# Aircraft Nomenclature and Aerodynamics

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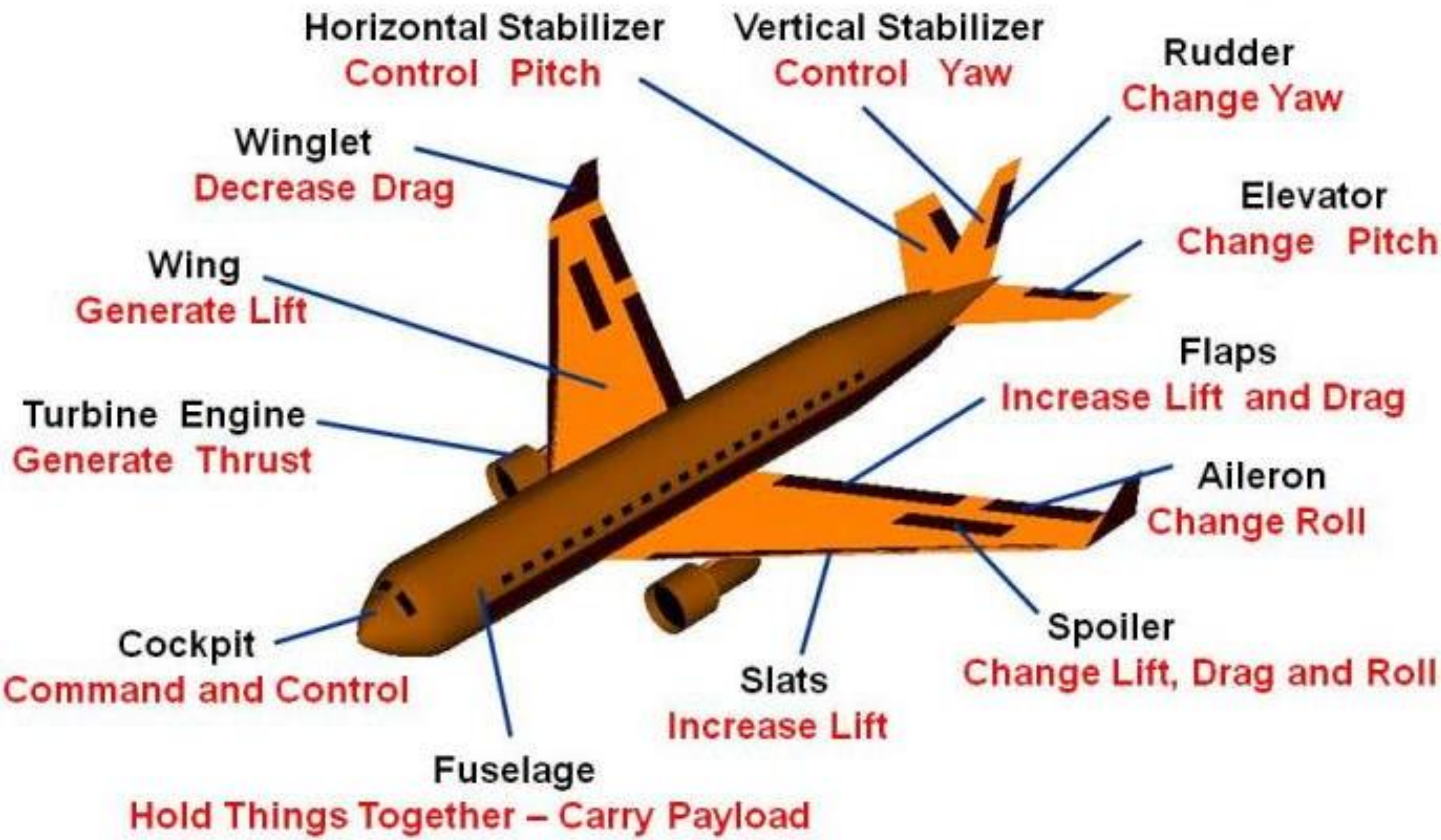
# Aircraft Nomenclature

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# *Aircraft Aerodynamics*

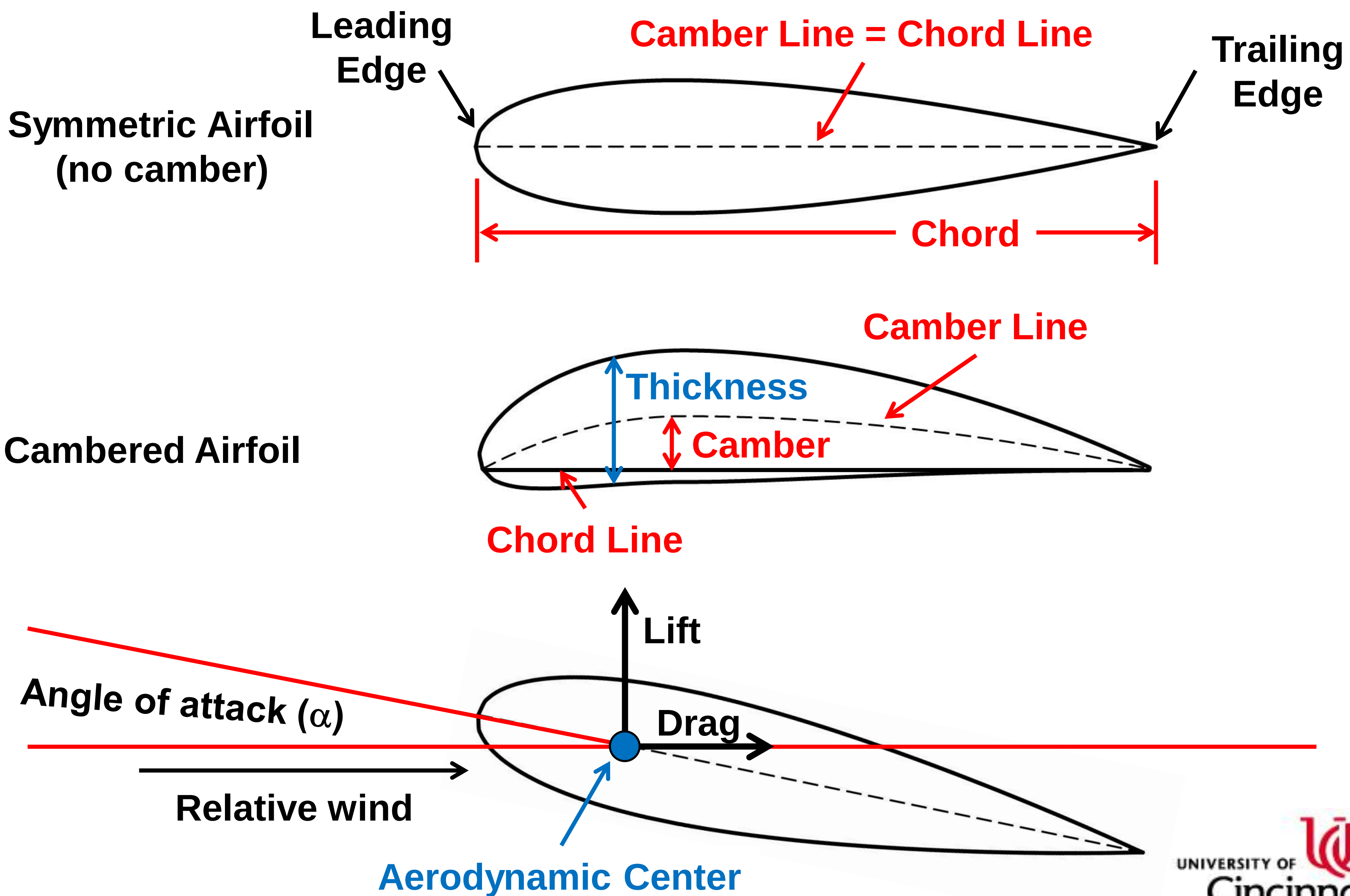
**Lift and Drag are defined by:**

- → **Airfoil characteristics**
- **Wing planform characteristics**
- **Wing / body / tail configuration**
- **Subsonic vs supersonic capability**

**Lift and Drag are a function of:**

- **Mach Number (minimum drag or zero-lift drag)**
- **Angle of attack (drag due to lift or induced drag)**
- **Altitude (Reynolds Number effect)**
- **Center of gravity (c.g.)**
- **Induced propulsion effects**
- **External store carriage**

# *Airfoil Nomenclature*

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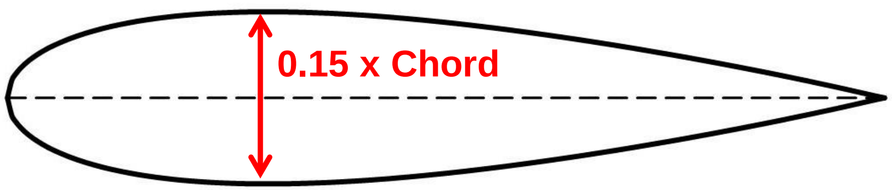
# *Airfoil Nomenclature*

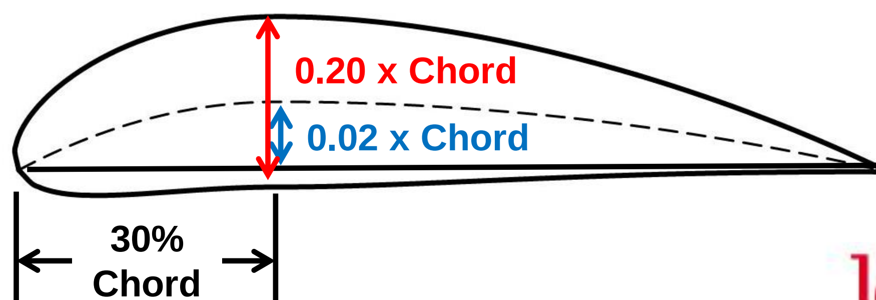
**The NACA four-digit wing sections define the profile by:**

- **1st digit is maximum camber as % of chord**
- **2nd digit is the distance of maximum camber from the airfoil leading edge in 10x% of chord**
- **Last two digits are the maximum airfoil thickness as % of chord**

**<u>NACA 0015</u>**
**Symmetric Airfoil**
**(no camber)**
**15% thickness**



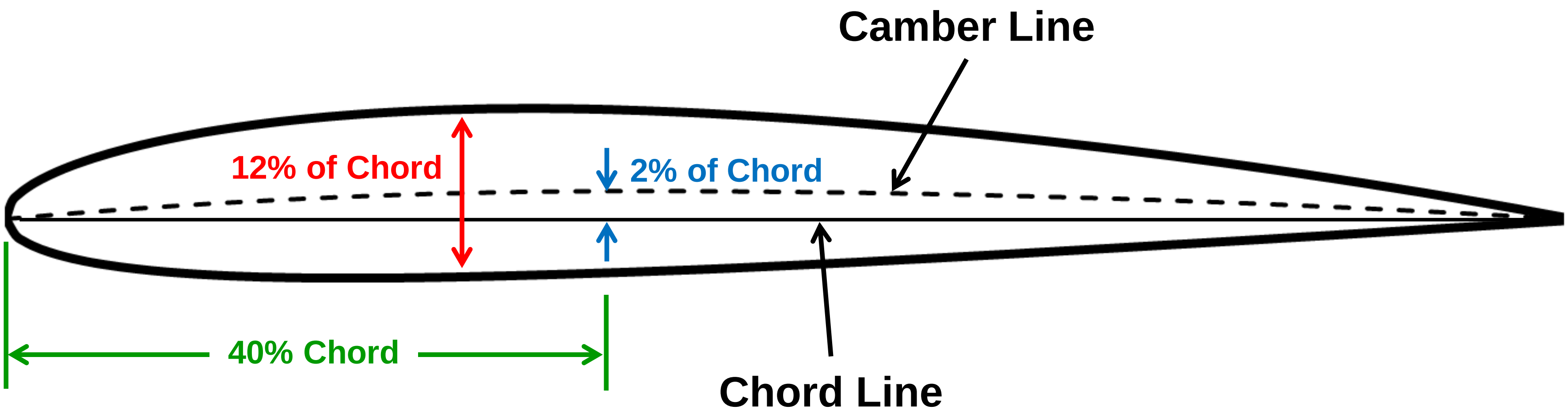

**<u>NACA 2320</u>**
**Max camber is 2% chord**
**Max camber occurs at 30% chord**
**20% thickness**



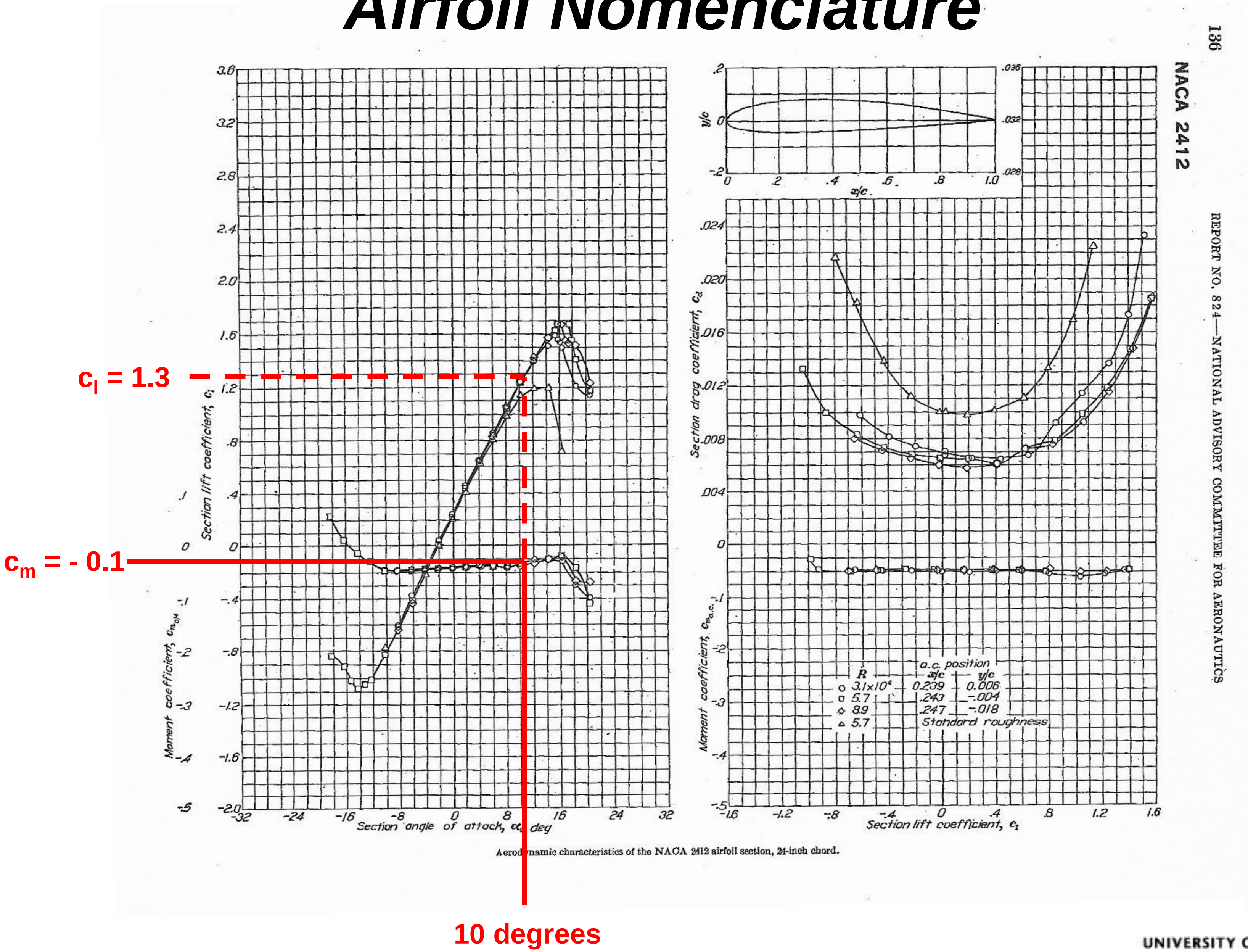
# Airfoil Nomenclature

**The NACA 2412 airfoil:**

- **Maximum camber is 2% of chord**
- **Maximum camber point is at 40% chord**
- **Maximum airfoil thickness is 12% of chord**



# Airfoil Nomenclature




Aerodynamic characteristics of the NACA 2412 airfoil section, 24-inch chord.

