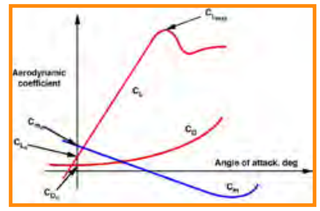
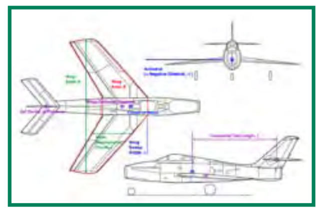
Low-Speed Aerodynamics

Robert Stengel, Aircraft Flight Dynamics, MAE 331, 2014

Learning Objectives

- 2D lift and drag
- Appreciate effects of Reynolds number
- Relationships between airplane shape and aerodynamic characteristics
- Distinguish between 2D and 3D lift and drag
- How to compute the static and dynamic effects of aerodynamic control surfaces
- Computational tools for simple calculations





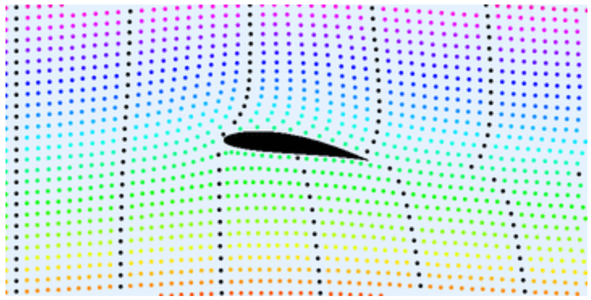
Reading:
Flight Dynamics
Aerodynamic Coefficients, 65-84

http://www.princeton.edu/~stengel/MAE331.html
http://www.princeton.edu/~stengel/FlightDynamics.html

Assignment #2
due: End of day, Sept 26, 2014

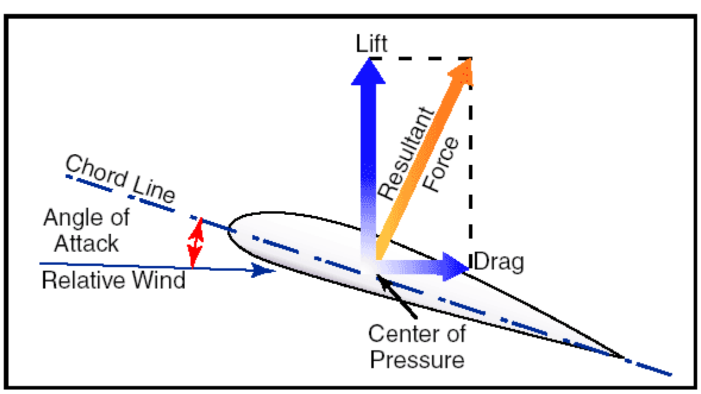
- Compute the trajectory of a balsa glider
- Computer simulation of the equations of motion
- Compare to the actual flight of the glider (Assignment #1)
- Similar to the flight of a paper airplane
- 2-person team assignment

2-Dimensional Aerodynamic Lift and Drag



Lift and Drag

- **Lift** is perpendicular to the free-stream airflow direction
- **Drag** is parallel to the free-stream airflow direction



Longitudinal Aerodynamic Forces

- **Non-dimensional force coefficients are dimensionalized by**
  - dynamic pressure, $\bar{q}$, *N/m²* *or lb/sq ft*
  - reference area, *S*, *m² of ft²*

$$Lift = C_L \bar{q} S = C_L \left(\frac{1}{2} \rho V^2 \right) S$$

$$Drag = C_D \bar{q} S = C_D \left(\frac{1}{2} \rho V^2 \right) S$$

Circulation of Incompressible Air Flow About a 2-D Airfoil

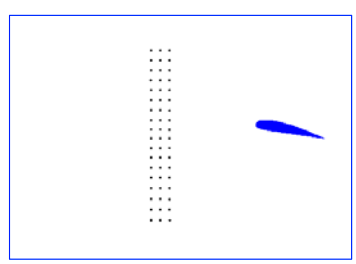
- **Bernoulli's equation (inviscid, incompressible flow)**

$$p_{static} + \frac{1}{2} \rho V^2 = \text{constant along streamline} = p_{stagnation}$$

- **Vorticity at point *x***

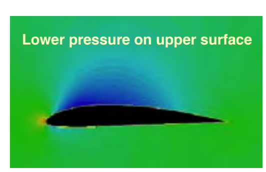
$$V_{upper}(x) = V_\infty + \Delta V(x)/2$$
$$V_{lower}(x) = V_\infty - \Delta V(x)/2$$

$$\gamma_{2-D}(x) = \frac{\Delta V(x)}{\Delta z(x)}$$



- **Circulation about airfoil**

$$\Gamma_{2-D} = \int_0^c \gamma_{2-D}(x) dx = \int_0^c \frac{\Delta V(x)}{\Delta z(x)} dx$$



Relationship Between Circulation and Lift

Differential pressure along chord section

$$\Delta p(x) = \left[p_{static} + \frac{1}{2}\rho_\infty\left(V_\infty + \Delta V(x)/2\right)^2\right] - \left[p_{static} + \frac{1}{2}\rho_\infty\left(V\infty - \Delta V(x)/2\right)^2\right]$$
$$= \frac{1}{2}\rho_\infty\left[\left(V_\infty + \Delta V(x)/2\right)^2 - \left(V_\infty - \Delta V(x)/2\right)^2\right]$$
$$= \rho_\infty V_\infty \Delta V(x) = \rho_\infty V_\infty \Delta z(x)\gamma_{2-D}(x)$$

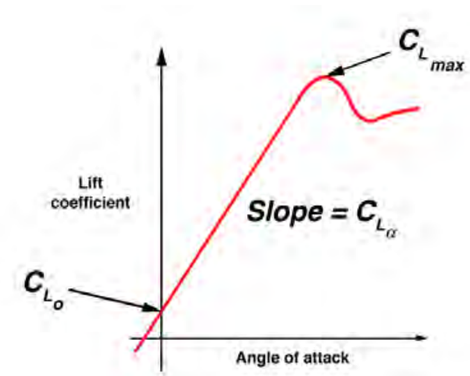
2-D Lift (inviscid, incompressible flow)

$$(Lift)_{2-D} = \int_0^c \Delta p(x)\,dx = \rho_\infty V_\infty \int_0^c \gamma_{2-D}(x)\,dx = \rho_\infty V_\infty (\Gamma)_{2-D}$$

$$\simeq \frac{1}{2}\rho_\infty V_\infty{}^2 c(2\pi\alpha)[\text{thin, symmetric airfoil}] + \rho_\infty V_\infty\left(\Gamma_{camber}\right)_{2-D}$$
$$\simeq \frac{1}{2}\rho_\infty V_\infty{}^2 c\left(C_{L_\alpha}\right)_{2-D}\alpha + \rho_\infty V_\infty\left(\Gamma_{camber}\right)_{2-D}$$

Lift vs. Angle of Attack

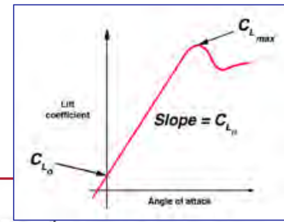
2-D Lift (inviscid, incompressible flow)



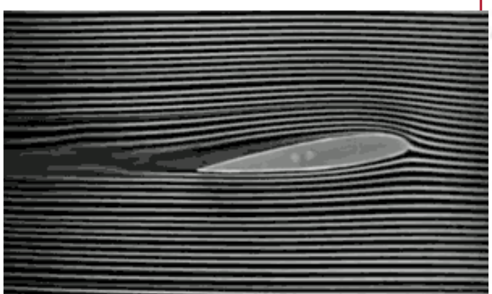
$$(\mathbf{Lift})_{2\text{-}D} \simeq \left[\frac{1}{2}\rho_\infty V_\infty{}^2 c\left(C_{L_\alpha}\right)_{2-D}\alpha\right] + \left[\rho_\infty V_\infty\left(\Gamma_{camber}\right)_{2-D}\right]$$

