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Aircraft Systems Engineering

Aerodynamics Primer

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Topics

- Geometry jargon
- Standard atmosphere
- Airflow variables
- Forces acting on aircraft
- Aerodynamic coefficients
- Lift curve
- Drag polar

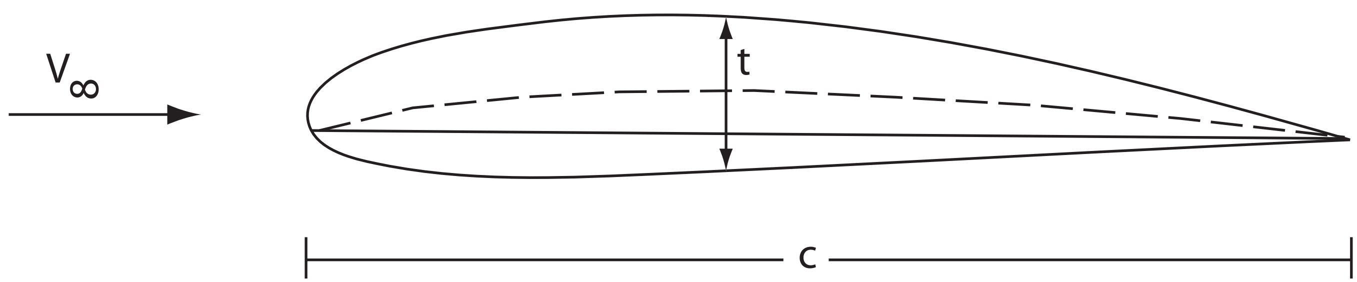
- Reference: Anderson, John D. Jr. Introduction to Flight, McGraw Hill, 3rd ed. 1989. All figures in this primer are taken from this source unless otherwise noted.
- Note: other sources need to be added.

Wing and Airfoil Nomenclature

t = thickness

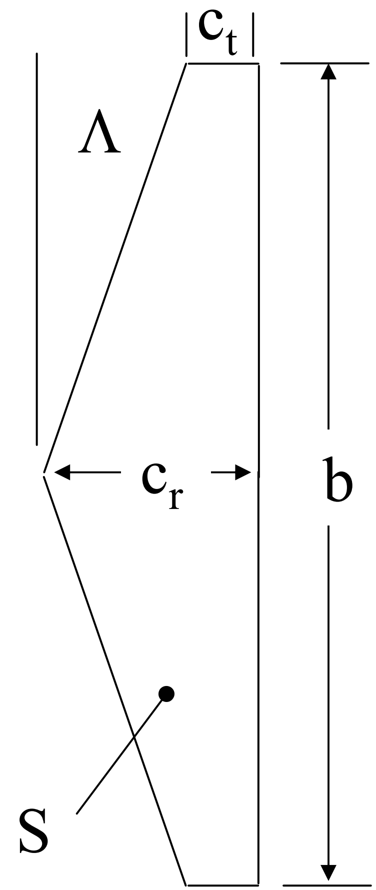
c = chord

t/c is an airfoil parameter



More Wing Nomenclature

- b = wing span
- S = wing area
- AR = aspect ratio=b^2/S
  - For $c_{avg} = S/b$, AR= b/c_{avg}
- $\lambda = c_t/c_r$ = taper ratio
- Λ = leading edge sweep angle
- Twist is the difference in the angle of the tip and root airfoil section chord lines .



Standard Atmosphere: The Environment for Aircraft Design

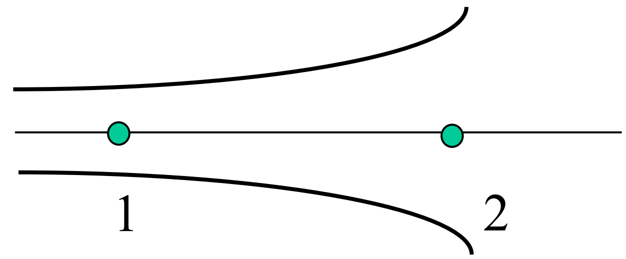
- The "standard atmosphere" is a reference condition.
  - Every day is different.
- Temperature T, pressure p, density ρ are functions of altitude h.
- Standard sea level conditions
  - $p = 1.01325 \times 10^5$ N/m^2 = 2116.2 lb/ft^2
  - $T = 288.16\ ^0K = 518.7\ ^0R$
  - $\rho = 1.2250$ kg/m^3 = 0.00278 slug/ft^3
- Handy calculator