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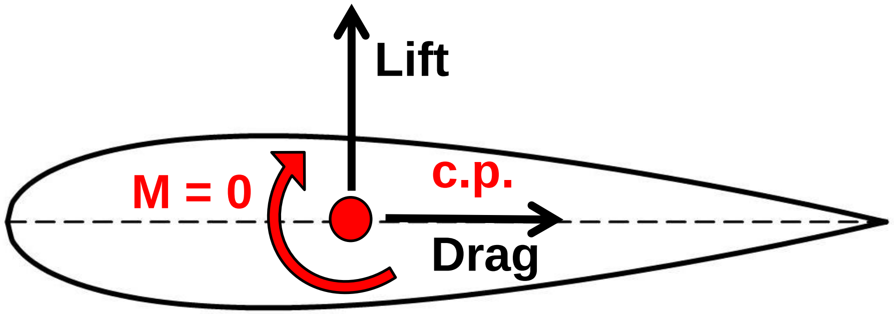
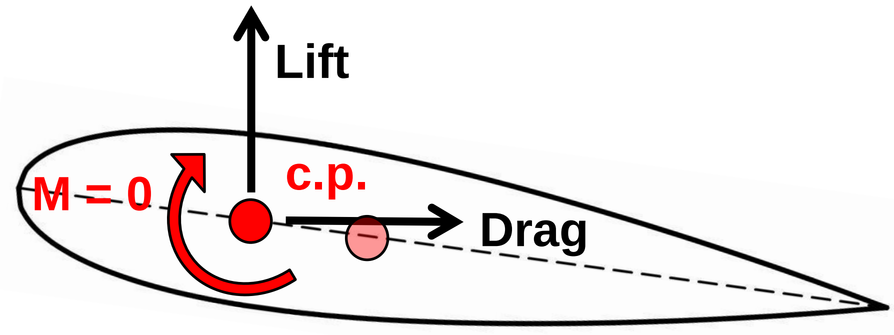
# *Center of Pressure*

**The Center of Pressure is the point on a body where the total moment due to aerodynamic forces is zero and where the lift and drag forces act**

**The Center of Pressure will move forward as angle of attack increases**

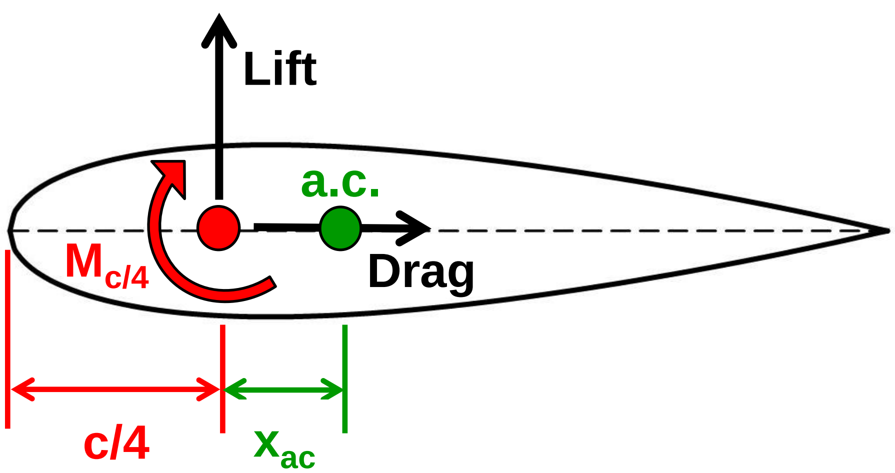


# *Aerodynamic Center*

**The Aerodynamic Center is the point on a body about which the moments are independent of angle of attack**

**$C_{M_{ac}}$ is constant over a practical range of $\alpha$**

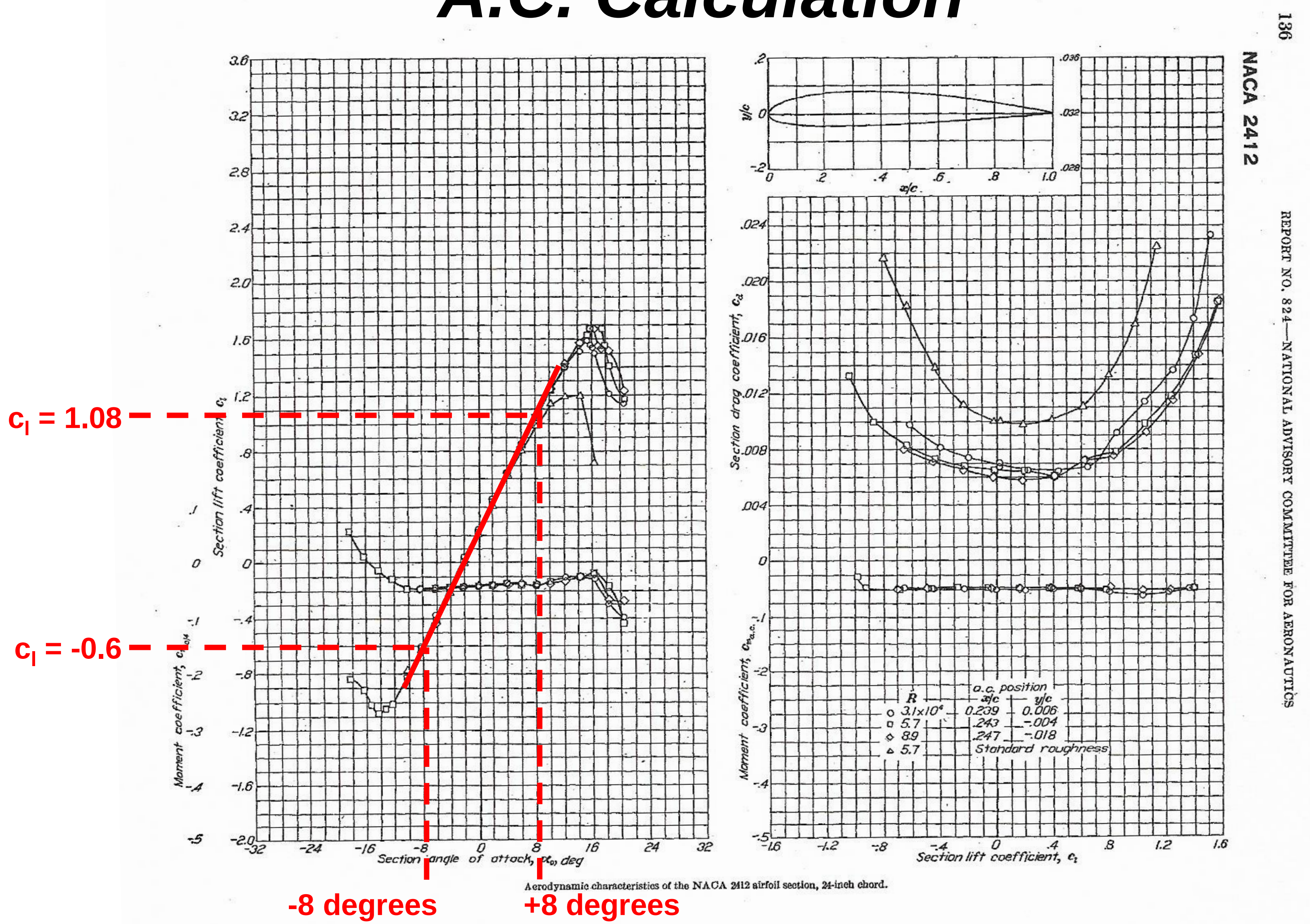



$$\boxed{\frac{x_{ac}}{c} = -\frac{m_0}{a_0}}$$

$$m_0 = \frac{dc_{m_{c/4}}}{d\alpha}$$

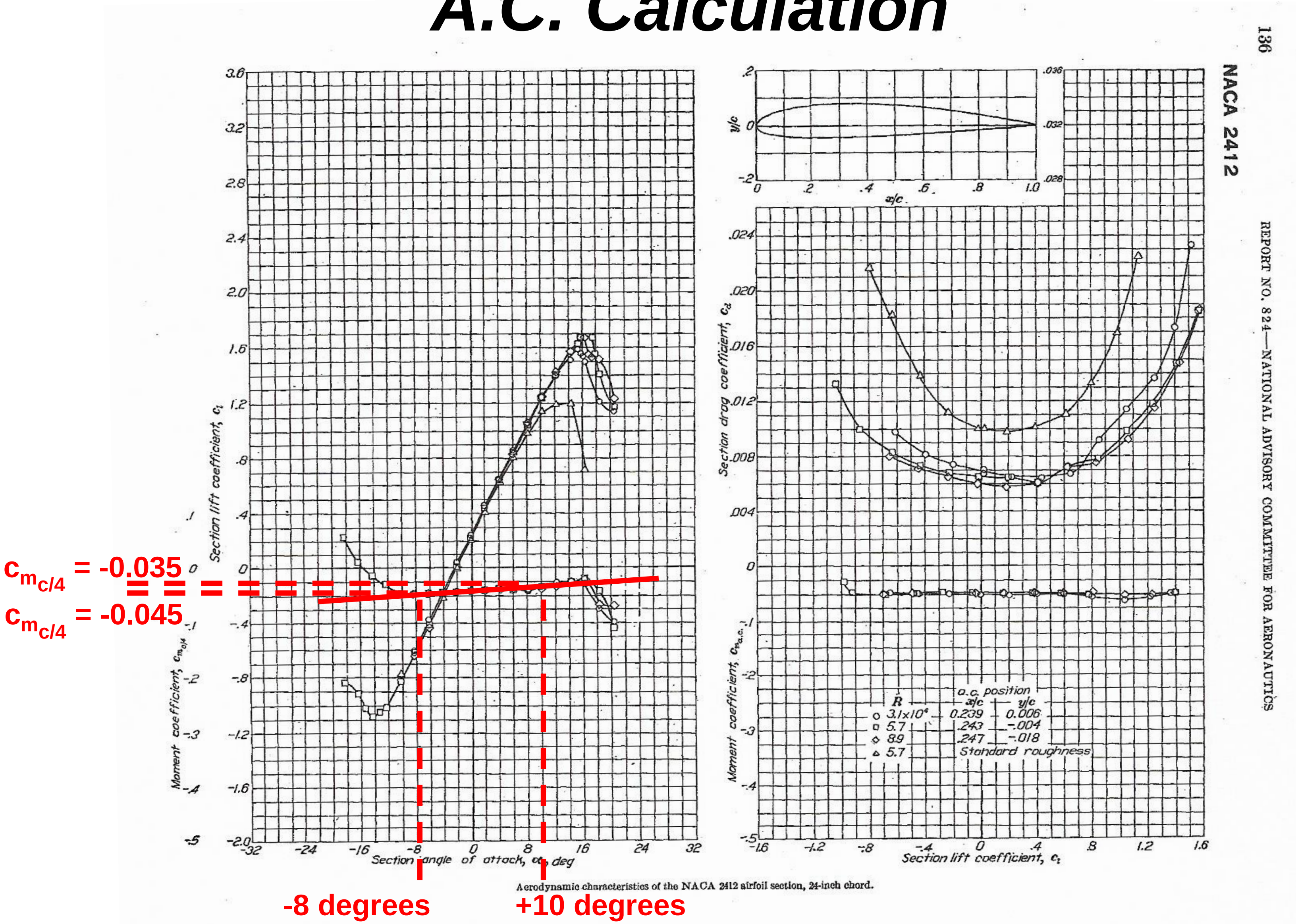
$$a_0 = \frac{dc_l}{d\alpha}$$

# A.C. Calculation




$$a_0 = \frac{dc_l}{d\alpha} = \frac{1.08 - (-0.60)}{8 - (-8)} = 0.105$$

# A.C. Calculation




Aerodynamic characteristics of the NACA 2412 airfoil section, 24-inch chord.

$$m_0 = \frac{dc_{m_{c/4}}}{d\alpha} = \frac{-0.035 - (-0.045)}{10 - (-8)} = 0.00056$$

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# *A.C. Calculation*

$$\mathbf{m_0} = \frac{\mathbf{dc_{m_{c/4}}}}{\mathbf{d\alpha}} = \frac{\mathbf{-0.035 - (-0.045)}}{\mathbf{10 - (-8)}} = \mathbf{0.00056}$$

$$\mathbf{a_0} = \frac{\mathbf{dc_l}}{\mathbf{d\alpha}} = \frac{\mathbf{1.08 - (-0.60)}}{\mathbf{8 - (-8)}} = \mathbf{0.105}$$

$$\frac{\mathbf{x_{ac}}}{\mathbf{c}} = -\frac{\mathbf{m_0}}{\mathbf{a_0}} = -\frac{\mathbf{0.00056}}{\mathbf{0.105}} = -\mathbf{0.53}\%$$

**The a.c. is at 25% - 0.53% = 24.47%**

**For most standard airfoil shapes, the a.c. is essentially at the quarter-chord point**

# *Airfoil Nomenclature*

**Other airfoil family groups:**

- **NACA five digit wing sections (NACA 23112)**
  - **More complex airfoil shapes than NACA four digit series**
- **1-series (NACA 16-123)**
  - **Airfoil shape mathematically derived by desired lift characteristics**
- **6-series (NACA $61_2$-315 a=0.5)**
  - **Airfoil design with an emphasis on maximizing laminar flow**
- **7-series (NACA 712A315 )**
  - **Advanced maximized laminar flow airfoil designs**
- **8-series**
  - **Supercritical wing designs for high transonic and supersonic flight**

# *Aircraft Aerodynamics*

## Lift Coefficient and Drag Coefficient are defined by:

$$C_L = \frac{nW}{qS} = C_{L_\alpha}(\alpha - \alpha_{L=0}) = a\,(\alpha - \alpha_{L=0})$$