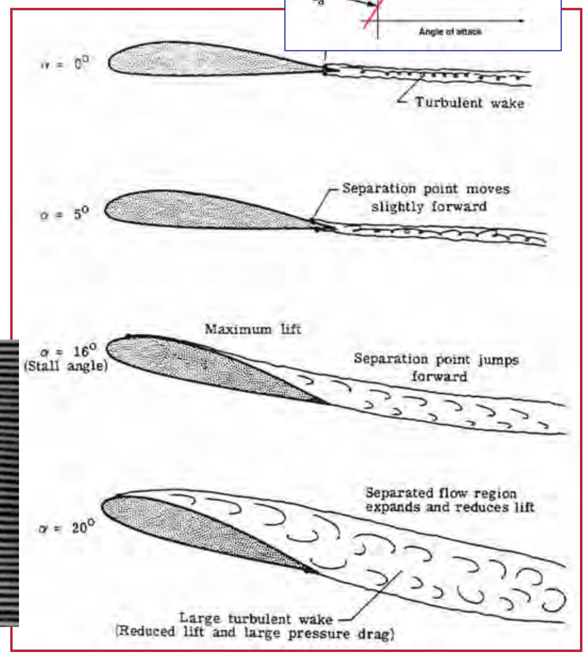
= **[Lift due to angle of attack] + [Lift due to camber]**

Typical Flow Variation with Angle of Attack



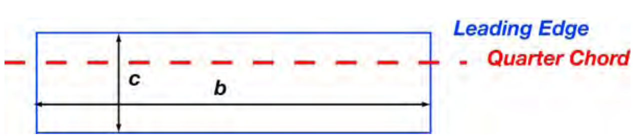
- At higher angles,
  - flow separates
  - wing loses lift
- Flow separation produces stall





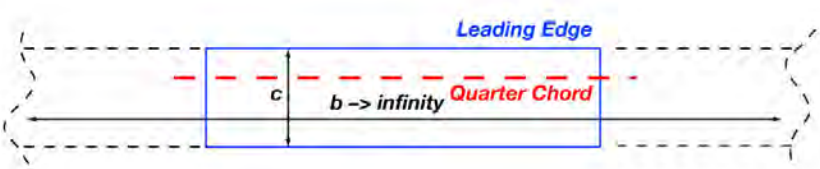
What Do We Mean by 2-Dimensional Aerodynamics?

Finite-span wing –> finite aspect ratio

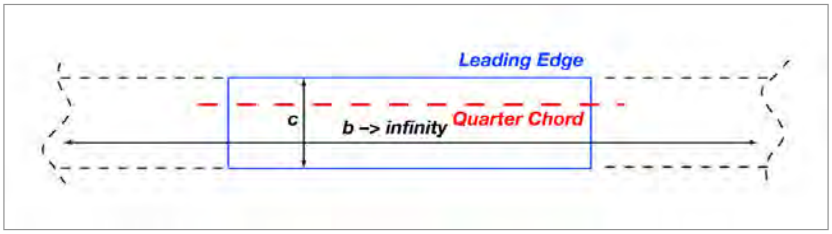


$$AR = \frac{b}{c} \quad \text{rectangular wing}$$
$$= \frac{b \times b}{c \times b} = \frac{b^2}{S} \quad \text{any wing}$$

Infinite-span wing –> infinite aspect ratio



What Do We Mean by 2-Dimensional Aerodynamics?



- Assuming constant chord section, the "2-D Lift" is the same at any *y* station of the infinite-span wing

$$Lift_{3-D} = C_{L_{3-D}} \frac{1}{2}\rho V^2 S = C_{L_{3-D}} \frac{1}{2}\rho V^2 (bc) \quad \text{[Rectangular wing]}$$

$$\Delta\left(Lift_{3-D}\right) = C_{L_{3-D}} \frac{1}{2}\rho V^2 c\Delta y$$

$$\lim_{\Delta y \to 0} \Delta\left(Lift_{3-D}\right) = \lim_{\Delta y \to 0}\left(C_{L_{3-D}} \frac{1}{2}\rho V^2 c\Delta y\right) \Rightarrow \text{"2-D Lift"} = C_{L_{2-D}} \frac{1}{2}\rho V^2 c$$

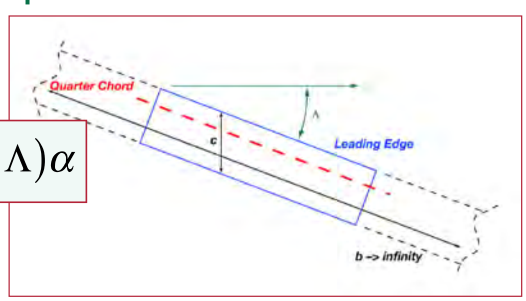
Effect of Sweep Angle on Lift

- Unswept wing, 2-D lift slope coefficient
  - Inviscid, incompressible flow
  - Referenced to chord length, *c*, rather than wing area

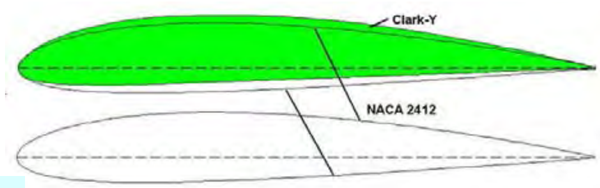
$$C_{L_{2-D}} = \alpha\left(\frac{\partial C_L}{\partial \alpha}\right)_{2-D} = \alpha\left(C_{L_\alpha}\right)_{2-D} = (2\pi)\alpha \quad \text{[Lifting-line Theory]}$$

- Swept wing, 2-D lift slope coefficient
  - Inviscid, incompressible flow

$$C_{L_{2-D}} = \alpha\left(C_{L_\alpha}\right)_{2-D} = (2\pi\cos\Lambda)\alpha$$

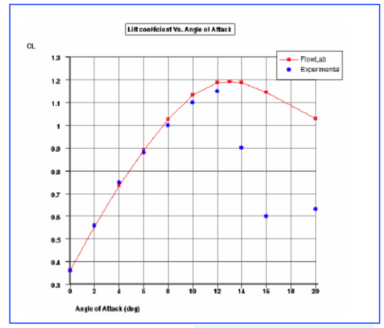


Classic Airfoil Profiles



NACA Airfoils
http://en.wikipedia.org/wiki/NACA_airfoil

- NACA 4-digit Profiles (*e.g., NACA 2412*)
  - Maximum camber as percentage of chord (2)
  - Distance of maximum camber from leading edge, (4) = 40%
  - Maximum thickness as percentage of chord (12)
- Clark Y (1922): Flat lower surface, 11.7% thickness
  - GA, WWII aircraft
  - Reasonable *L/D*
  - Benign computed stall characteristics
  - Experimental result is more abrupt



Fluent, Inc, 2007

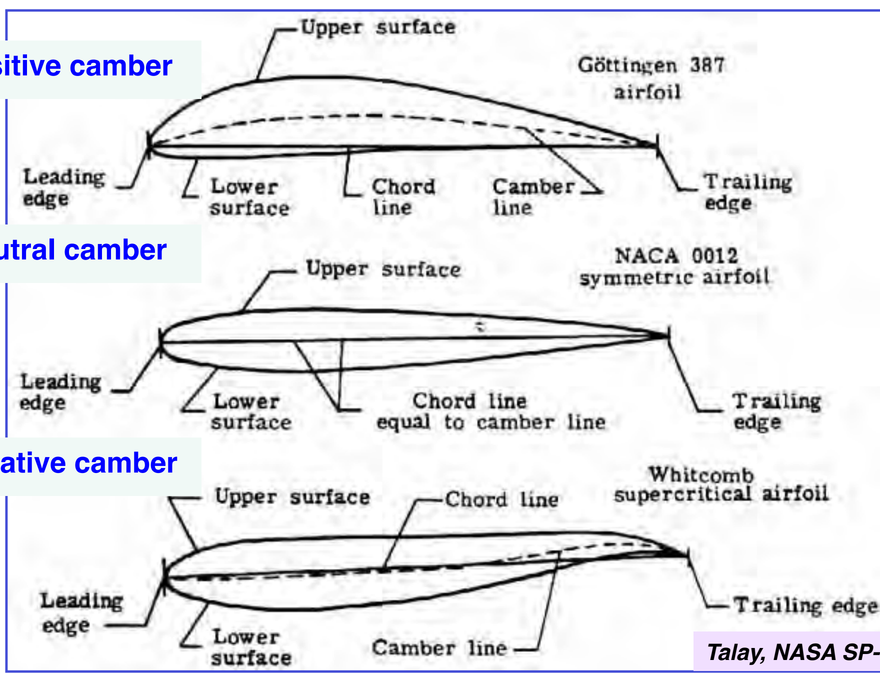
Clark Y Airfoil
http://en.wikipedia.org/wiki/Clark_Y