  http://aero.stanford.edu/StdAtm.html

Flow Velocities

- V_∞ called the freestream velocity
  - Units ft/sec, mph (1 mph = 1.47 fps), knot (1 kt = 1.69 fps=1.151 mph)
- a = speed of sound
  - Function of temperature: $a_1/a_2 = \mathrm{sqrt}(T_1/T_2)$
  - Function of altitude (standard sea level a = 1116.4 ft/sec)
- Mach number is ratio of velocity to speed of sound, M=V/a
  - $M_\infty = V_\infty / a_\infty$
  - $M_\infty < 1$ is subsonic flight, $M_\infty > 1$ is supersonic flight
  - M_∞ close to 1 (approx 0.8 to 1.2) is transonic flight

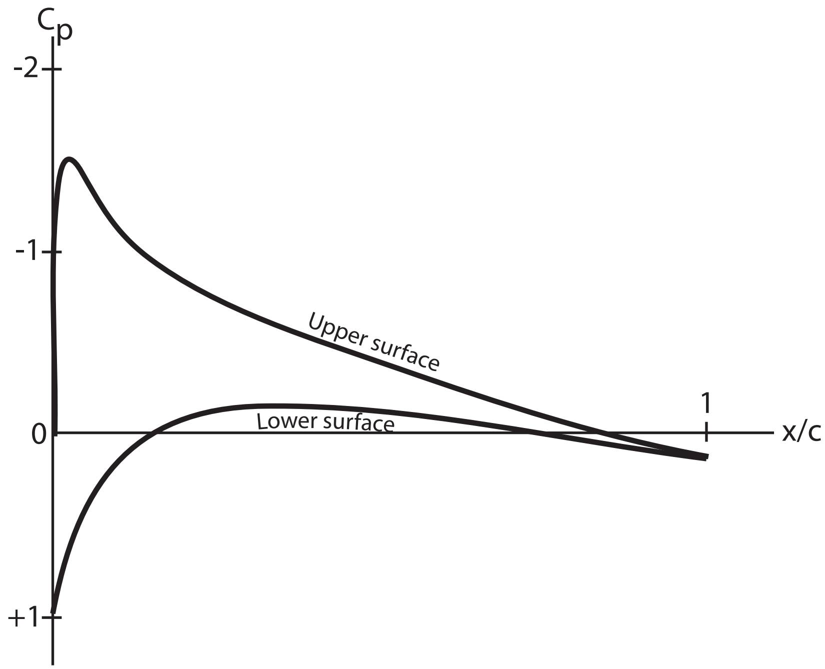
Pressures



- For $M < 0.3$, pressure and velocity are related by Bernoulli equation
  - For $M > 0.3$, pressure and velocity (or Mach number) are related, but equation is more involved
  - Further restricted to no losses due to friction.
- $p_1 + 0.5\rho V_1^2 = p_2 + 0.5\rho V_2^2 = p_0$
  - p called static pressure
  - $0.5\rho V^2$ called dynamic pressure = q
  - p_0 called stagnation pressure
  - p + q somewhat like potential plus kinetic energy

Pressure Coefficient

Lift proportional to area under curve



Pressure coefficient for a conventional airfoil: NACA 0012 airfoil at $\alpha = 3^0$.

- Due to geometry of airfoil, the velocity, and therefore the pressure, vary.
  - Manifestation of lift
- It is convenient to express this as a pressure coefficient

  $C_p = (p - p_\infty)/ q_\infty$
- From Bernoulli Eq and assuming density is constant (ok for $M < 0.3$),

  $C_p = 1 - (V/ V_\infty)^2$
- Pick out some features on figure at left

Forces

Wing imparts downward force on fluid, fluid imparts upward force on wing generating lift.