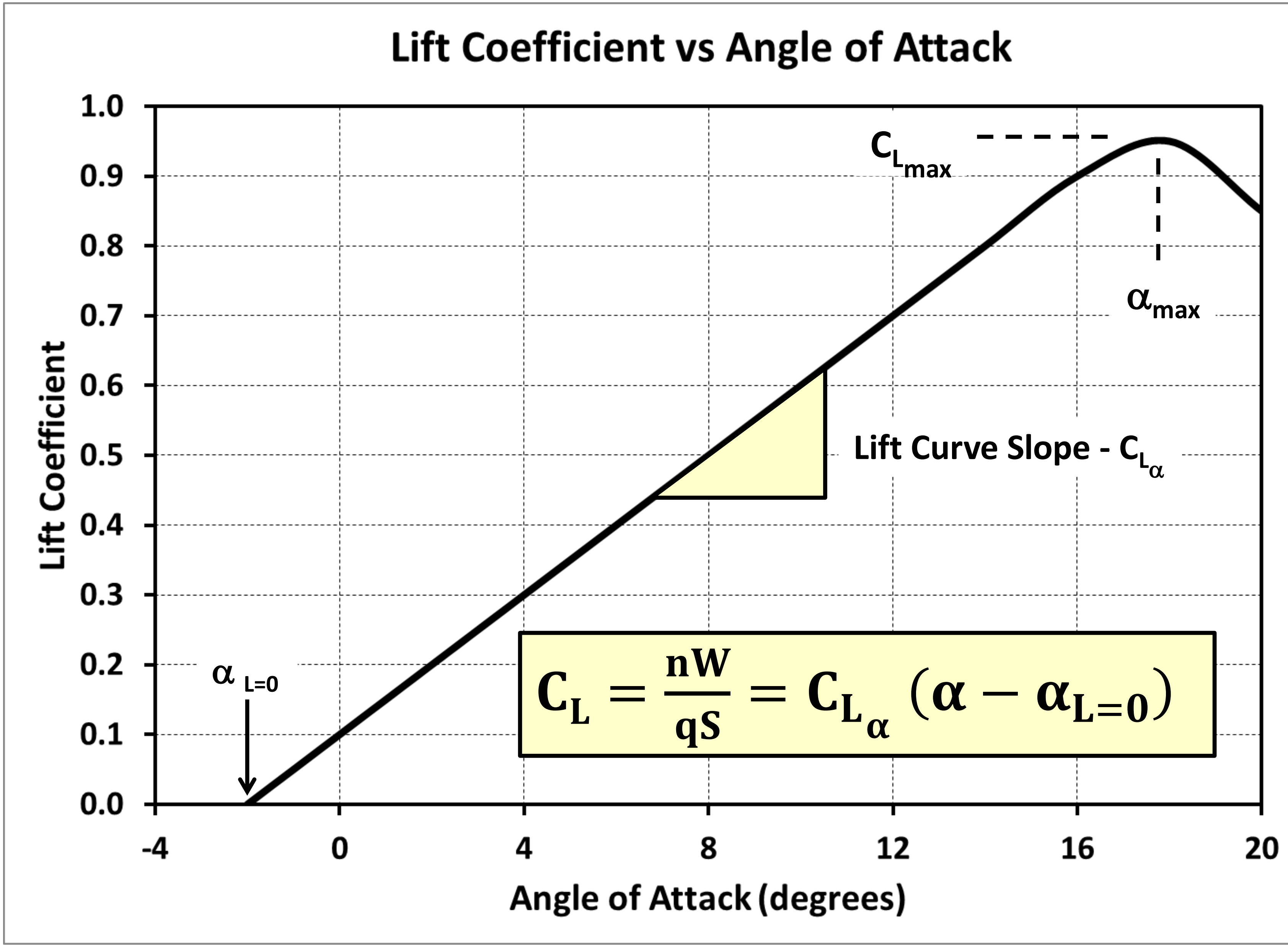
$$q = \frac{1}{2}\rho V^2 = (q/M^2)\,M^2$$

$$V = a_\infty M$$

$$C_D = \frac{D}{qS}$$

n = load factor (g's)
W = aircraft weight (lb or kg)
q = dynamic pressure (lb/ft$^2$ or kg/m$^2$)
S = wing reference area (ft$^2$ or m$^2$)
$\rho$ = density (slugs/ft$^3$ or kg/m$^3$)
V = velocity (ft/sec or m/sec)
M = Mach Number
$a_\infty$ = speed of sound (ft/sec or m/sec)
a = lift curve slope (1/degree or 1/radian)

# Aircraft Aerodynamics



# *Aircraft Aerodynamics*

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# *Aircraft Aerodynamics*

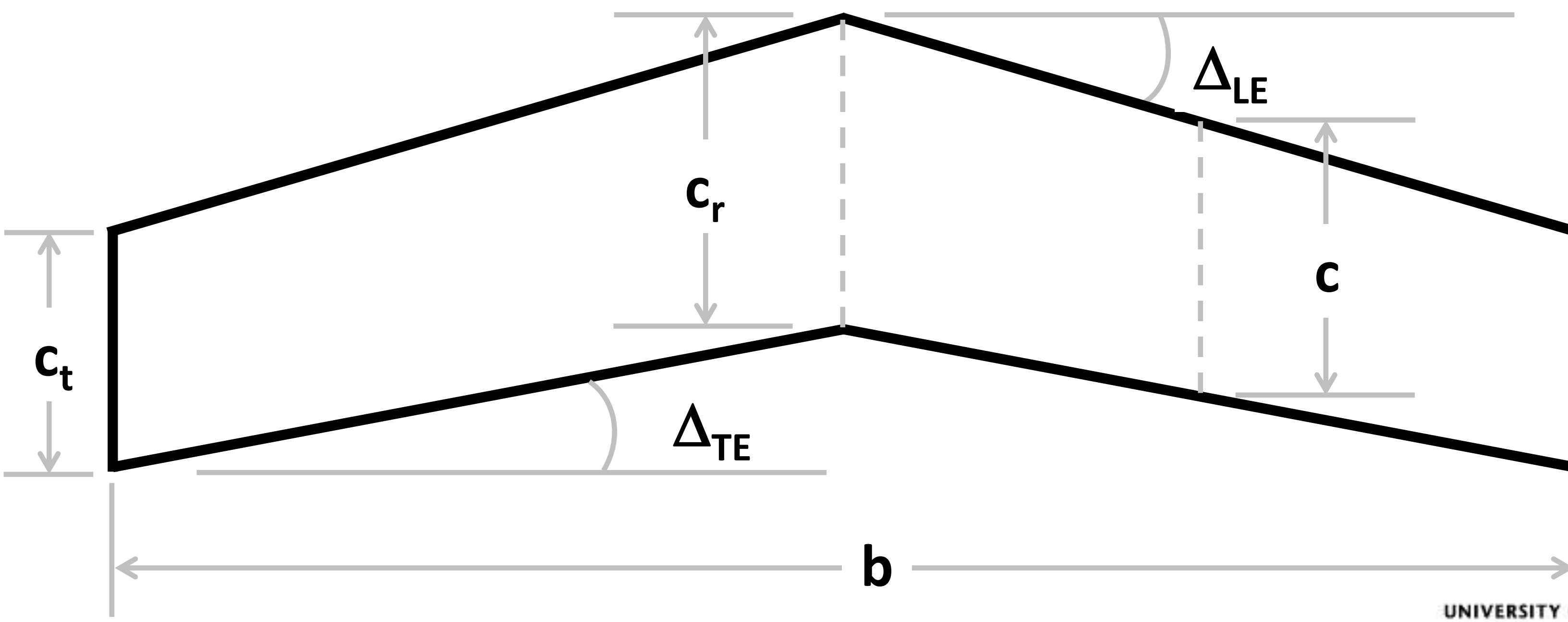
<u>**Wing Planform Characteristics**</u>

**Wing Area (S)**
**Wing Span (b)**
**Average Chord (c)**
**Root Chord ($c_r$)**
**Tip Chord ($c_t$)**
**Leading Edge Sweep ($\Delta_{LE}$)**
**Trailing Edge Sweep ($\Delta_{TE}$)**
**Aspect Ratio (AR)**
**Taper Ratio ($\lambda$)**

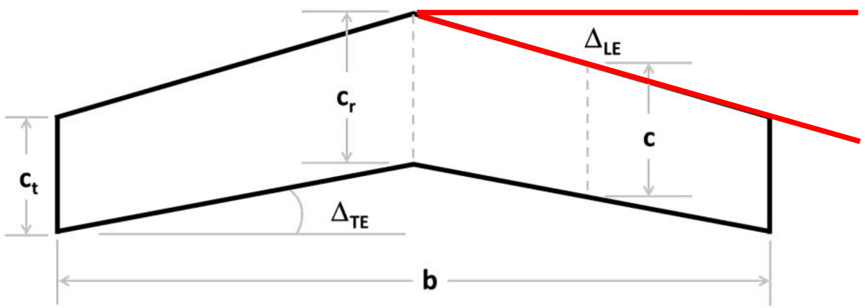
$$\mathbf{S = b\ c}$$

$$\mathbf{AR = \frac{b^2}{S} = \frac{b}{c}}$$

$$\boldsymbol{\lambda = \frac{c_t}{c_r}}$$



# *Aircraft Aerodynamics*




**<u>Wing Sweep</u> (Δ)**

**Indicator of an aircraft's subsonic cruise speed**

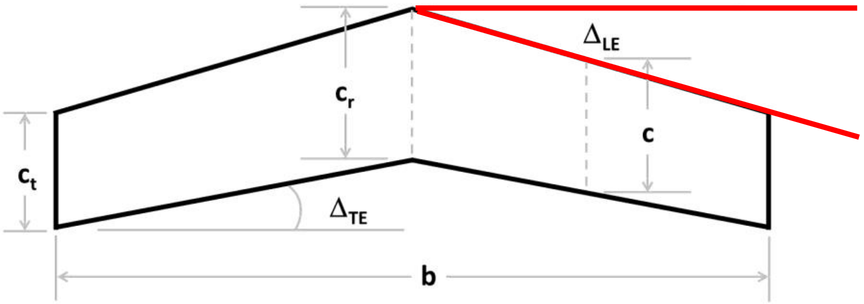
**Affects Divergence Mach Number**

**<u>Low wing sweep</u> (0 to 20 degrees) – sailplanes, gliders**
**High aspect ratio (AR = 20 - 25)**
**Slower cruise speed (0.2 - 0.6 Mach)**

**<u>Medium wing sweep</u> (20 to 40 degrees) – airliners, cargo, bombers**
**Medium aspect Ratio (AR = 8 - 10)**
**Moderate cruise speed (0.6 - 0.85 Mach)**

**<u>High wing sweep</u> (40 to 70 degrees) – fighters, supersonic aircraft**
**Low aspect ratio (AR = 2 - 4)**
**Faster cruise speeds (0.8 - 0.9 Mach)**

# *Aircraft Aerodynamics*

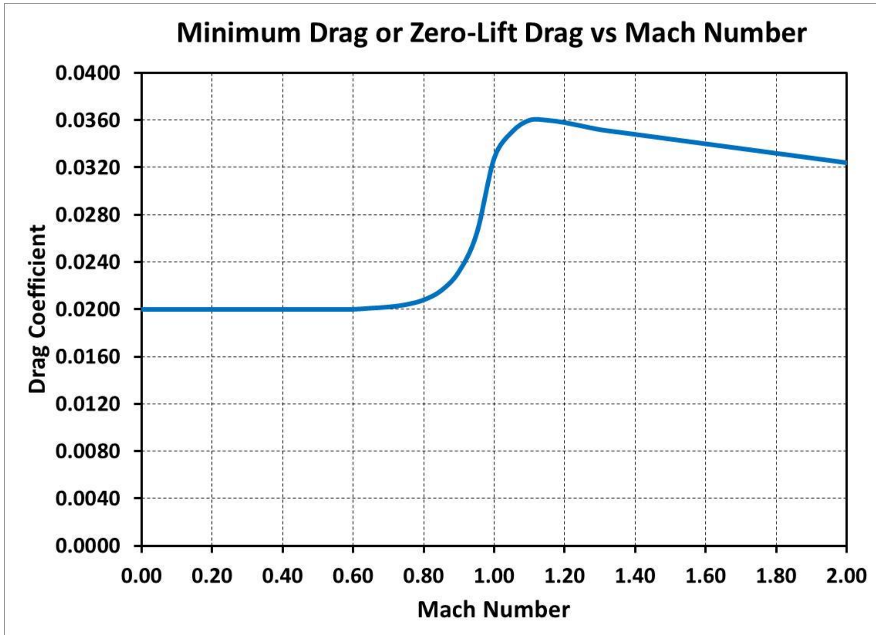




<u>Low wing sweep</u> (0 to 20 degrees) 0
High aspect ratio (AR = 20 - 25) 21
Slower cruise speed (0.2 - 0.6 Mach)

<u>High wing sweep</u> (40 to 70 degrees) 45
Low aspect ratio (AR = 2 - 4) 3
Faster cruise speeds (0.8 - 0.9 Mach)


<u>Medium wing sweep</u> (20 to 40 degrees) 25
Medium aspect Ratio (AR = 8 - 10) 8
Moderate cruise speed (0.6 - 0.85 Mach)