Typical Airfoil Profiles

Positive camber

Neutral camber

Negative camber



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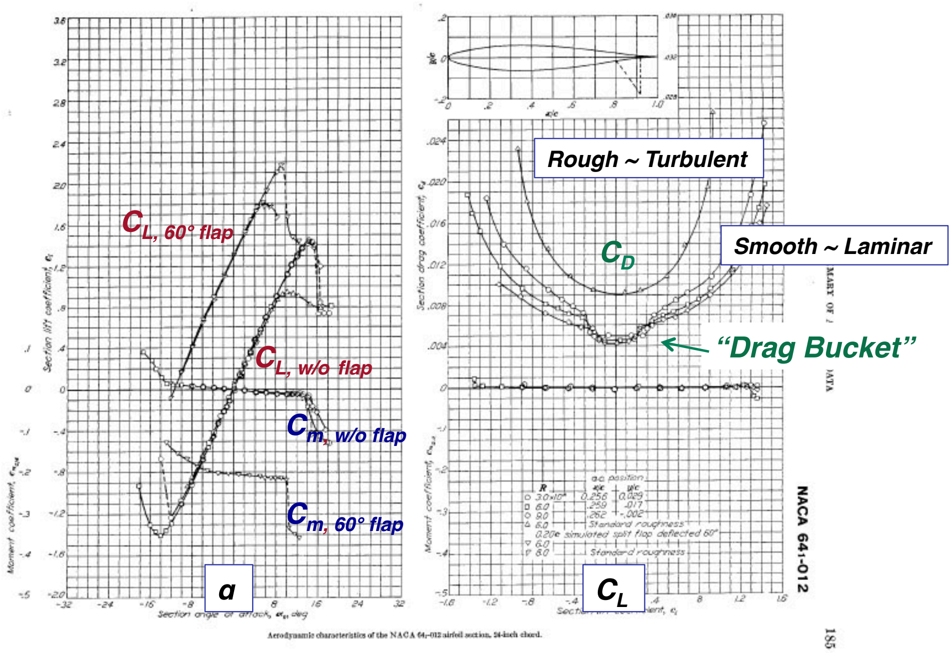
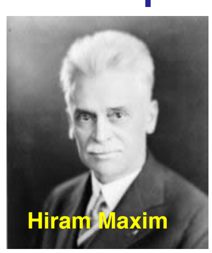
NACA 64_1-012 Chord Section Lift, Drag, and Moment (NACA TR-824)

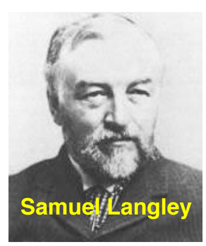


Historical Factoid

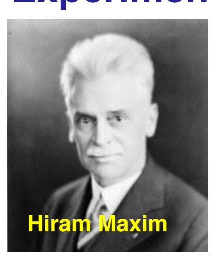
Measuring Lift and Drag with Whirling Arms and Early Wind Tunnels

Whirling Arm Experimentalists



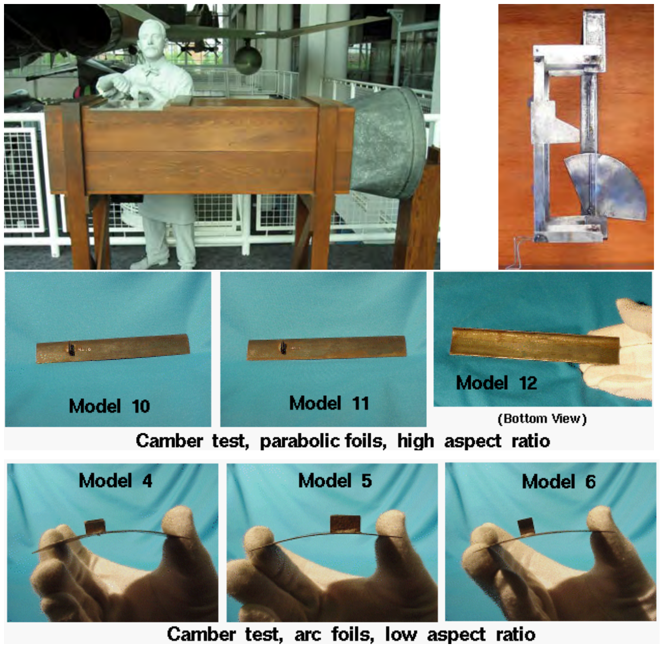


Wind Tunnel Experimentalists

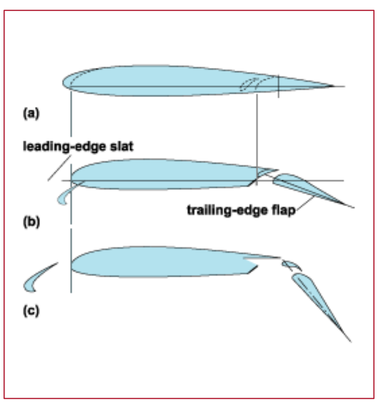


Historical Factoid

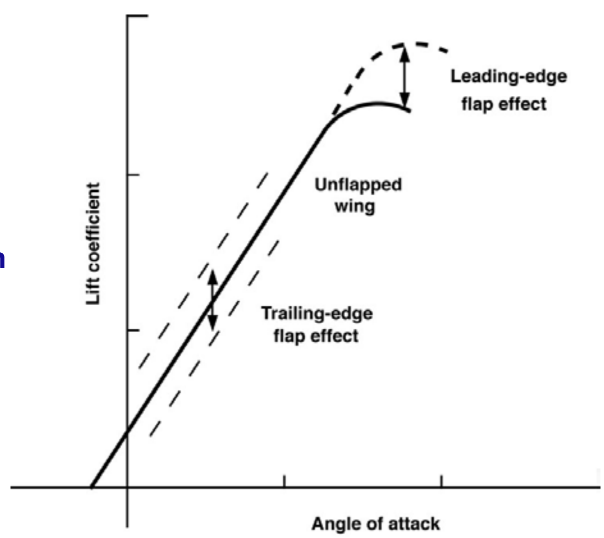
Wright Brothers Wind Tunnel



Flap Effects on Aerodynamic Lift



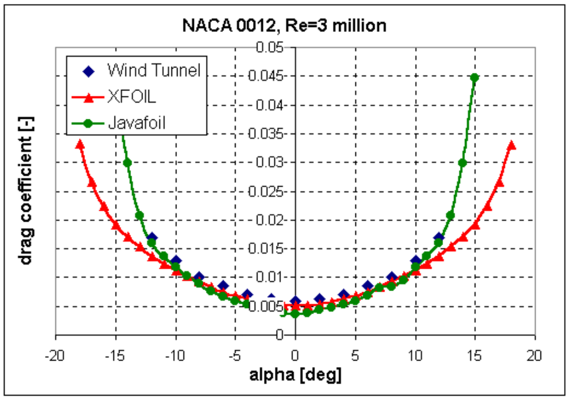
- Camber modification
- Trailing-edge flap deflection shifts C_L up and down
- Leading-edge flap (*slat*) deflection increases stall α
- Same effect applies for other control surfaces
  - Elevator (horizontal tail)
  - Ailerons (wing)
  - Rudder (vertical tail)



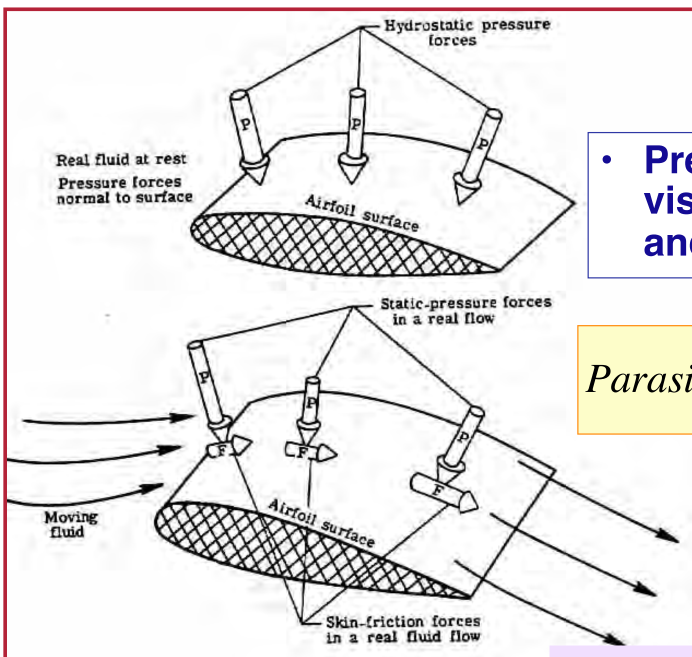
Aerodynamic Drag

$$Drag = C_D \frac{1}{2}\rho V^2 S \approx \left(C_{D_0} + \varepsilon C_L^2\right)\frac{1}{2}\rho V^2 S$$

$$\approx \left[C_{D_0} + \varepsilon\left(C_{L_o} + C_{L_\alpha}\alpha\right)^2\right]\frac{1}{2}\rho V^2 S$$