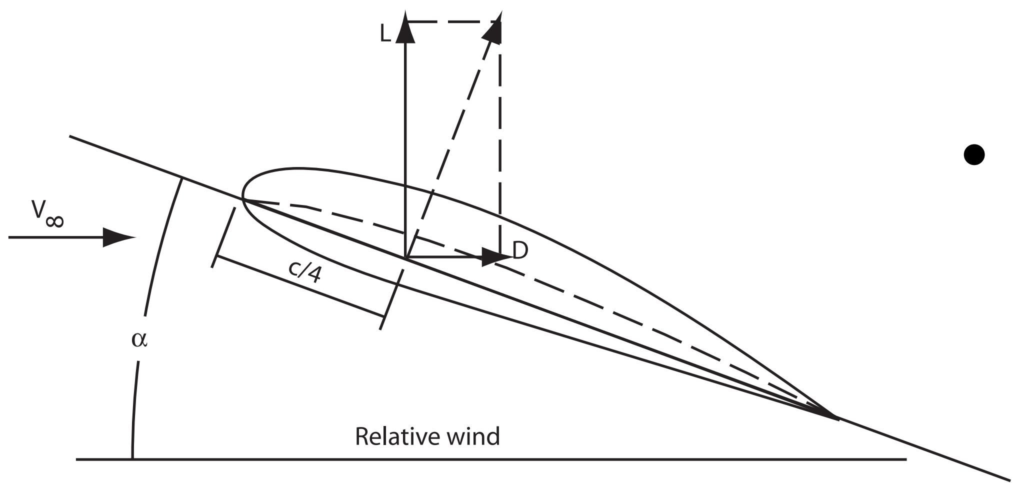
Lift = Weight for steady level flight.

Drag is balanced by thrust for non-accelerating flight.

Aerodynamic leverage - lift is 10-30 times bigger than drag!

For 1 pound of thrust get 10-30 pounds of lift.

L, D Definitions



- Resultant force on body resolved into Lift L and Drag D
- By definition,
  - L is perpendicular to relative wind
  - D is parallel to relative wind