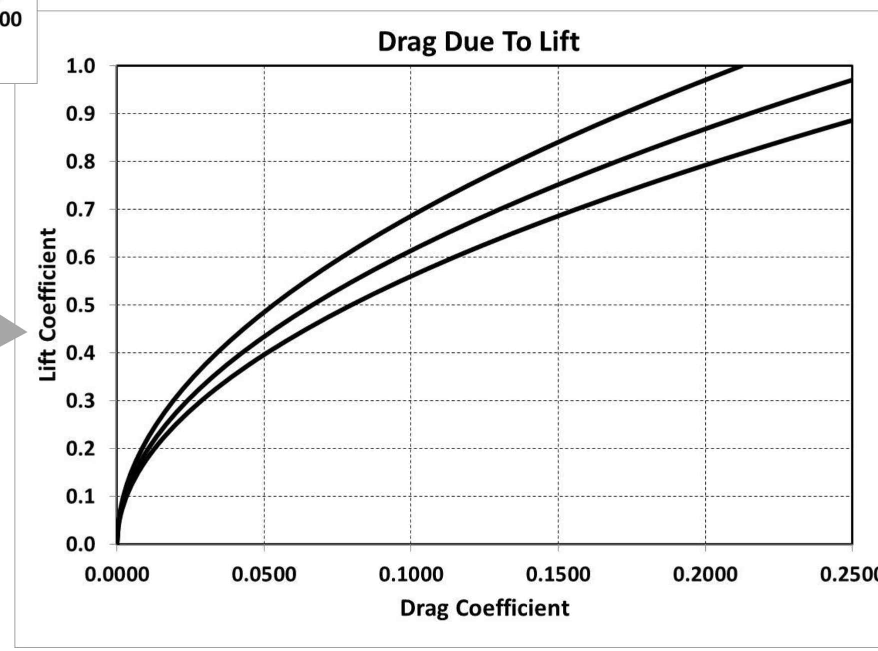
# *Aircraft Aerodynamics*



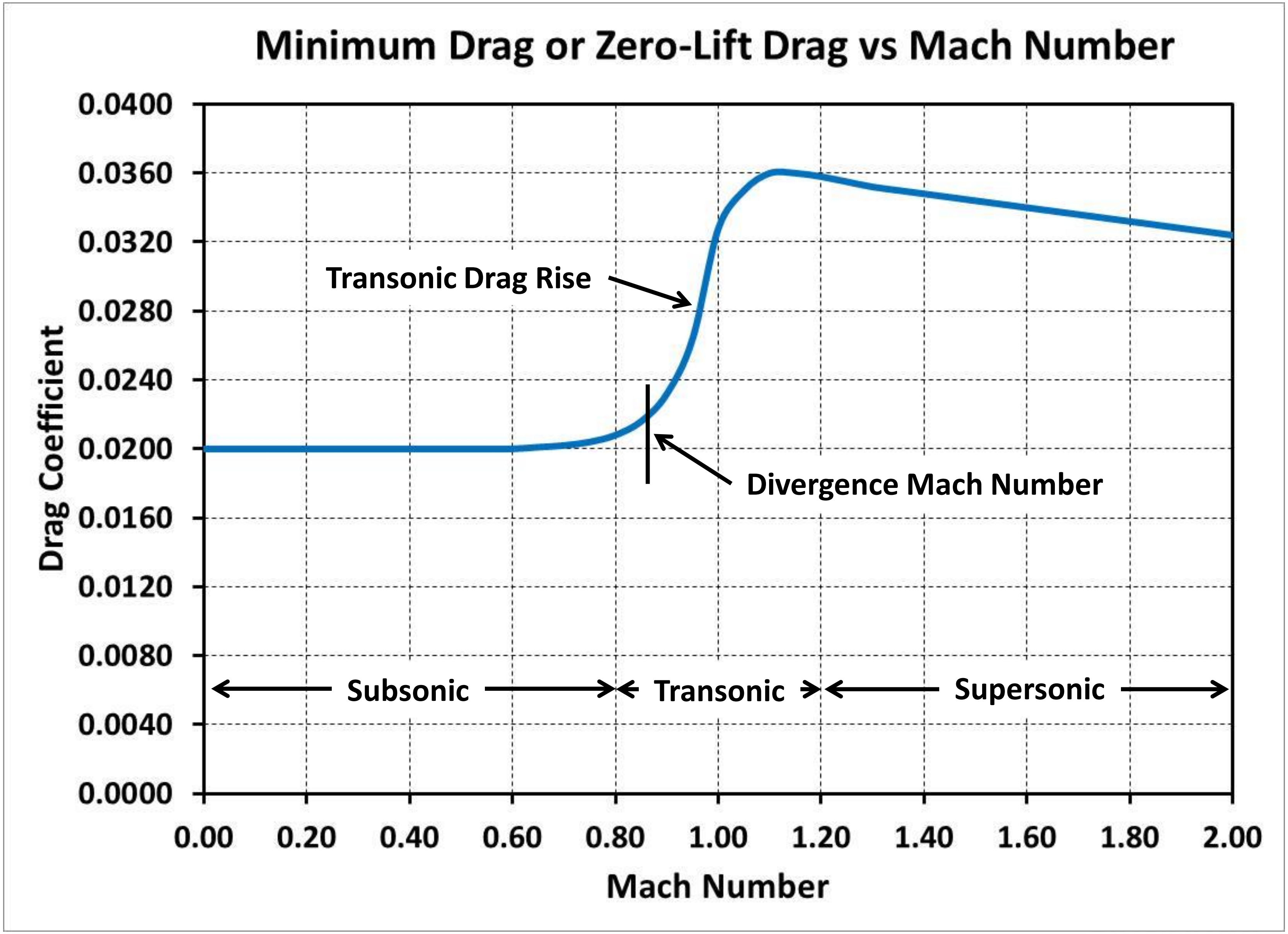

$$C_{D_0} \sim f\,(M, h)$$

$$C_{D_L} \sim f\,(C_L, M, c.g.)$$

$$C_D = C_{D_0} + K\,C_L^{\;2}$$

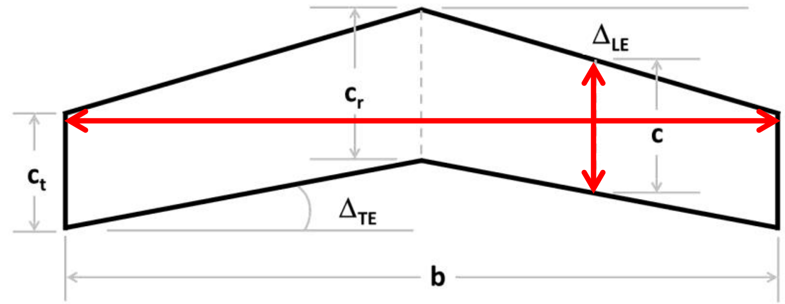


# Aircraft Aerodynamics



# *Aircraft Aerodynamics*

$$AR = \frac{b^2}{S} = \frac{b}{c}$$




Aspect Ratio (AR)