Parasitic Drag, C_{D_o}



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- Pressure differential, viscous shear stress, and separation

$$Parasitic\ Drag = C_{D_0}\frac{1}{2}\rho V^2 S$$

Reynolds Number and Boundary Layer

$$\text{eynolds Number} = \mathrm{Re} = \frac{\rho V l}{\mu} = \frac{V l}{\nu}$$

here

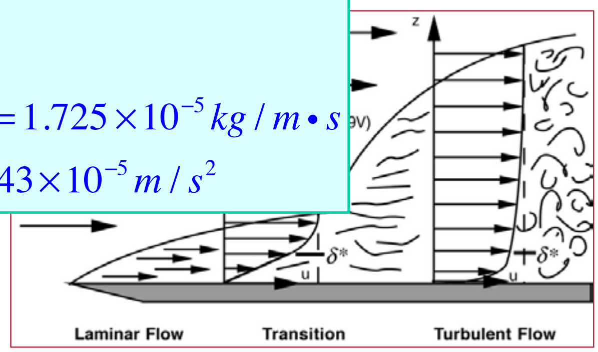
$= \textit{air density}$

$= \textit{true airspeed}$

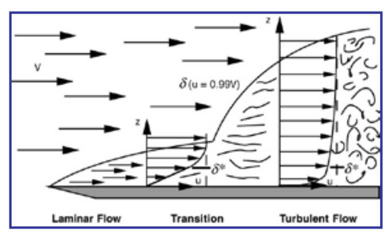
$= \textit{characteristic length}$

$= \textit{absolute (dynamic) viscosity} = 1.725 \times 10^{-5}\, kg / m \bullet s$

$= \textit{kinematic viscosity (SL)} = 1.343 \times 10^{-5}\, m / s^2$



Reynolds Number, Skin Friction, and Boundary Layer



- **Skin friction coefficient for a flat plate**

$$C_f = \frac{\textit{Friction Drag}}{\bar{q} S_{wet}}$$

$$\textit{where} \quad S_{wet} = \textit{wetted area}$$

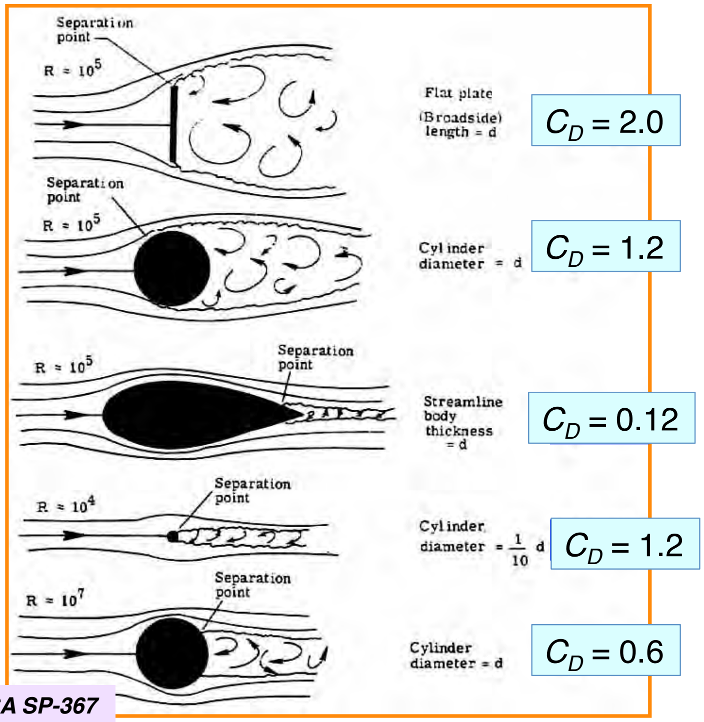
Wetted Area: Total surface area of the wing or aircraft, subject to skin friction

- **Boundary layer thickens in transition, then thins in turbulent flow**

$$C_f \approx 1.33 \mathrm{Re}^{-1/2} \quad [\textit{laminar flow}]$$

$$\approx 0.46 \left(\log_{10} \mathrm{Re}\right)^{-2.58} \quad [\textit{turbulent flow}]$$

Effect of Streamlining on Parasitic Drag



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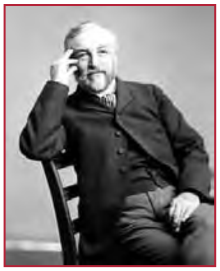
Subsonic C_{D_o} Estimate (Raymer)

Table 12.3 Equivalent skin friction coefficients

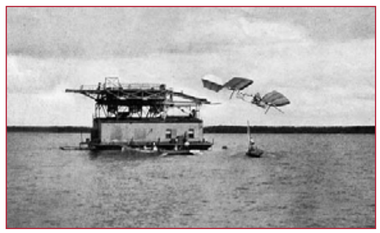
$C_{D_0} = C_{fe} \dfrac{S_{wet}}{S_{ref}}$	C_{fe}-subsonic
Bomber and civil transport	0.0030
Military cargo (high upsweep fuselage)	0.0035
Air Force fighter	0.0035
Navy fighter	0.0040
Clean supersonic cruise aircraft	0.0025
Light aircraft – single engine	0.0055
Light aircraft – twin engine	0.0045
Prop seaplane	0.0065
Jet seaplane	0.0040

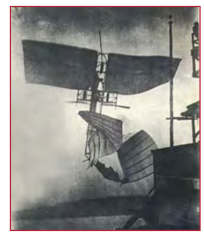


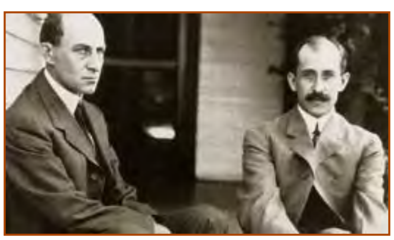
Historical Factoid

Samuel Pierpoint Langley *(1834-1906)*

- Astronomer supported by Smithsonian Institution
- Whirling-arm experiments
- 1896: Langley's steam-powered *Aerodrome* model flies 3/4 mile
- Oct 7 & Dec 8, 1903: Manned aircraft flights end in failure







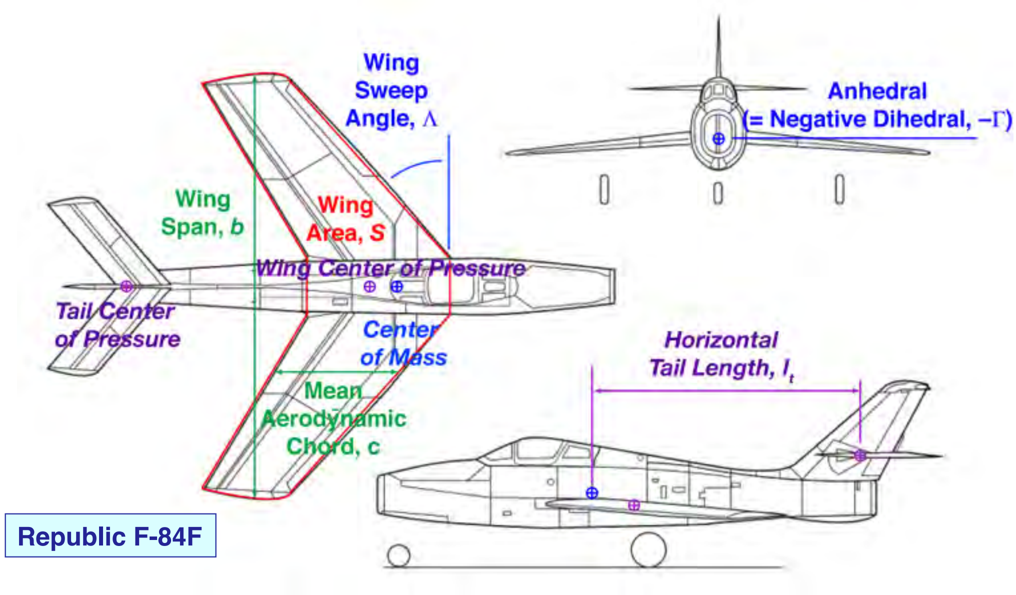
Historical Factoid

Wilbur *(1867-1912)* and Orville *(1871-1948)* Wright

- Bicycle mechanics from Dayton, OH
- Self-taught, empirical approach to flight
- Wind-tunnel, kite, and glider experiments
- Dec 17, 1903: Powered, manned aircraft flight ends in success