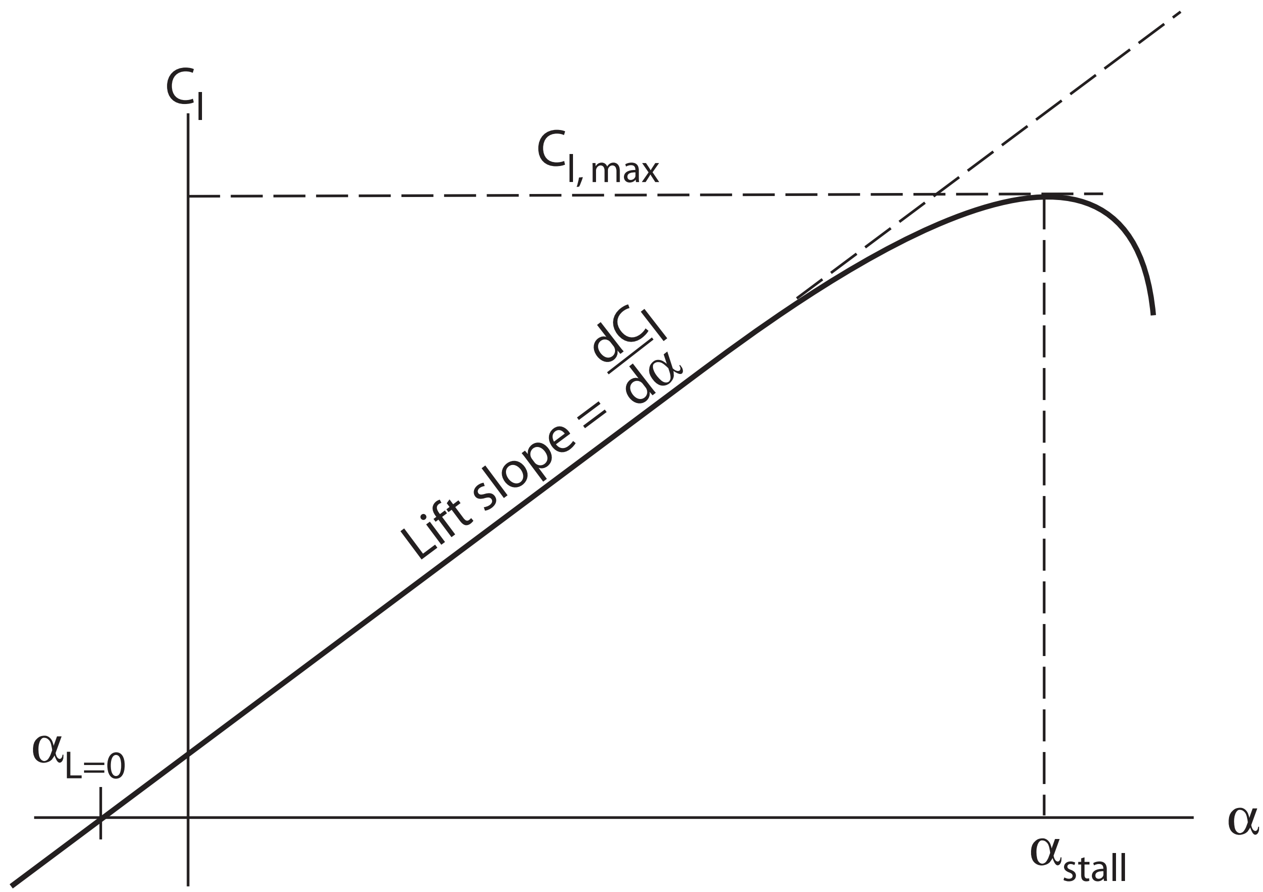
Force Coefficients

- It is convenient to use non-dimensional forms of the forces, called coefficients

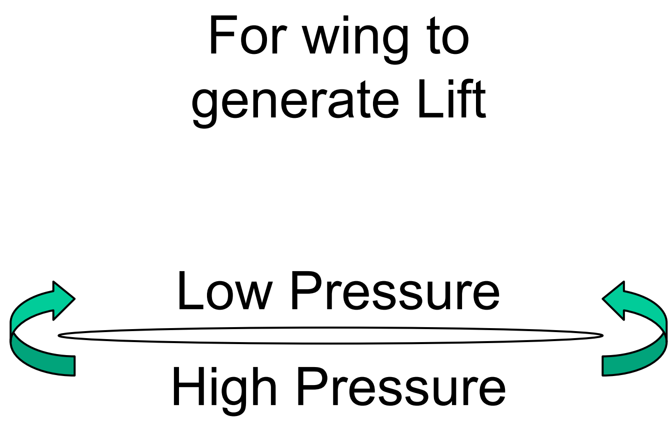
$$C_L = \frac{L}{qS},\ C_D = \frac{D}{qS} \text{ where } q = \frac{1}{2}\rho_\infty V_\infty^2$$

- Allows scaling between different size aircraft (wind tunnel models vs full scale), different velocities, altitudes, etc.
- Can use different ways, e.g.
  - If C_L, S, q are known, then L = C_LSq
  - If L=W and C_L, S are known, then flight speed which gives level flight is $V_\infty = \sqrt{\frac{2W}{\rho_\infty C_L S}}$

Lift Curve


C_l
$C_{l,max}$
Lift slope = $\frac{dC_l}{d\alpha}$
$\alpha_{L=0}$
α
α_{stall}

Lift Generates A Vortex



Kinetic energy in freestream redistributed to cross flow. It represents an unrecoverable loss called drag due to lift, or induced drag.

Drag Due to Friction

- Friction due to fluid viscosity acting on total surface of aircraft causes a skin friction drag.

Drag

- Independent of Lift $C_{D_0} = f(\mathrm{Re}, M_\infty, shape)$
  - Skin friction
  - Pressure changes due to boundary layer
  - Flow separation due to shock (lecture 5)
  - Shock wave drag (lecture 5)
- Plus lift dependent
  - Induced (vortex drag) $C_{D_i} = \dfrac{C_L^2}{\pi AR\, e}$, e < 1
  - Viscous and wave drag to do lift $C_D = kC_L^2 = f(\alpha, M_\infty, \mathrm{Re})$
- Total Drag

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