Indicator of an aircraft's drag due to lift

$$C_D = C_{D_0} + K\, C_L{}^2$$

$$K = \frac{1}{\pi\, AR\, e}$$

**High aspect ratio (AR = 20 - 25) – sailplanes, gliders**

**Long narrow wing**

**Less induced drag at low speeds, more drag at high speeds**

**Lower roll rate – more inertia**

**Higher bending stresses and deflections – less efficient wing structure**

**Low aspect ratio (AR = 2 - 4) – fighters, supersonic aircraft**

**Short stubby wing**

**More induced drag at low speeds, less drag at high speeds**

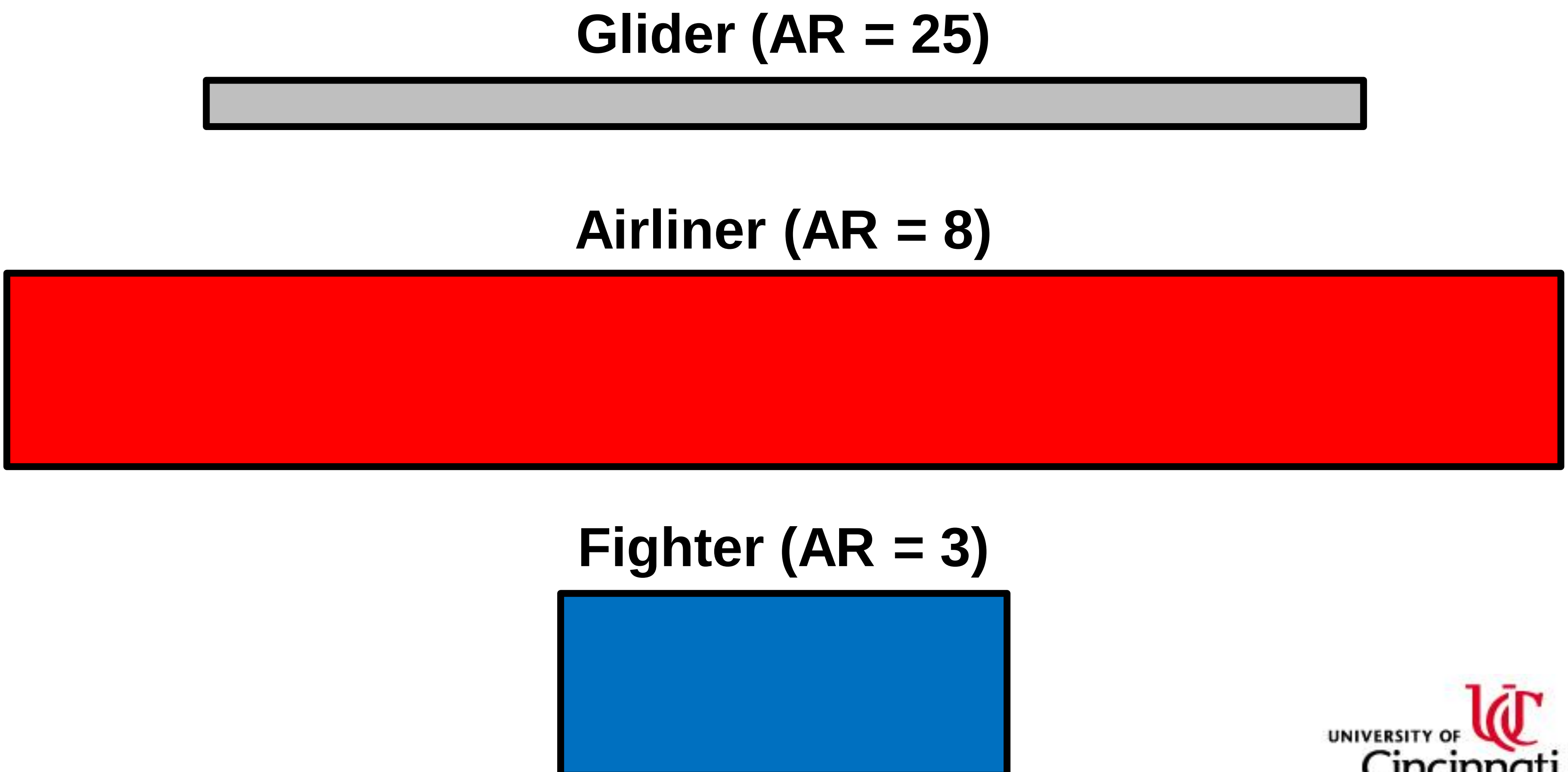
**Higher roll rate – less inertia**

**Lower bending stresses and deflections – more efficient wing structure**

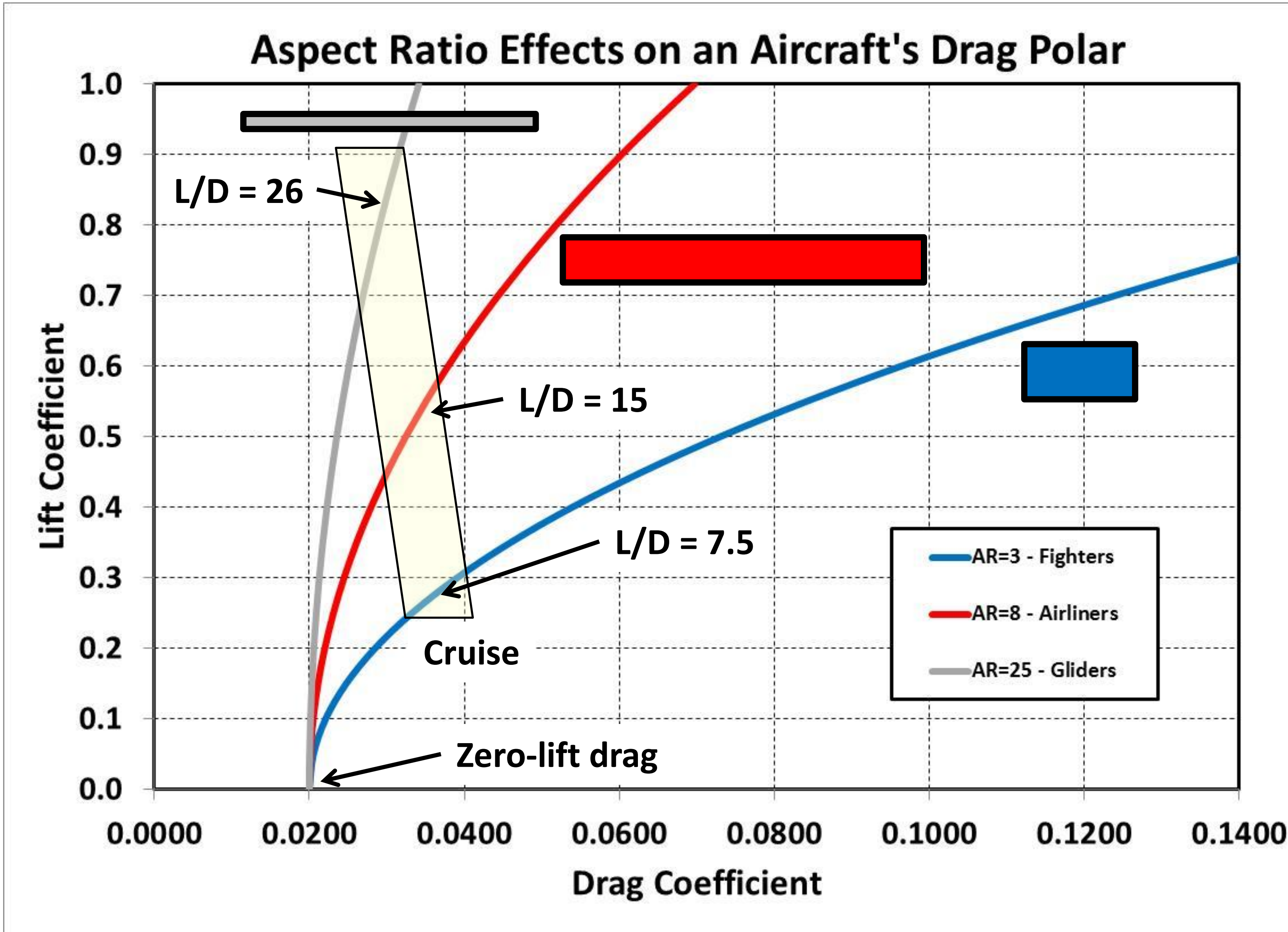
# *Aircraft Aerodynamics*

## Aspect Ratio Comparisons

**(wingspans are to scale)**



# *Aircraft Aerodynamics*



# *Aircraft Aerodynamics*

**Reynolds Number (Re):**

**Named after Osborne Reynolds (1842 – 1912)**

**Expressed as the ratio of momentum forces to viscous forces**

**Equates wind tunnel testing to flight test data**

$$\mathbf{Re} = \frac{\rho \, V \, c}{\mu}$$

**$\rho$ = density (slugs/ft$^3$ or kg/m$^3$)**

**V = velocity (ft/sec or m/sec)**

**c = characteristic length (ft or m)**

**$\mu$ = kinematic viscosity (slugs/ft-sec or kg/m-sec)**

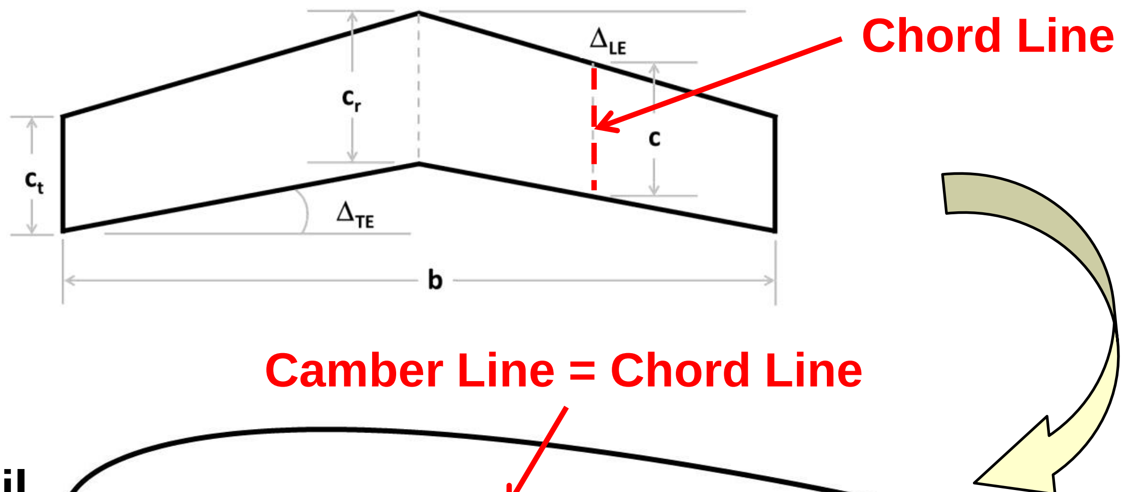
# Aircraft Aerodynamics

## Other Wing Planform Characteristics

**Airfoil Camber**

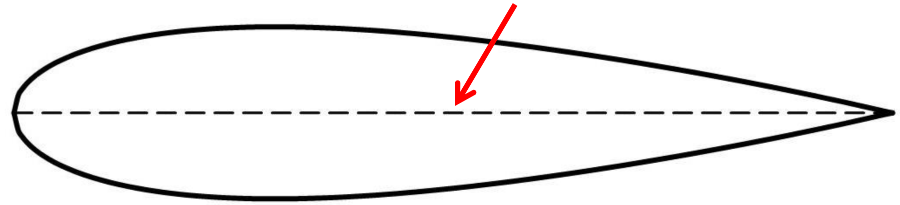
Spanwise Twist

Wing Dihedral



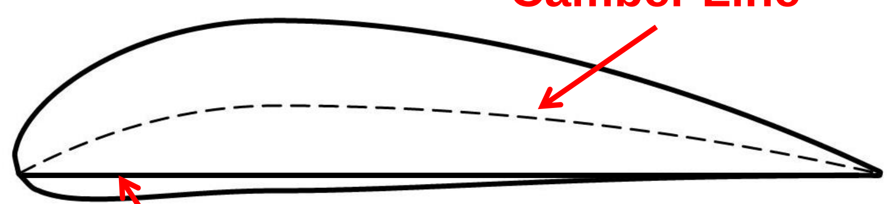

Camber Line = Chord Line

**Symmetric Airfoil (no camber)**



Camber Line

**Cambered Airfoil**



Chord Line

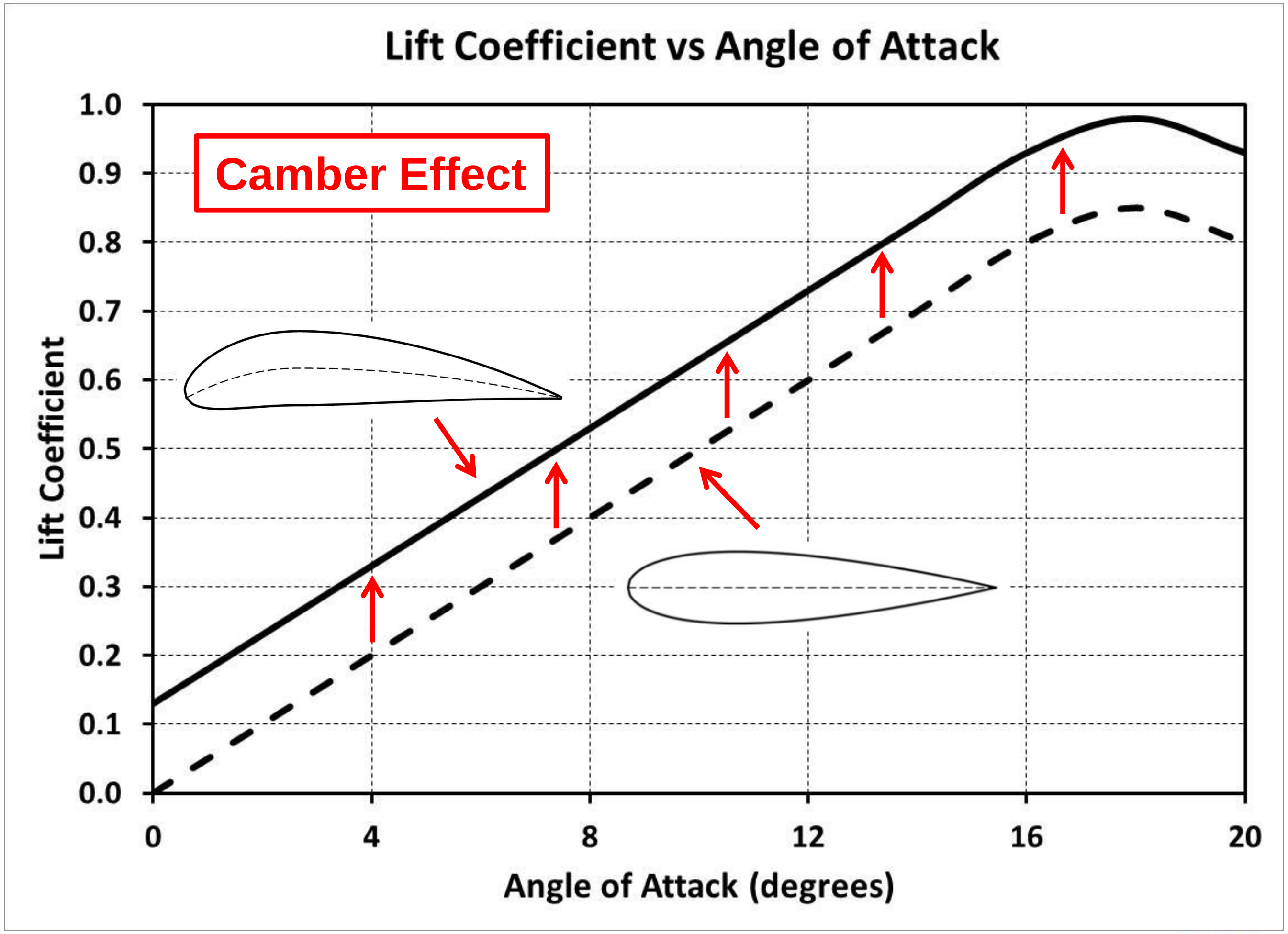
# Aircraft Aerodynamics

## Other Wing Planform Characteristics

**Airfoil Camber**

Spanwise Twist

Wing Dihedral



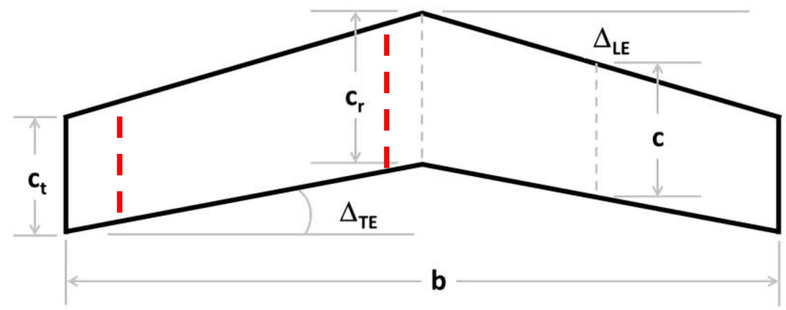
# Aircraft Aerodynamics

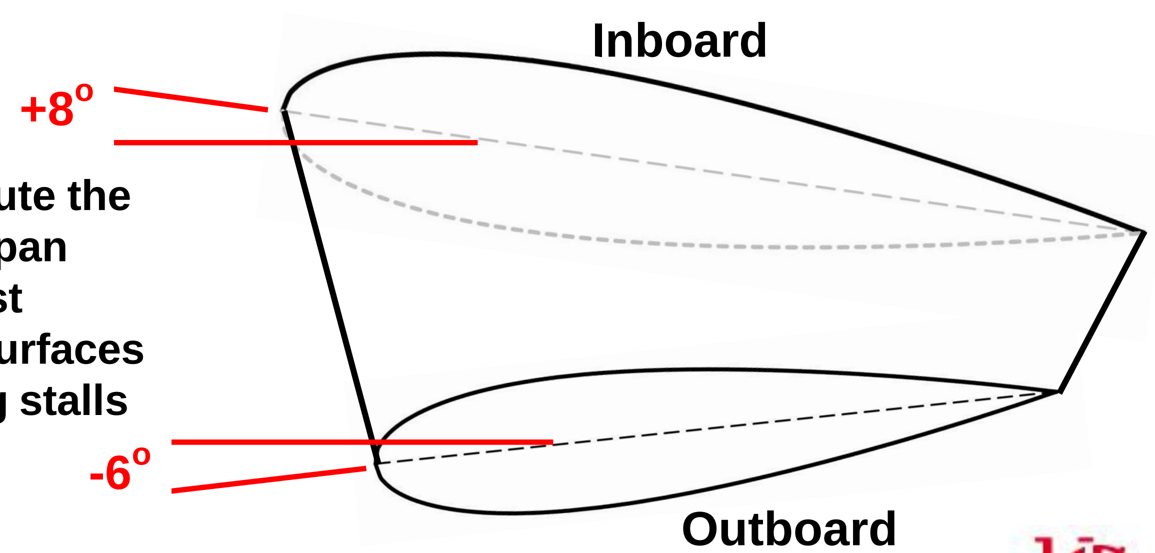
## Other Wing Planform Characteristics

Airfoil Camber

**Spanwise Twist**

Wing Dihedral



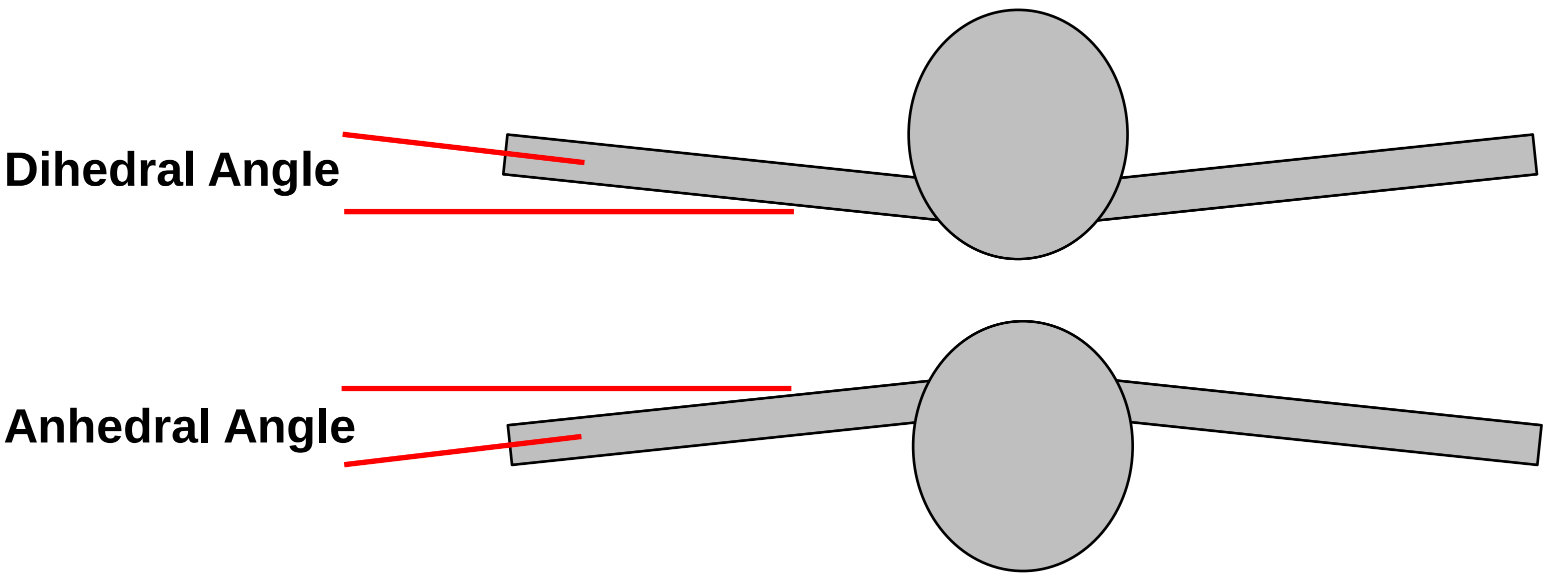

**Spanwise twist helps to distribute the aerodynamic loads along the span**
**-- allows the wing tip to stall last**
**-- keeps the outboard control surfaces active while the inboard wing stalls**

# *Aircraft Aerodynamics*

## Other Wing Planform Characteristics

Airfoil Camber
Spanwise Twist
**Wing Dihedral**

**Wing dihedral stabilizes lateral stability**
**-- keeps the wings level after a gust**
**-- normally used on low-wing aircraft**
**Wing anhedral enhances maneuverability**
**-- de-stabilizes lateral stability**
**-- normally used on high-wing aircraft & fighters**