Description of Aircraft Configurations

A Few Definitions



Wing Planform Variables

Aspect Ratio

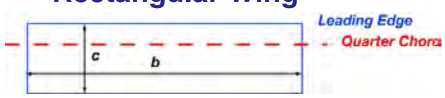
$$AR = \frac{b}{c} \quad rectangular\ wing$$

$$= \frac{b \times b}{c \times b} = \frac{b^2}{S} \quad any\ wing$$

Taper Ratio

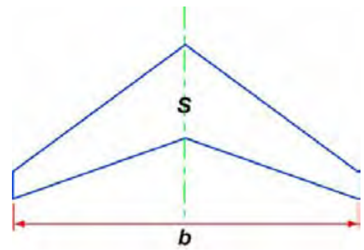
$$\lambda = \frac{c_{tip}}{c_{root}} = \frac{\text{tip chord}}{\text{root chord}}$$

Rectangular Wing



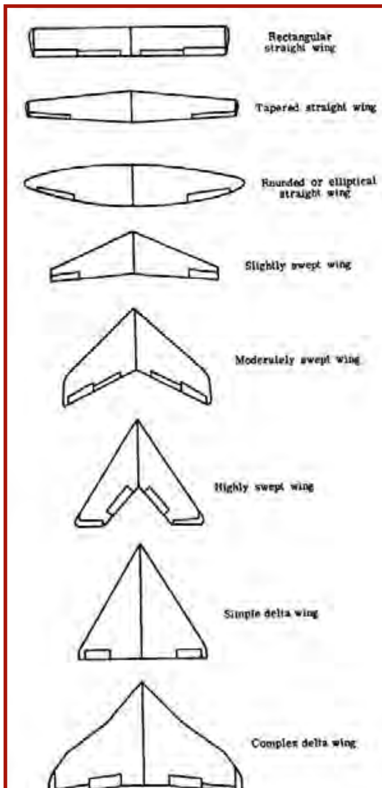
Delta Wing

Swept Trapezoidal Wing



Wing Design Parameters

- **Planform**
  - Aspect ratio
  - Sweep
  - Taper
  - Complex geometries
  - Shapes at root and tip
- **Chord section**
  - Airfoils
  - Twist
- **Movable surfaces**
  - Leading- and trailing-edge devices
  - Ailerons
  - Spoilers
- **Interfaces**
  - Fuselage
  - Powerplants
  - Dihedral angle



(b) Examples of wing planform.

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Mean Aerodynamic Chord and Wing Aerodynamic Center

- **Mean aerodynamic chord (m.a.c.) ~ mean geometric chord**

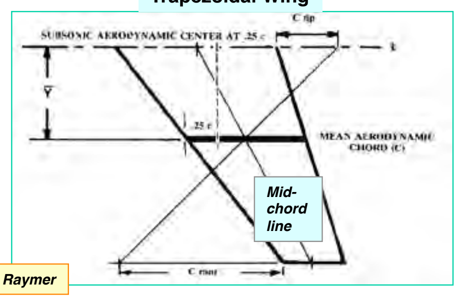
$$\bar{c} = \frac{1}{S}\int_{-b/2}^{b/2} c^2(y)\,dy$$

$$= \left(\frac{2}{3}\right)\frac{1+\lambda+\lambda^2}{1+\lambda}c_{root} \quad \text{[for trapezoidal wing]}$$

$$\lambda = \frac{c_{tip}}{c_{root}} = \frac{\text{tip chord}}{\text{root chord}}$$

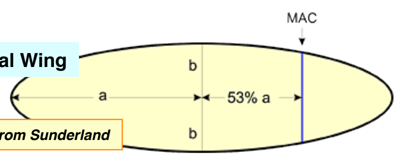
- **Axial location of the wing's subsonic aerodynamic center (a.c.)**
  - **Determine spanwise location of m.a.c.**
  - **Assume that aerodynamic center is at 25% m.a.c.**

Trapezoidal Wing



from Raymer

Elliptical Wing

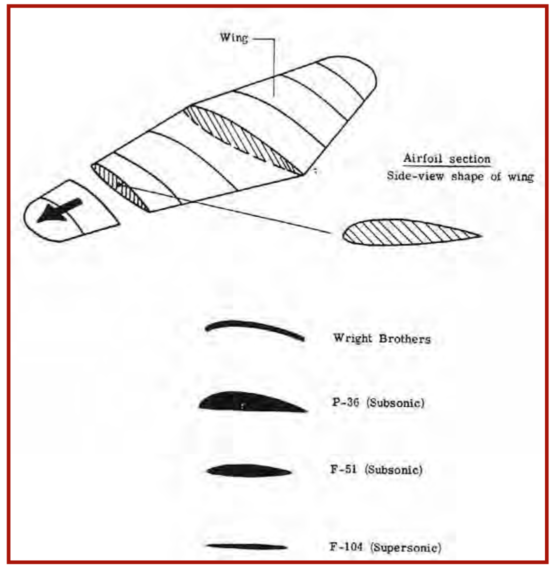


from Sunderland

3-Dimensional Aerodynamic Lift and Drag

Airfoil Effects

- Camber increases zero-α lift coefficient
- Thickness
  - increases α for stall and softens the stall break
  - reduces subsonic drag
  - increases transonic drag
  - causes abrupt pitching moment variation (more to follow)
- Profile design
  - can reduce center-of-pressure (static margin, *TBD*) variation with α
  - affects leading-edge and trailing-edge flow separation



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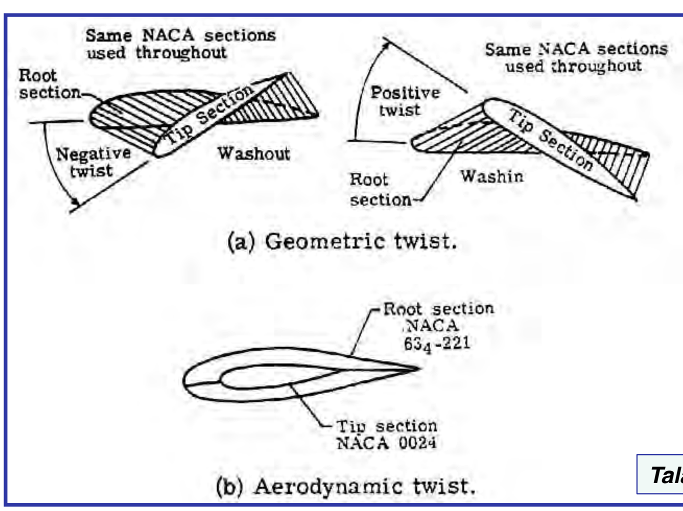
Wing Twist Effects

- Washout twist
  - reduces tip angle of attack
  - typical value: 2° - 4°
  - changes lift distribution (interplay with taper ratio)
  - reduces likelihood of tip stall
  - allows stall to begin at the wing root
    - separation "burble" produces buffet at tail surface, warning of stall
  - improves aileron effectiveness at high α



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Aerodynamic Strip Theory

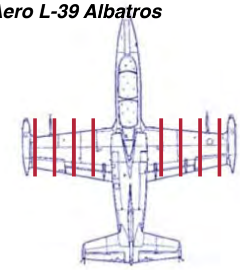
- Airfoil section may vary from tip-to-tip
  - Chord length
  - Airfoil thickness
  - Airfoil profile
  - Airfoil twist
- **3-D Wing Lift**: Integrate 2-D lift coefficients of airfoil sections across finite span
- Incremental lift along span

$$dL = C_{L_{2-D}}(y)c(y)\bar{q}dy$$
$$= \frac{dC_{L_{3-D}}(y)}{dy}c(y)\bar{q}dy$$

- 3-D wing lift

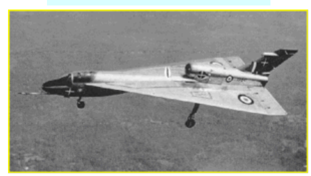
$$L_{3-D} = \int_{-b/2}^{b/2} C_{L_{2-D}}(y)c(y)\bar{q}\,dy$$

Aero L-39 Albatros



Bombardier Dash 8

Handley Page HP.115



Effect of Aspect Ratio on 3-Dimensional Wing Lift Slope Coefficient

(Incompressible Flow)

High Aspect Ratio (> 5) Wing

$$C_{L_\alpha} \triangleq \left(\frac{\partial C_L}{\partial \alpha}\right)_{3-D} = \frac{2\pi AR}{AR+2} = 2\pi\left(\frac{AR}{AR+2}\right)$$

Low Aspect Ratio (< 2) Wing

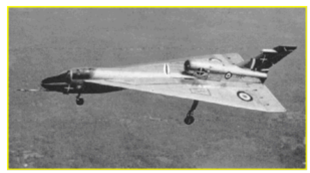
$$C_{L_\alpha} = \frac{\pi AR}{2} = 2\pi\left(\frac{AR}{4}\right)$$

