Aircraft Systems Engineering

Aerodynamics Primer

Prof. Earll Murman
Topcs

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

• 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
- \( \text{AR} = \text{aspect ratio} = \frac{b^2}{S} \)
  - For \( c_{\text{avg}} = \frac{S}{b} \), \( \text{AR} = \frac{b}{c_{\text{avg}}} \)
- \( \lambda = \frac{c_t}{c_r} = \text{taper ratio} \)
- \( \Lambda = \text{leading edge sweep angle} \)
- 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 x 10^5 N/m^2 = 2116.2 lb/ft^2
  – T = 288.16 °K = 518.7 °R
  – ρ = 1.2250 kg/m^3 = 0.00278 slug/ft^3

• Handy calculator
  http://aero.stanford.edu/StdAtm.html
Flow Velocities

- $V_\infty$ 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: $a_1/a_2 = \sqrt{T_1/T_2}$
  - 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
  - $M_\infty$ 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

- 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
  \[ C_p = \frac{p - p_\infty}{q_\infty} \]
- From Bernoulli Eq and assuming density is constant (ok for \( M < 0.3 \)),
  \[ C_p = 1 - \left( \frac{V}{V_\infty} \right)^2 \]
- Pick out some features on figure at left

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

\[ C_L = \frac{L}{qS}, \quad C_D = \frac{D}{qS} \text{ where } q = \frac{1}{2} \rho \infty V^2 \]

- 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 \( L = C_L S q \)
  - 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

Lift slope = \( \frac{dC_l}{d\alpha} \)

\( C_l,_{\text{max}} \)

\( \alpha_{L=0} \)

\( \alpha_{\text{stall}} \)
Lift Generates A Vortex

For wing to generate Lift

Low Pressure

High Pressure

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 \( C_{D_0} = f(Re,M_\infty,\text{shape}) \)
  - 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) \( C_{D_i} = \frac{C^2}{\pi AR e} \), \( e < 1 \)
  - Viscous and wave drag to do lift \( C_D = kC_L^2 = f(\alpha,M_\infty,Re) \)

• Total Drag
  \[ C_D = C_{D_0} + \frac{C^2}{\pi AR e} + kC_L^2 \]