**Anhedral angle = - Dihedral Angle**

# *Aircraft Aerodynamics*

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# *Finite Wing*

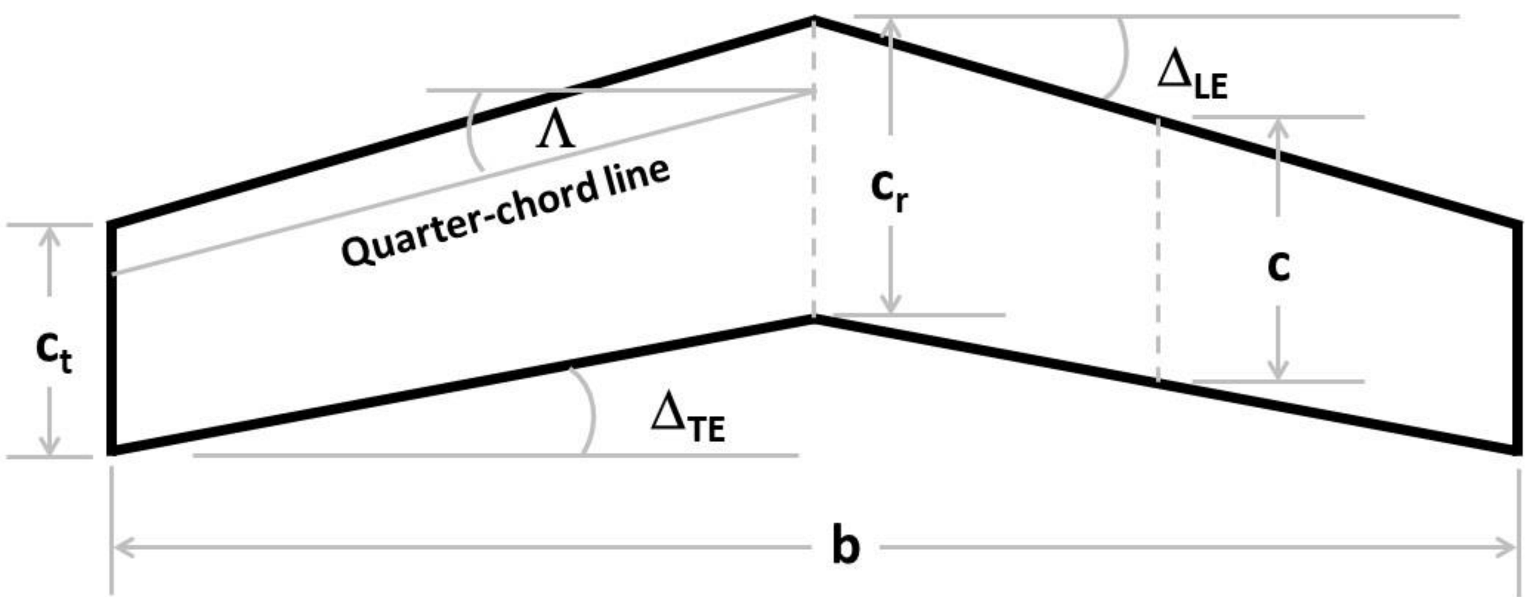
$$\mathbf{S = b\,c}$$

$$\mathbf{AR = \frac{b^2}{S} = \frac{b}{c}}$$

$$\boldsymbol{\lambda = \frac{c_t}{c_r}}$$

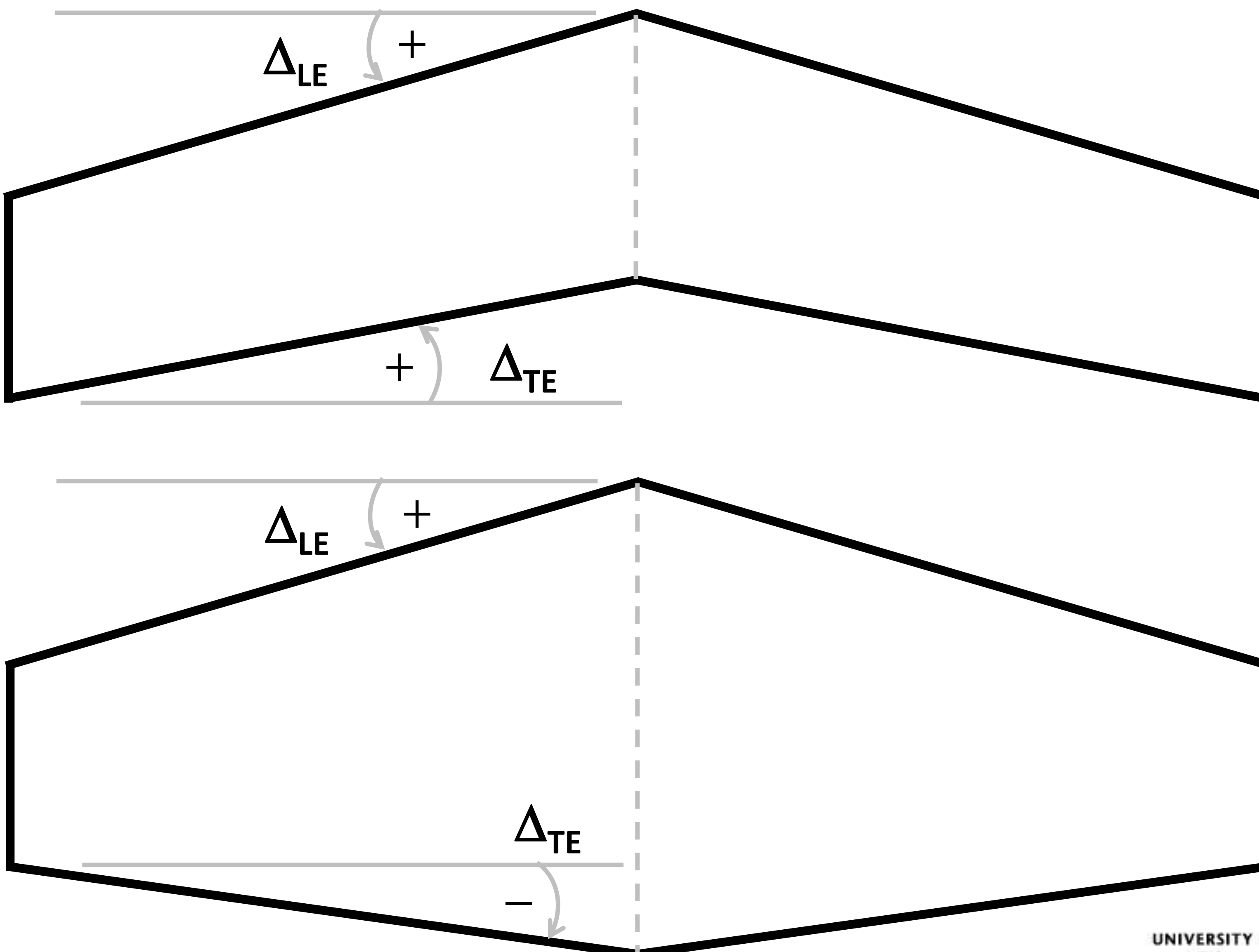
**<u>Wing Planform Characteristics</u>**

| | |
|---|---|
| **Wing Area (S)** | **Leading Edge Sweep ($\Delta_{LE}$)** |
| **Wing Span (b)** | **Trailing Edge Sweep ($\Delta_{TE}$)** |
| **Average Chord (c)** | **Aspect Ratio (AR)** |
| **Root Chord ($c_r$)** | **Taper Ratio ($\lambda$)** |
| **Tip Chord ($c_t$)** | **Quarter-Chord Angle ($\Lambda$)** |

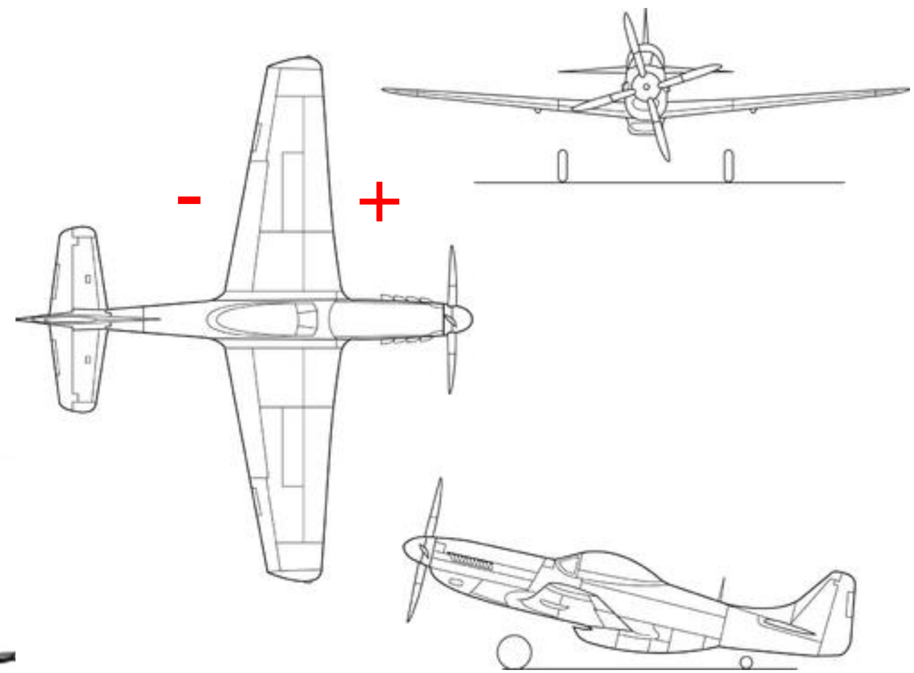


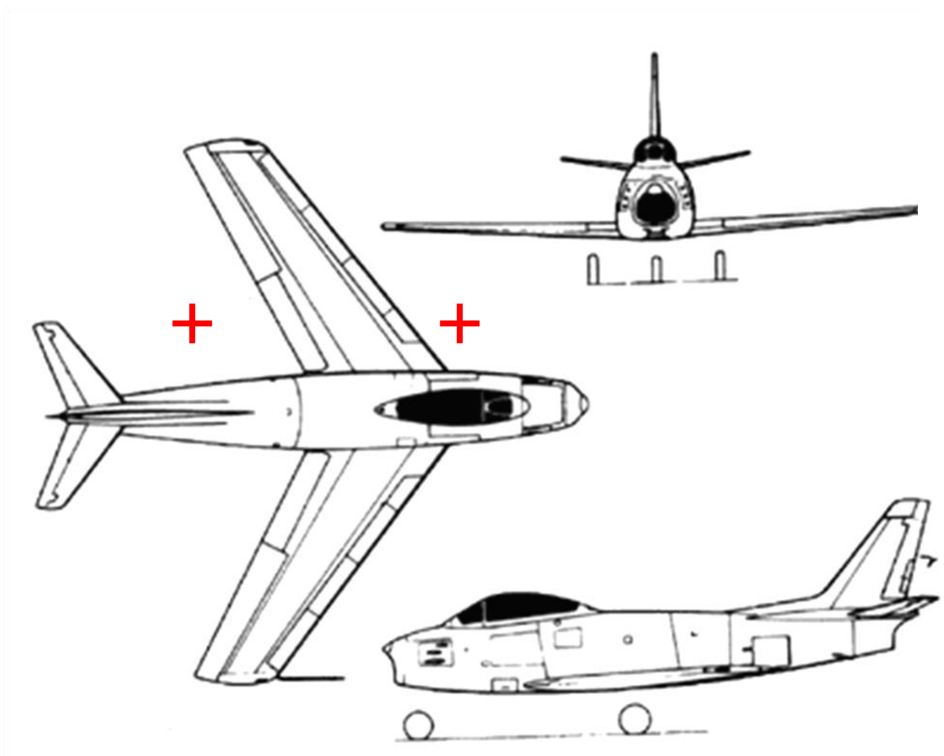

$$\Delta_{c/4} = \tan^{-1}[\tan\Delta_{LE} - 0.25 * c_r * (1-\lambda)/(b/2)]$$

# *Finite Wing*

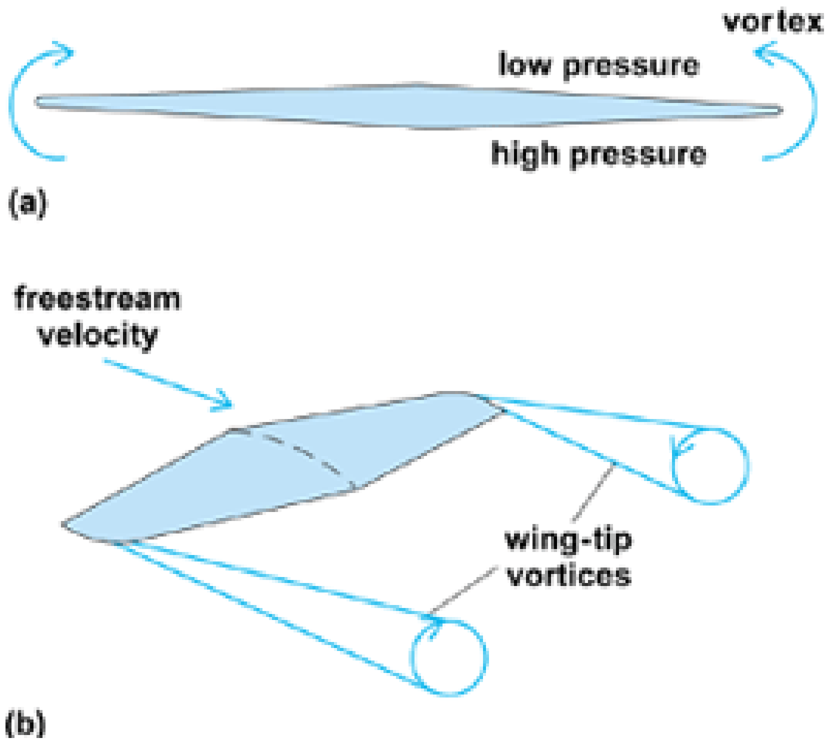


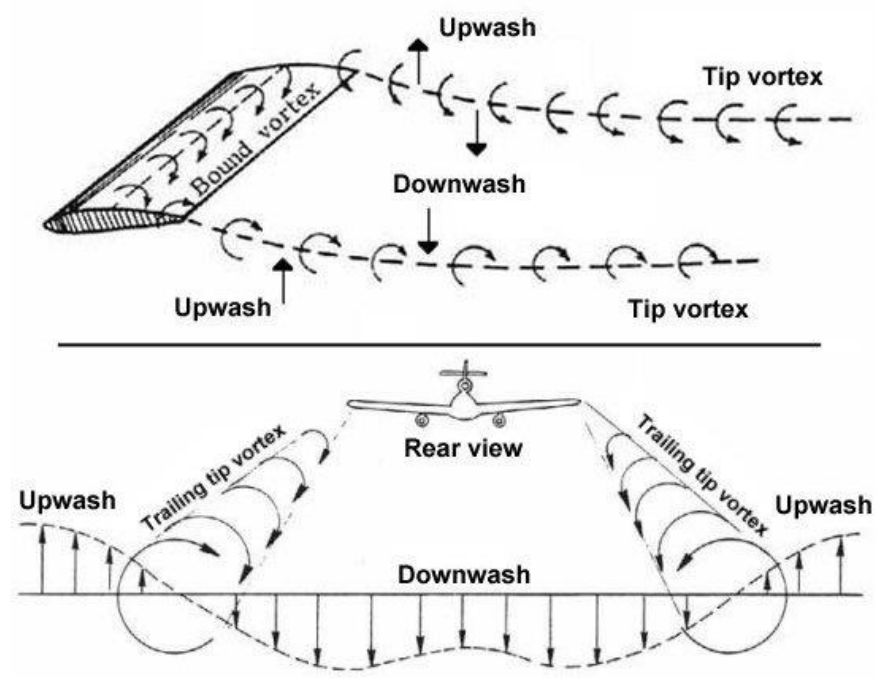
# *Finite Wing*



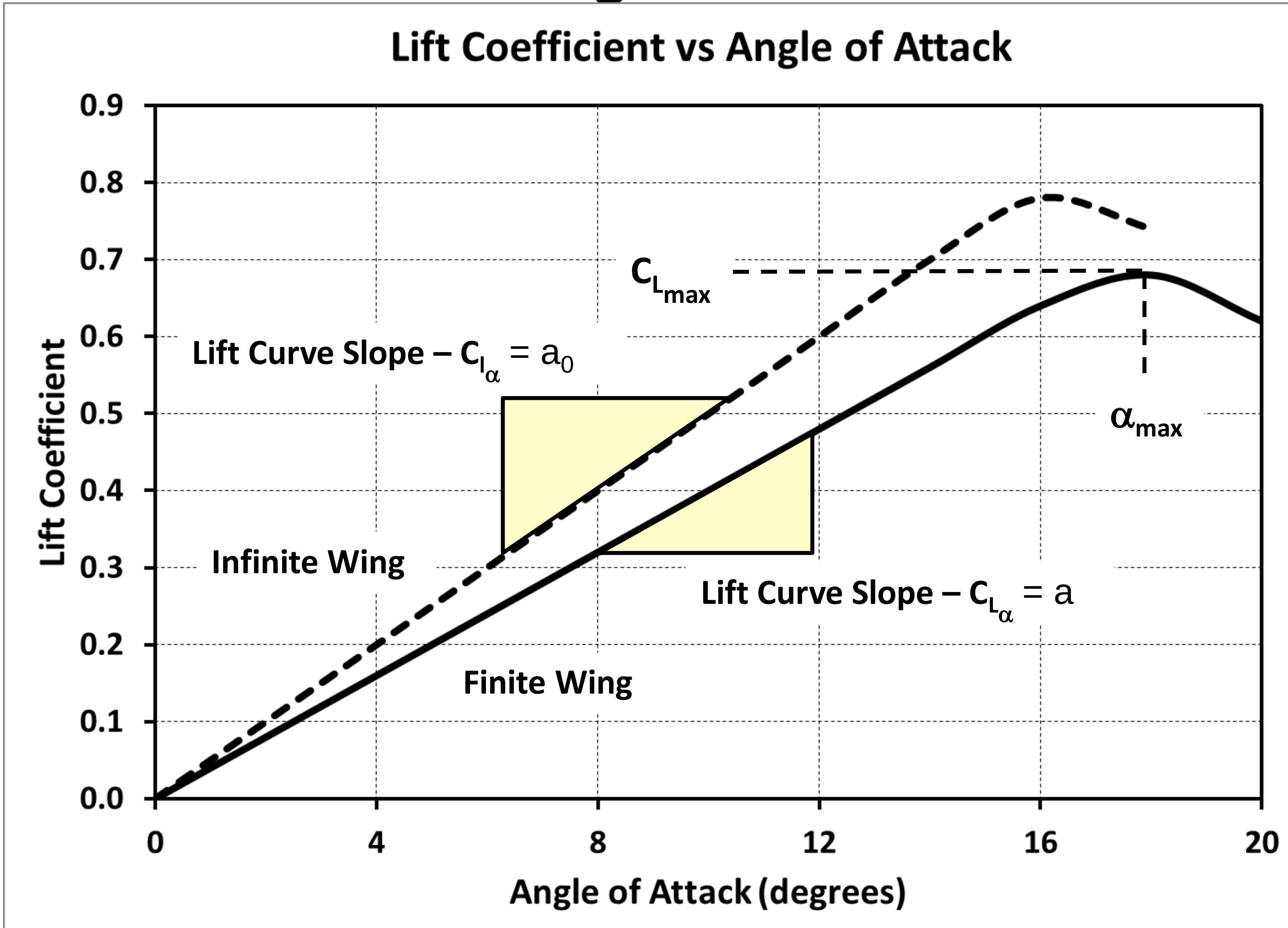
# *Finite Wing*




**A finite wing introduces vortices and a phenomenon called "downwash" which changes the lift curve**

# Finite Wing Lift Curve



# *Finite Wing Lift Curve*

**Look at 3 types of planforms:**
**- High aspect ratio straight wing**
**- Low aspect ratio straight wing**
**- Swept wing**