Effect of Aspect Ratio on 3-D Wing Lift Slope Coefficient

(Incompressible Flow)

All Aspect Ratios (Helmbold equation)

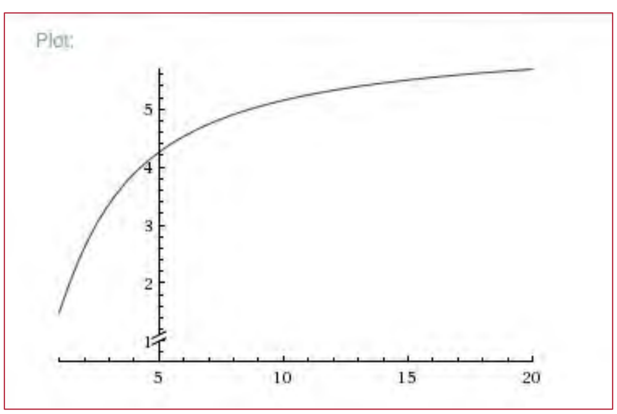
$$C_{L_\alpha} = \frac{\pi AR}{\left[1 + \sqrt{1 + \left(\frac{AR}{2}\right)^2}\right]}$$



Effect of Aspect Ratio on 3-D Wing Lift Slope Coefficient

- **All Aspect Ratios (Helmbold equation)**
  - **Wolfram Alpha**

plot(pi A / (1+sqrt(1 + (A / 2)^2)), A=1 to 20)



Historical Factoids

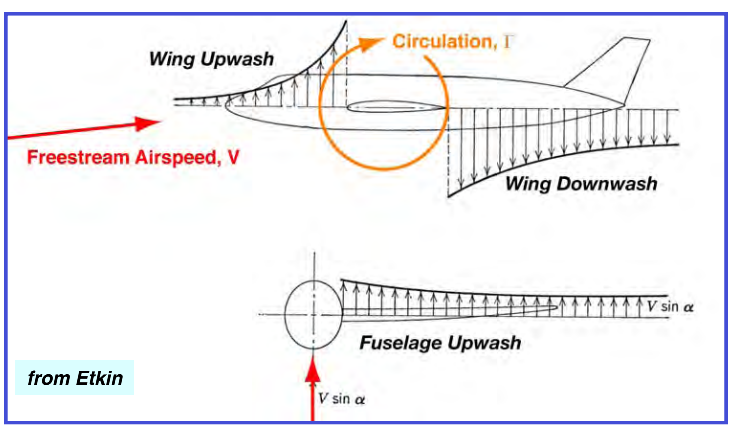
- 1906: 2nd successful aviator: Alberto Santos-Dumont, standing!
  - High dihedral, forward control surface
- Wrights secretive about results until 1908; few further technical contributions

- 1908: Glenn Curtiss *et al* incorporate ailerons
  - Wright brothers sue for infringement of 1906 US patent (and win)

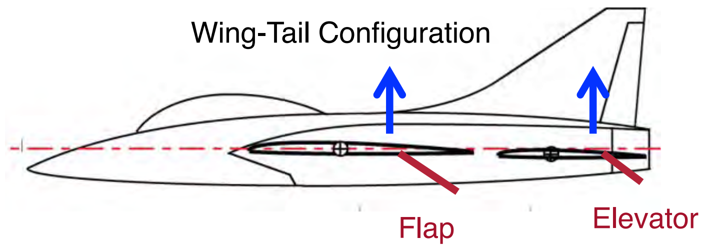
- 1909: Louis Bleriot's flight across the English Channel

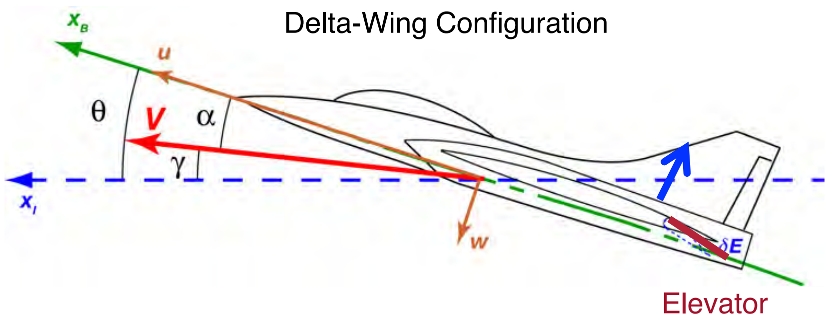
Wing-Fuselage Interference Effects

- Wing lift induces
  - Upwash in front of the wing
  - Downwash behind the wing, having major effect on the tail
  - Local angles of attack over canard and tail surface are modified, affecting net lift and pitching moment
- Flow around fuselage induces upwash on the wing, canard, and tail



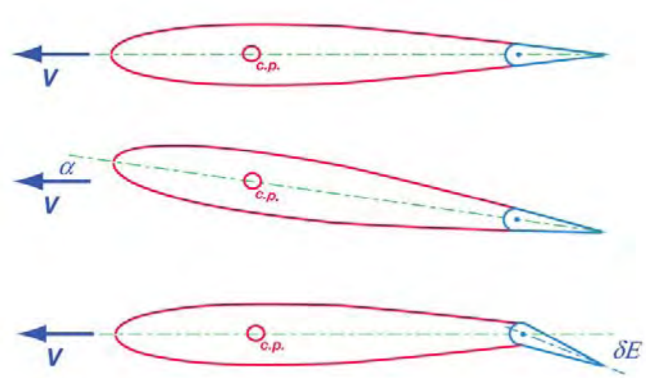
Longitudinal Control Surfaces



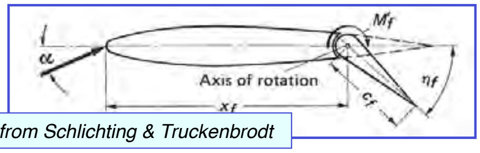


Angle of Attack and Control Surface Deflection

- **Horizontal tail with elevator control surface**
- **Horizontal tail at positive angle of attack**
- **Horizontal tail with positive elevator deflection**

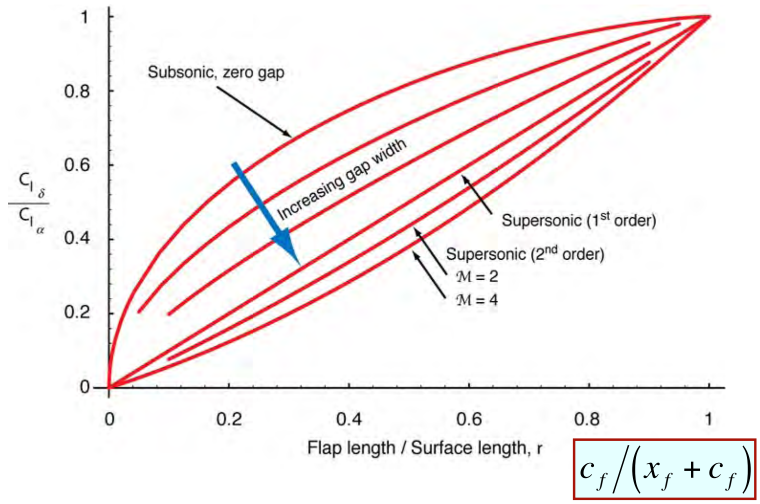


Control Flap Carryover Effect on Lift Produced By Total Surface



from Schlichting & Truckenbrodt

$$\frac{C_{L_{\delta E}}}{C_{L_\alpha}} \; vs. \; \frac{c_f}{x_f + c_f}$$



Lift due to Elevator Deflection

- **Lift coefficient variation due to elevator deflection**

$$C_{L_{\delta E}} \triangleq \frac{\partial C_L}{\partial \delta E} = \tau_{ht} \eta_{ht} \left(C_{L_\alpha}\right)_{ht} \frac{S_{ht}}{S}$$

$$\Delta C_L = C_{L_{\delta E}} \delta E$$

τ_{ht} = Carryover effect

η_{ht} = Tail efficiency factor

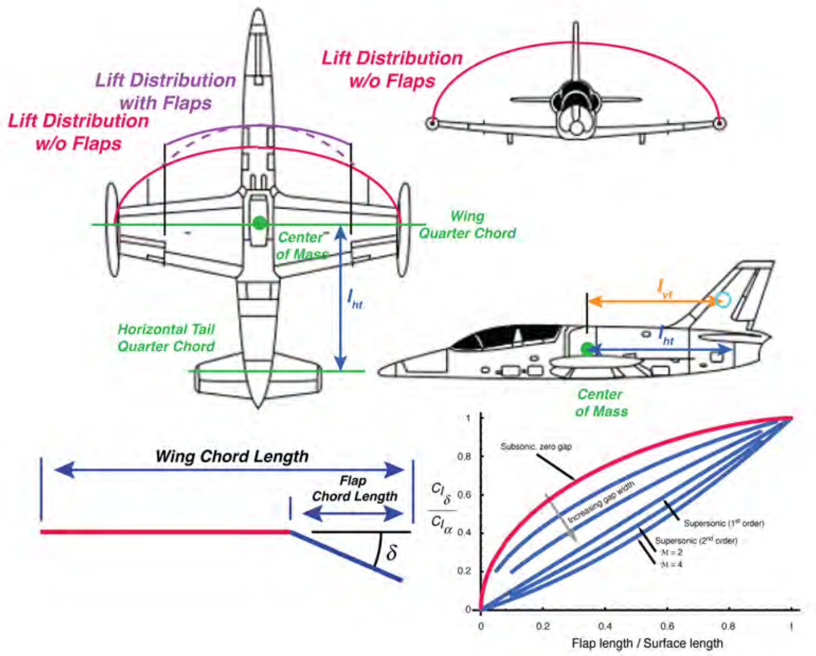
$\left(C_{L_\alpha}\right)_{ht}$ = Horizontal tail lift-coefficient slope

