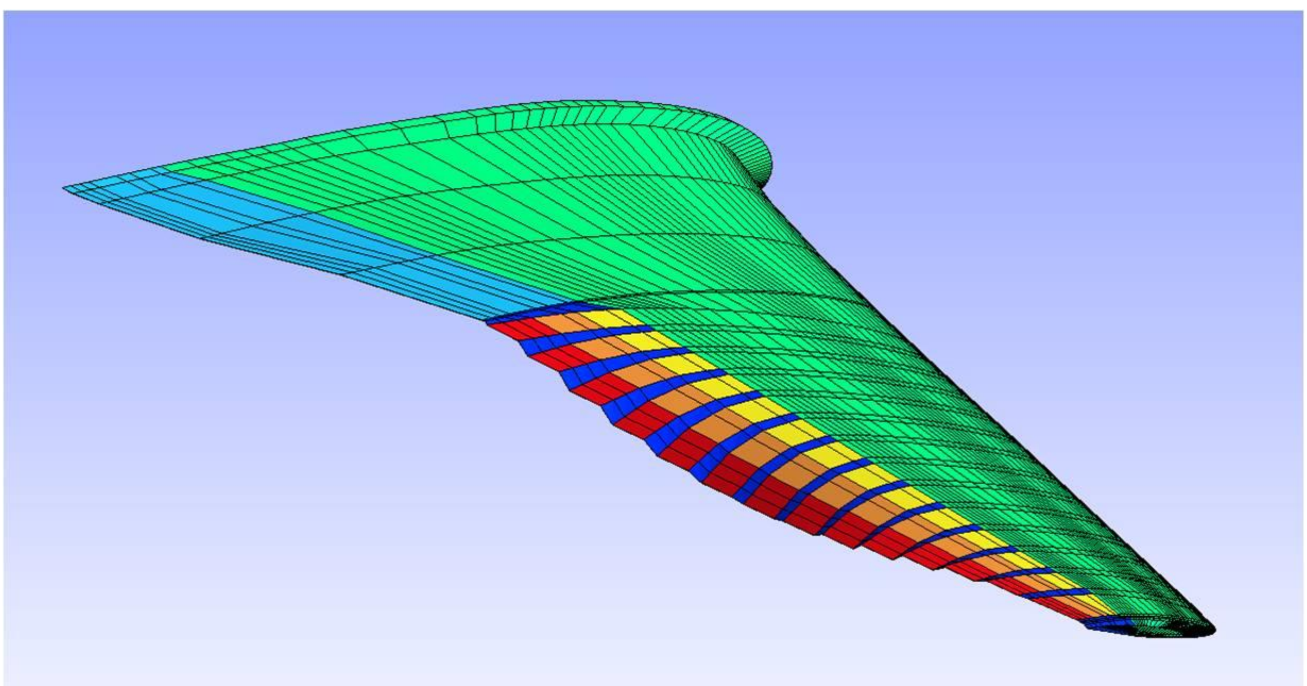

NASA Adaptive Compliant Trailing Edge (2014)