**Look at 3 speed regimes:**
**- Low speed (incompressible flow)**
**- Subsonic speed (compressible flow)**
**- Supersonic speed**

# *Finite Wing Lift Curve*

**High aspect ratio straight wing**

$$\mathbf{a} = \frac{\mathbf{a_0}}{\mathbf{1} + \dfrac{\mathbf{a_0}}{\boldsymbol{\pi}\,\mathbf{e_1}\,\mathbf{AR}}}$$

**Low speed**

$$\mathbf{a} = \frac{\mathbf{a_0}}{\sqrt{\mathbf{1} - \mathbf{M^2}} + \dfrac{\mathbf{a_0}}{\boldsymbol{\pi}\,\mathbf{e_1}\,\mathbf{AR}}}$$

**Subsonic**

$$\mathbf{a} = \frac{\mathbf{4}}{\sqrt{\mathbf{M^2} - \mathbf{1}}}$$

**Supersonic**

**Derived from Prandtl's lifting line theory and Prandtl-Glauert rule**

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# Finite Wing Lift Curve

**Low aspect ratio straight wing**

$$a = \frac{a_0}{\sqrt{1 + \left(\frac{a_0}{\pi AR}\right)^2} + \frac{a_0}{\pi\, AR}}$$ **Low speed**

$$a = \frac{a_0}{\sqrt{1 - M^2 + \left(\frac{a_0}{\pi AR}\right)^2} + \frac{a_0}{\pi\, AR}}$$ **Subsonic**

$$a = \frac{4}{\sqrt{M^2 - 1}}\left(1 - \frac{1}{2AR\sqrt{M^2 - 1}}\right)$$ **Supersonic**

**Derived from Helmbold's equation and Hoerner & Borst**

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# *Finite Wing Lift Curve*

**Swept wing**

$$\mathbf{a} = \frac{\mathbf{a_0 \cos\Lambda}}{\sqrt{\mathbf{1} + \left(\frac{\mathbf{a_0 \cos\Lambda}}{\boldsymbol{\pi}\mathbf{AR}}\right)^{\mathbf{2}}} + \frac{\mathbf{a_0 \cos\Lambda}}{\boldsymbol{\pi}\ \mathbf{AR}}}$$

**Low speed**

$$\mathbf{a} = \frac{\mathbf{a_0 \cos\Lambda}}{\sqrt{\mathbf{1} - \mathbf{M^2 \cos^2\Lambda} + \left(\frac{\mathbf{a_0 \cos\Lambda}}{\boldsymbol{\pi}\mathbf{AR}}\right)^{\mathbf{2}}} + \frac{\mathbf{a_0 \cos\Lambda}}{\boldsymbol{\pi}\ \mathbf{AR}}}$$

**Subsonic**

**a = very complicated methodology** **Supersonic**

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# *Aircraft Aerodynamics*

<u>Critical Mach Number</u> ($M_{crit}$)

- The freestream velocity when any local Mach Number exceeds 1.0 on any surface of the aircraft
- Largely depends on the shape of the wing or fuselage

<u>Drag Divergence Mach Number</u> ($M_{DD}$)

- Occurs at $M > M_{crit}$
- Causes shock-induced separation with a rapid increase in drag and a decrease in lift
- Strongly depends on the wing's sweep angle

$$\mathbf{M_{crit} = 1.0 - 0.065\left(100\ \frac{t_{max}}{c}\right)^{0.6}} \qquad \mathbf{M_{DD} = \frac{0.7}{\cos \Delta_{LE}}}$$

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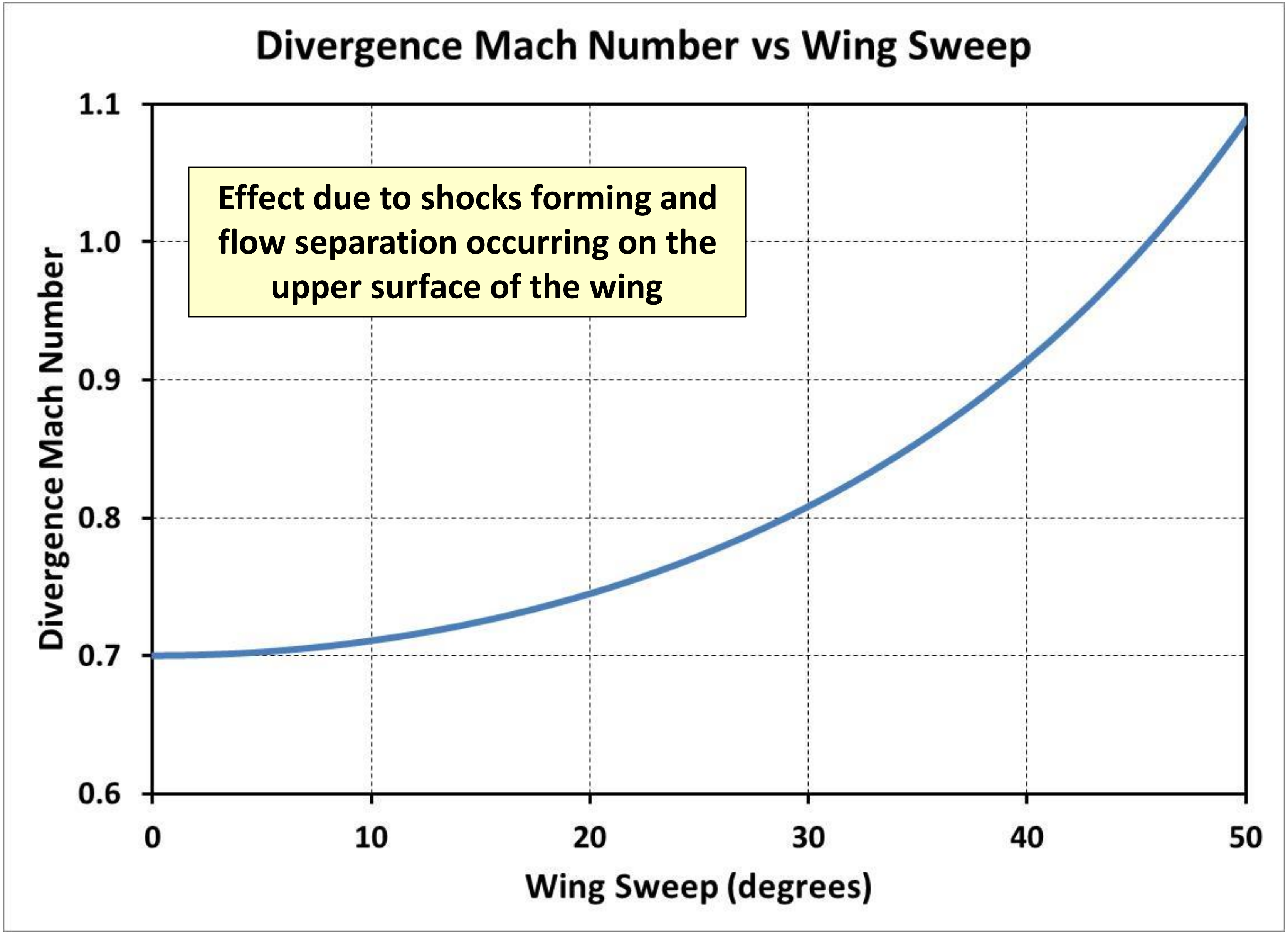
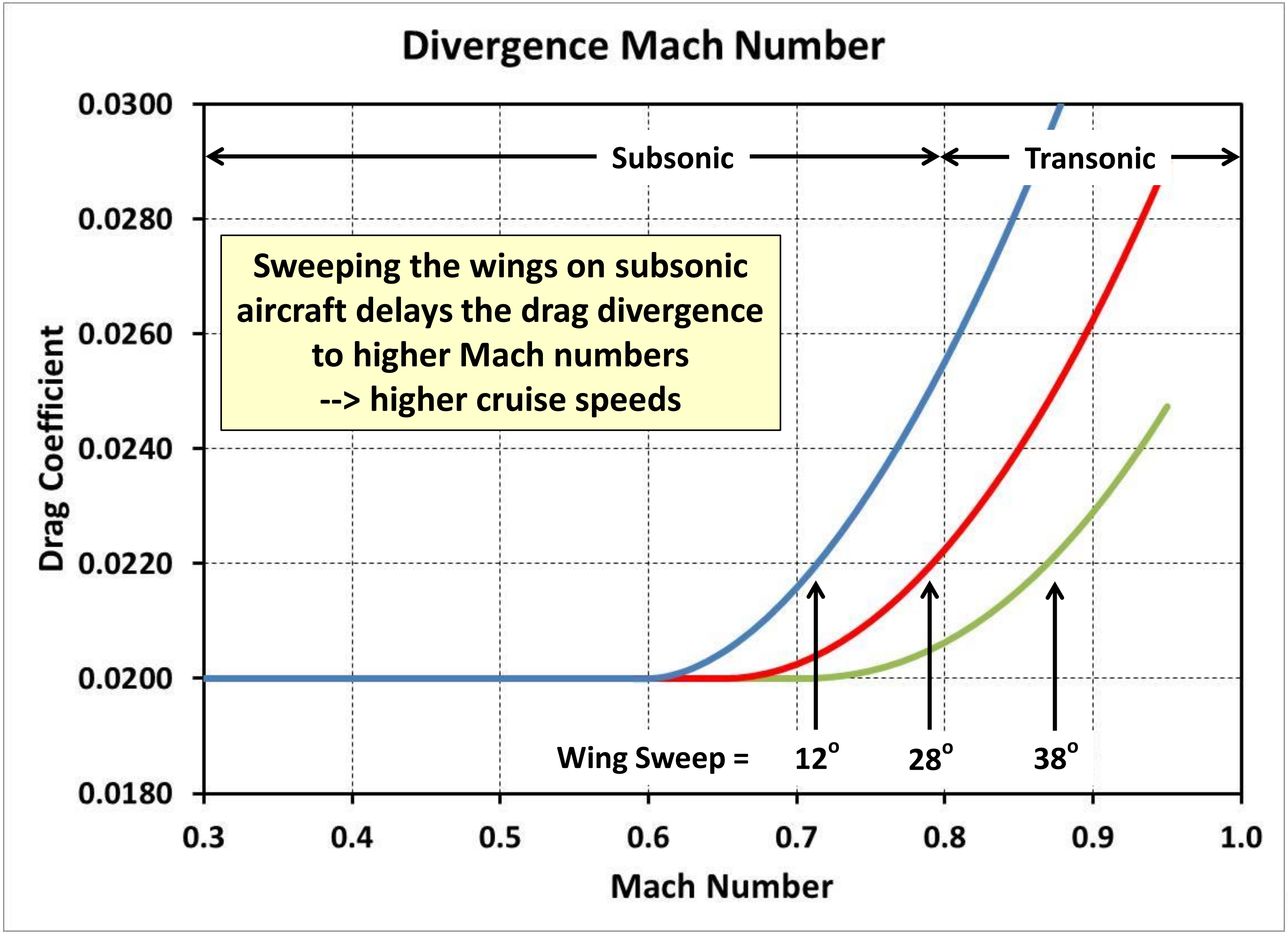
# Aircraft Aerodynamics



# *Aircraft Aerodynamics*



# *Aircraft Aerodynamics*

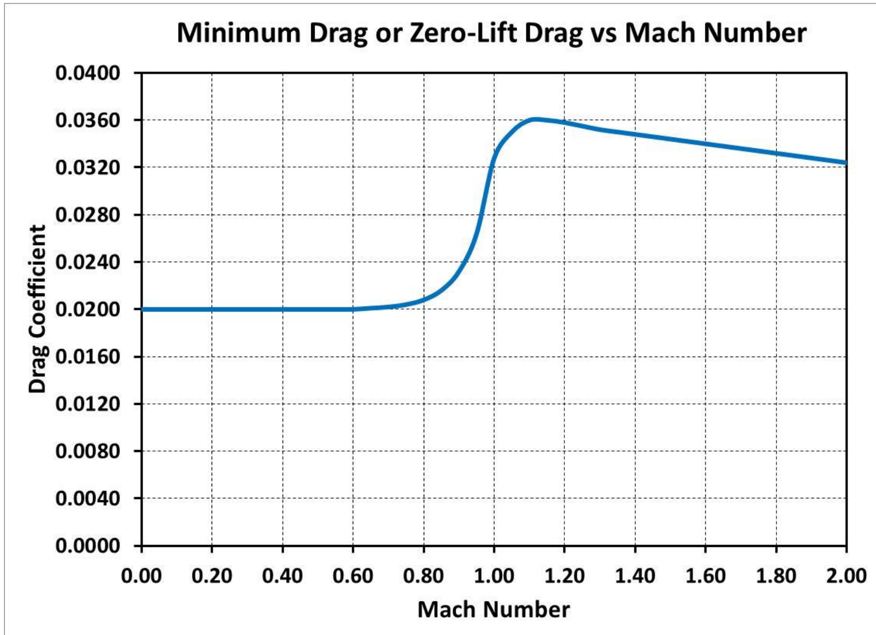
**Lift and Drag are defined by:**

- **Airfoil characteristics**
- **Wing planform characteristics**
- **Wing / body / tail configuration**
- **Subsonic vs supersonic capability**

**Lift and Drag are a function of:**

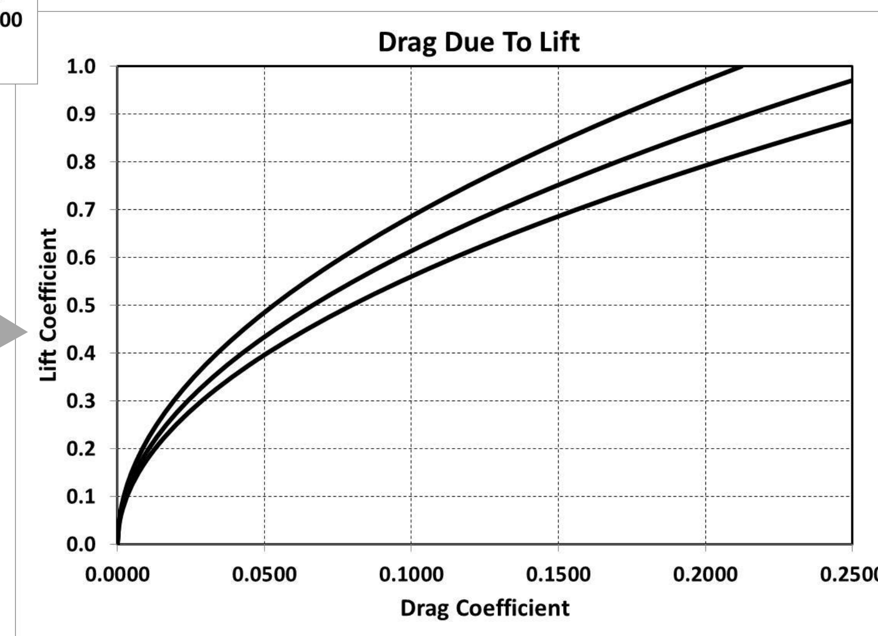
- ⟶ **Mach Number (minimum drag or zero-lift drag)**
- ⟶ **Angle of attack (drag due to lift or induced drag)**
- ⟶ **Altitude (Reynolds Number effect)**
- ⟶ **Center of gravity (c.g.)**
- **Induced propulsion effects**
- **External store carriage**