S_{ht} = Horizontal tail reference area

- **Lift variation due to elevator deflection**

$$\Delta L = C_{L_{\delta E}} \bar{q} S \delta E$$

Example of Configuration and Flap Effects



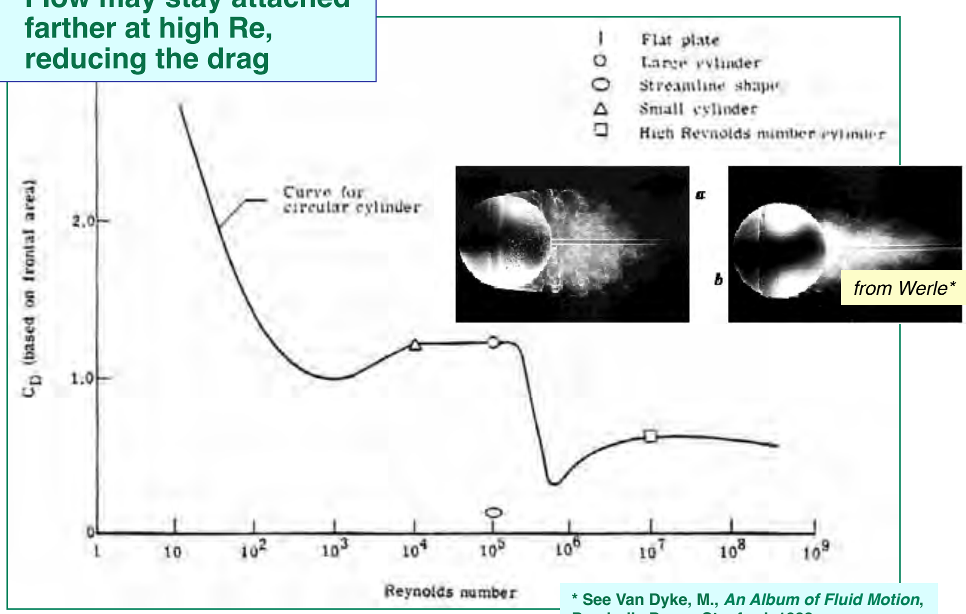
Next Time:
Induced Drag and High-Speed Aerodynamics

Reading:
Flight Dynamics
Aerodynamic Coefficients, 85-96
Airplane Stability and Control
Chapter 1

Supplementary Material

Typical Effect of Reynolds Number on Parasitic Drag

- **Flow may stay attached farther at high Re, reducing the drag**

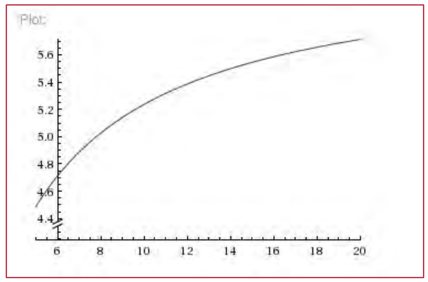


*** See Van Dyke, M., *An Album of Fluid Motion*, Parabolic Press, Stanford, 1982**

Effect of Aspect Ratio on 3-Dimensional Wing Lift Slope Coefficient

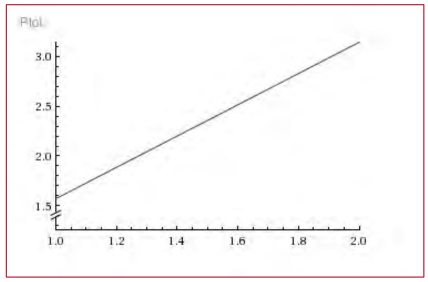
- **High Aspect Ratio (> 5) Wing**
  - **Wolfram Alpha**

plot(2 pi (a/(a+2)), a=5 to 20)



- **Low Aspect Ratio (< 2) Wing**
  - **Wolfram Alpha**

plot(2 pi (a / 4), a=1 to 2)



Aerodynamic Stall, Theory and Experiment

- **Flow separation produces stall**
- **Straight rectangular wing, AR = 5.536, NACA 0015**
- **Hysteresis for increasing/decreasing *α***

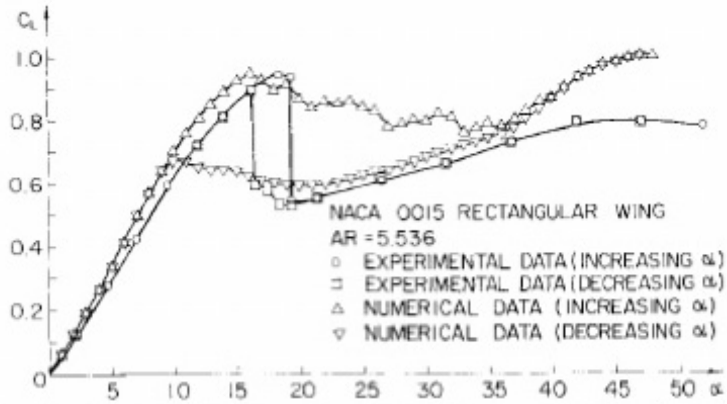


Fig. 3 Lift coefficient vs angle of attack for a rectangular wing with an NACA 0015 airfoil; comparison between experiment[7] and the present numerical technique.

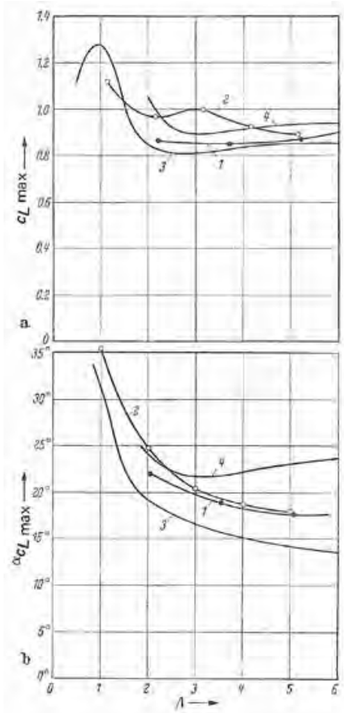
Anderson et al, 1980

Maximum Lift of Rectangular Wings

Schlicting & Truckenbrodt, 1979

Maximum Lift Coefficient, $C_{L\,max}$

Angle of Attack for $C_{L\,max}$



Aspect Ratio

Figure 3-53 Maximum lift coefficients of rectangular wings ($\varphi = 0$) and swept-back wings of constant chord ($\varphi \neq 0$), Reynolds number $Re \approx 10^6$. (*a*) Maximum lift coefficient $c_{L\,max}$ vs. aspect ratio Λ. (*b*) angle of attack α for $c_{L\,max}$ vs. aspect ratio Λ. Curve 1, $\varphi = 0°$; profile NACA 0015, from Bussmann and Kopfermann [25]. Curve 2, $\varphi = 45°$; profile NACA 0012, from Truckenbrodt [85]. Curve 3, $\varphi = 0°$; $\delta \approx 0.10$, mean values of various measurements. Curve 4, $\varphi = 35°$; $\delta \approx 0.10$, mean values of various measurements.