# *Finite Wing Drag*



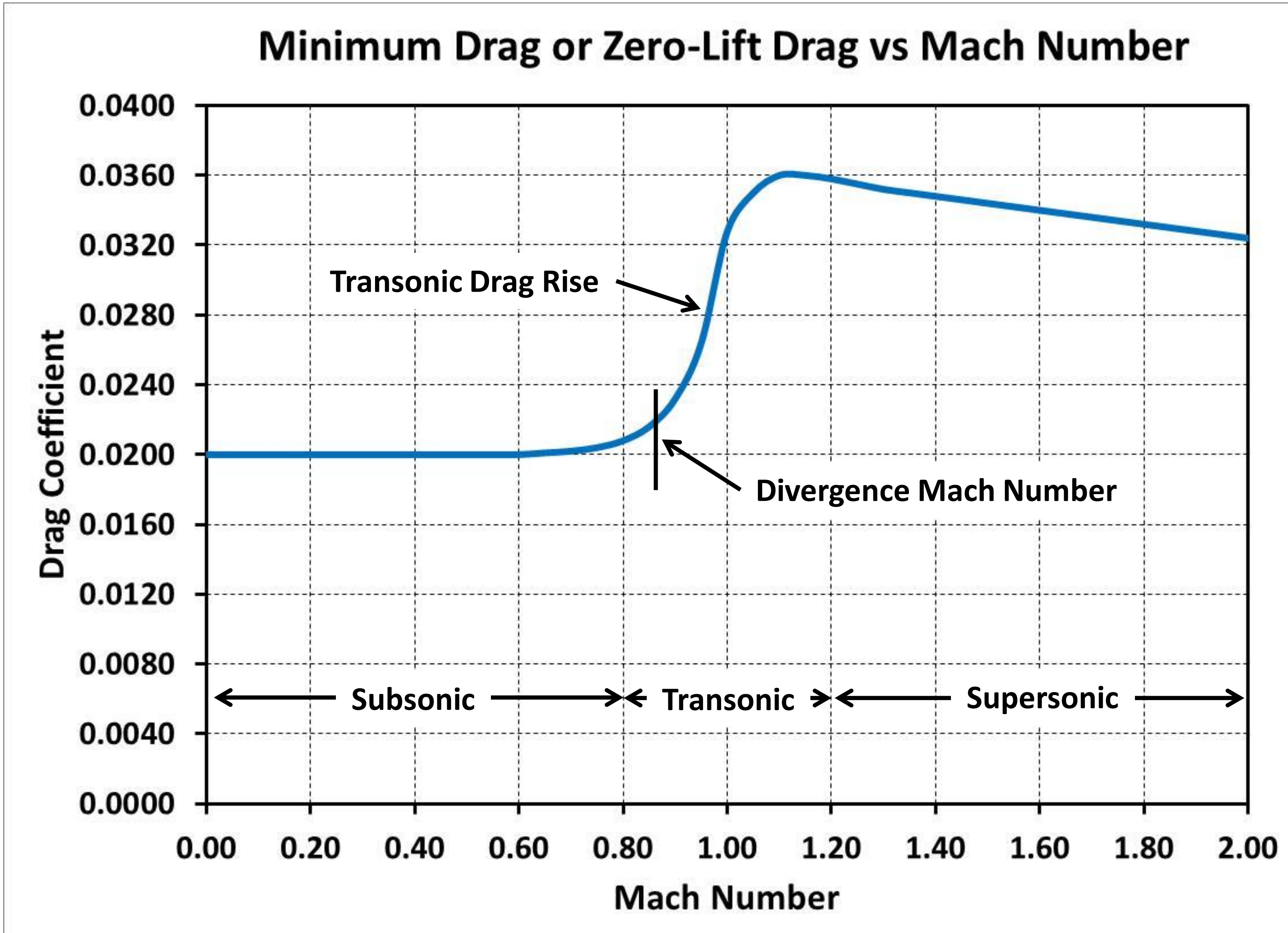

$$C_{D_0} \sim f\,(M, h)$$

$$C_{D_L} \sim f\,(C_L, M, c.g.)$$




$$C_D = C_{D_0} + K\,C_L^{\;2}$$

# *Finite Wing Drag*



# *Finite Wing Drag*

**Minimum Drag or Zero-Lift Drag includes:**

- **Skin friction drag**
- **Pressure drag**
- **Interference drag**
- **Parasite drag**
- **Protuberance drag**
- **Leakage drag**

**Other types of drag to take into account:**

- **Landing gear drag**
- **Flap drag**
- **External store drag**
- **Trim drag**

# *Aircraft Drag Polar*

$$\boxed{C_L = \frac{W\,n}{q\,S}}$$

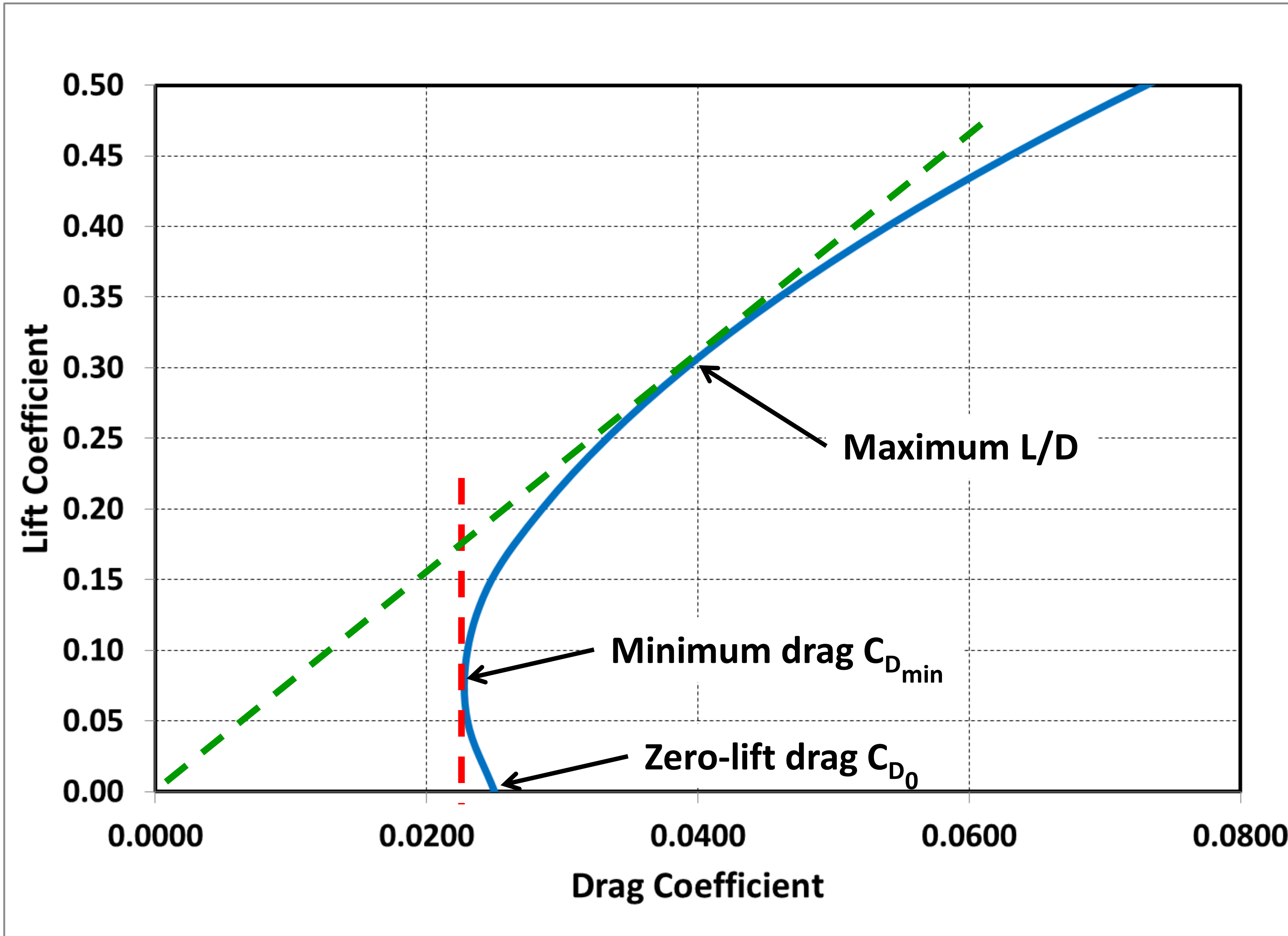
$$\boxed{C_D = C_{D_0} + \frac{1}{\pi\,AR\,e}\,{C_L}^2}$$

$$\boxed{\frac{L}{D} = \frac{C_L}{C_D}}$$

**W ~ aircraft weight (lbs)**
**n ~ load factor (g's)**
**q ~ dynamic pressure (lb/ft$^2$)**
**S ~ wing reference area (ft$^2$)**

**$C_L$ ~ lift coefficient**
**$C_D$ ~ drag coefficient**
**$C_{D_0}$ ~ zero-lift drag coefficient**
**AR ~ aspect ratio**
**e ~ span efficiency factor**

# *Aircraft Drag Polar*

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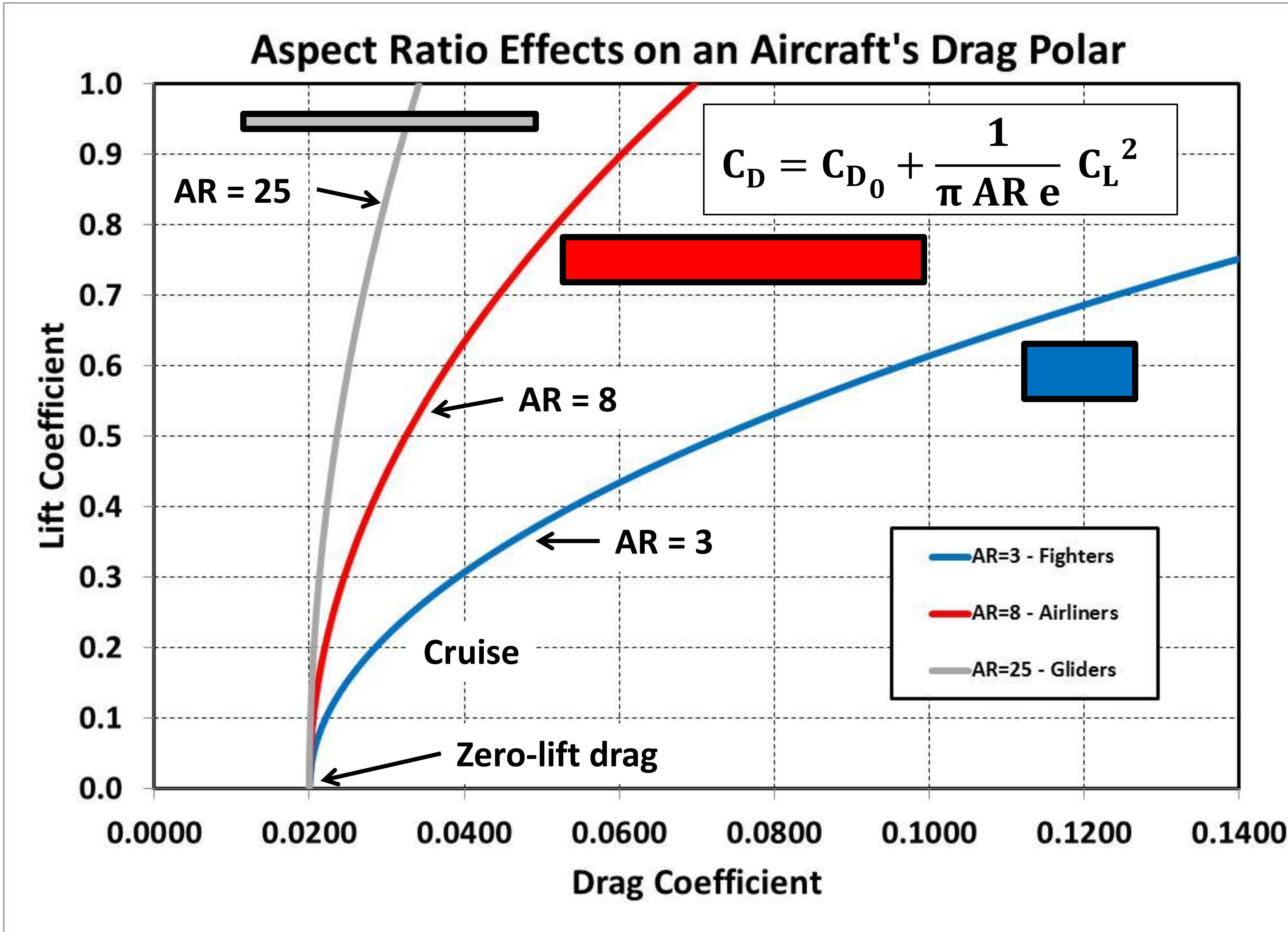
# *Finite Wing Drag*



# Example Calculations

**Drag Polar**

$$\mathbf{C_D = C_{D_0} + \frac{1}{\pi\, AR\, e}\, C_L^{\,2} \;= C_{D_0} + K\, C_L^{\,2}}$$

$$\mathbf{C_L = \frac{W\, n}{q\, S} = \frac{W\, n}{\frac{1}{2}\, \rho\, V^2\, S} = \frac{W\, n}{\left(q/M^2\right) M^2\, S}}$$

**Example Aircraft Characteristics:**

$$\mathbf{W = 20{,}000\ lb \quad S = 800\ ft^2 \quad C_{D_0} = 0.0185 \quad K = 0.07}$$

**For an aircraft at 1 g, 0.60 Mach, and 20,000 ft:**

$$\mathbf{C_L = \frac{W\, n}{\left(q/M^2\right) M^2\, S} = \frac{20{,}000}{(680.7)\left(0.60^2\right)(800)} = 0.1020}$$

$$\mathbf{C_D = C_{D_0} + K\, C_L^{\,2} \;= 0.0185 + (0.07)(.1020)^2 = 0.0192}$$

# *Homework Assignment*

**HW #3 – Aerodynamics**
**(due by 11:59 pm ET on Monday)**
**Reading – Chapter 2 in textbook**

**<u>HW Help Session</u>**
**Monday 1:00 – 2:00 pm ET**

**<u>Posted on Canvas</u>**
**HW #3 Assignment with instructions, tips, and checklist**
**HW #3 Template for data table in Excel**

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# Questions?