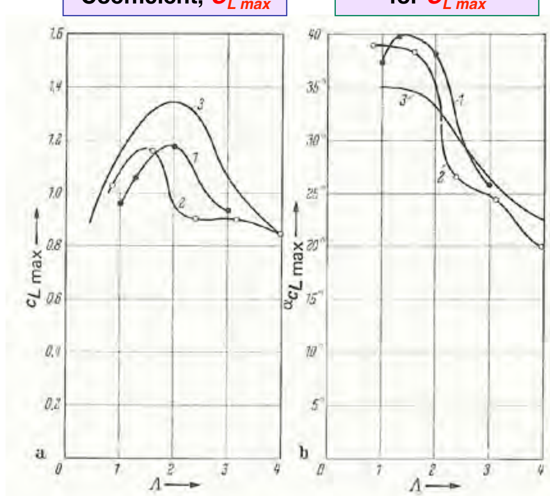
φ : Sweep angle

δ: Thickness ratio

Maximum Lift of Delta Wings with Straight Trailing Edges

Maximum Lift Coefficient, $C_{L\,max}$

Angle of Attack for $C_{L\,max}$



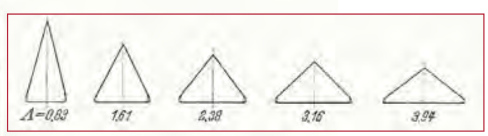


Figure 3-55 Maximum lift coefficients of delta wings, Reynolds number $Re \approx 10^6$. (*a*) Maximum lift coefficient $c_{L\,max}$ vs. aspect ratio Λ. (*b*) Angle of attack α for $c_{L,max}$ vs. aspect ratio Λ. Curve 1, delta wing; $\lambda = 0$; profile NACA 0012, from Lange and Wacke [25]. Curve 2, delta wing; $\lambda = \frac{1}{8}$; profile NACA 0012, from Truckenbrodt [85]. Curve 3, mean values of various measurements.

Aspect Ratio

Aspect Ratio

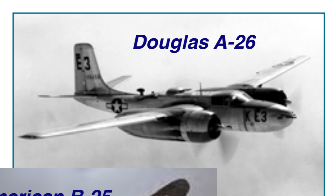
λ: Taper ratio

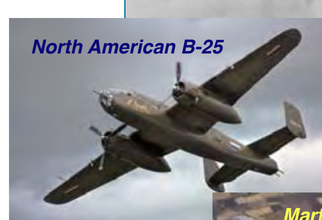
Schlicting & Truckenbrodt, 1979

Aft Flap vs. All-Moving Control Surface

- Carryover effect of aft flap
  – Aft-flap deflection can be almost as effective as full surface deflection at subsonic speeds
  – Negligible at supersonic speed
- Aft flap
  – Mass and inertia lower, reducing likelihood of mechanical instability
  – Aerodynamic hinge moment is lower
  – Can be mounted on structurally rigid main surface

Multi-Engine Aircraft of World War II



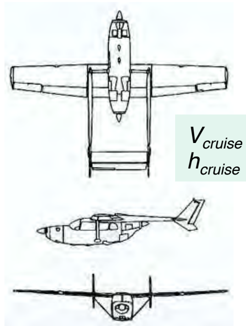


- Large W.W.II aircraft had unpowered controls:
  – High foot-pedal force
  – Rudder stability problems arising from balancing to reduce pedal force
- Severe engine-out problem for twin-engine aircraft

$\boxed{C_{n_o}, C_{l_o}}$

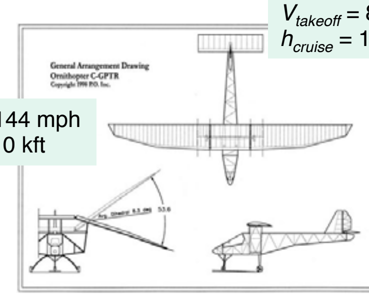
Medium to High Aspect Ratio Configurations

Cessna 337



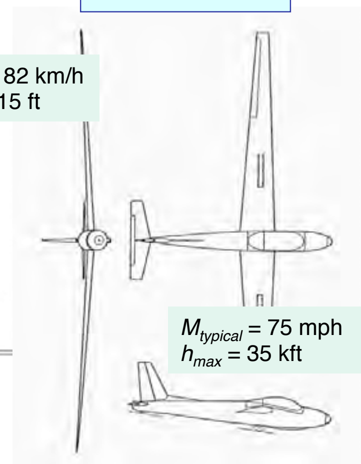
V_{cruise} = 144 mph
h_{cruise} = 10 kft

DeLaurier Ornithopter



$V_{takeoff}$ = 82 km/h
h_{cruise} = 15 ft

Schweizer 2-32



$M_{typical}$ = 75 mph
h_{max} = 35 kft

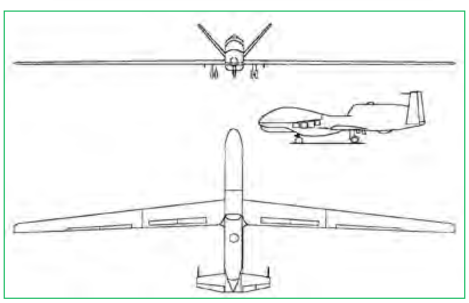
Boeing 777-300

M_{cruise} = 0.84
h_{cruise} = 35 kft

- Typical for subsonic aircraft

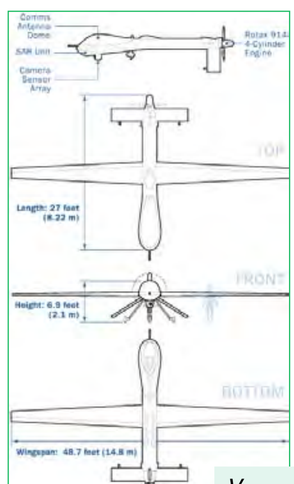
Uninhabited Air Vehicles

Northrop-Grumman/Ryan Global Hawk

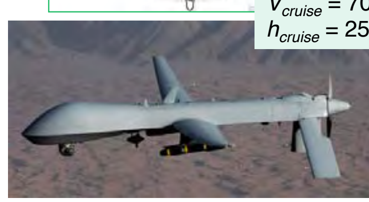


V_{cruise} = 310 kt
h_{cruise} = 50 kft

General Atomics Predator



V_{cruise} = 70-90 kt
h_{cruise} = 25 kft

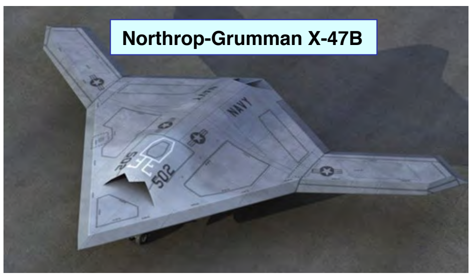


Stealth and Small UAVs

Lockheed-Martin RQ-170

General Atomics Predator-C (Avenger)

Northrop-Grumman X-47B

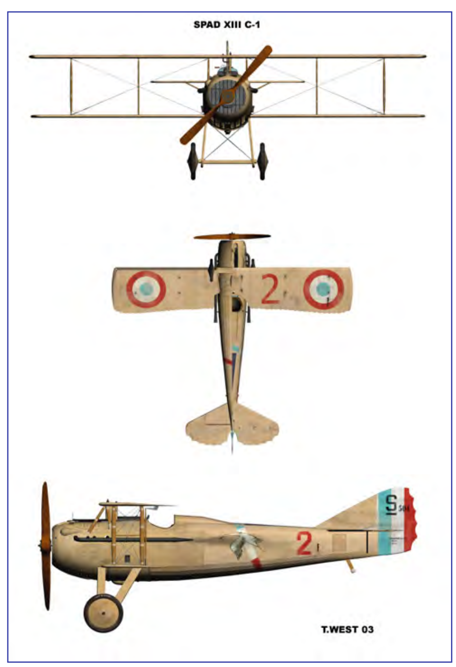


InSitu/Boeing ScanEagle

http://en.wikipedia.org/wiki/Stealth_aircraft

Subsonic Biplane

- Compared to monoplane
  - Structurally stiff (guy wires)
  - Twice the wing area for the same span
  - Lower aspect ratio than a single wing with same area and chord
  - Mutual interference
  - Lower maximum lift
  - Higher drag (interference, wires)
- Interference effects of two wings
  - Gap
  - Aspect ratio
  - Relative areas and spans
  - Stagger



Some Videos

Flow over a narrow airfoil, with downstream vortices

http://www.youtube.com/watch?v=zsO5BQA_CZk

Flow over transverse flat plate, with downstream vortices

http://www.youtube.com/watch?v=0z_hFZx7qvE

Laminar vs. turbulent flow

http://www.youtube.com/watch?v=WG-YCpAGgQQ&feature=related

Smoke flow visualization, wing with flap

http://www.youtube.com/watch?feature=fvwp&NR=1&v=eBBZF_3DLCU/

1930s test in NACA wind tunnel

http://www.youtube.com/watch?v=3_WgkVQWtno&feature=related