Aerodynamics and Flight Performance Lesson

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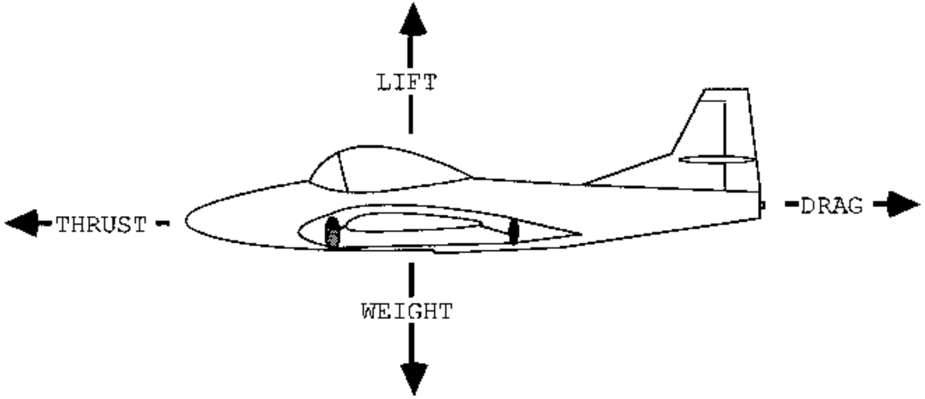
Agenda

- Basic Aerodynamic Concepts
- Calculations
- Airspeed Types
- Wing Geometry
- Boundary Layer and Types of Flow
- Drag Polar
- Flight Envelopes
- Vortices and Ground Effect
- CFD Applications

Four Forces of Flight

- Lift - upward force that is created by the wing
- Weight - downward force due to gravity, acts through the CG
- Thrust - propellant forward force, produced by the powerplant
- Drag - rearward force, caused by disruption of airflow by various factors



In equilibrium (steady, straight and level flight)... $\sum F = 0$

How to Calculate the Forces in Flight

$$L = \frac{1}{2}\rho v^2 S C_L$$

$$D = \frac{1}{2}\rho v^2 S C_D$$

L or D = Lift or Drag force

ρ = density of air at altitude

V = velocity of aircraft (m/s)

S = wing area (m)

C_L, C_D = coefficient of lift, drag

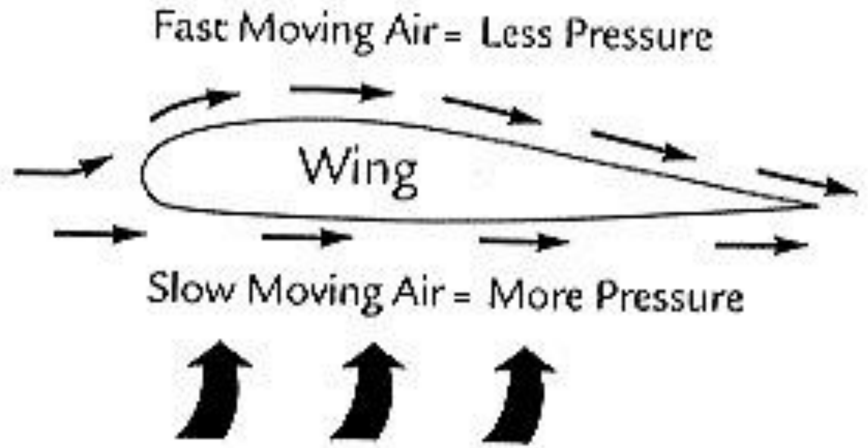
How to Calculate the Forces in Flight (Continued)

Thrust - Drag = Mass * Acceleration

Weight = Mass * Gravity

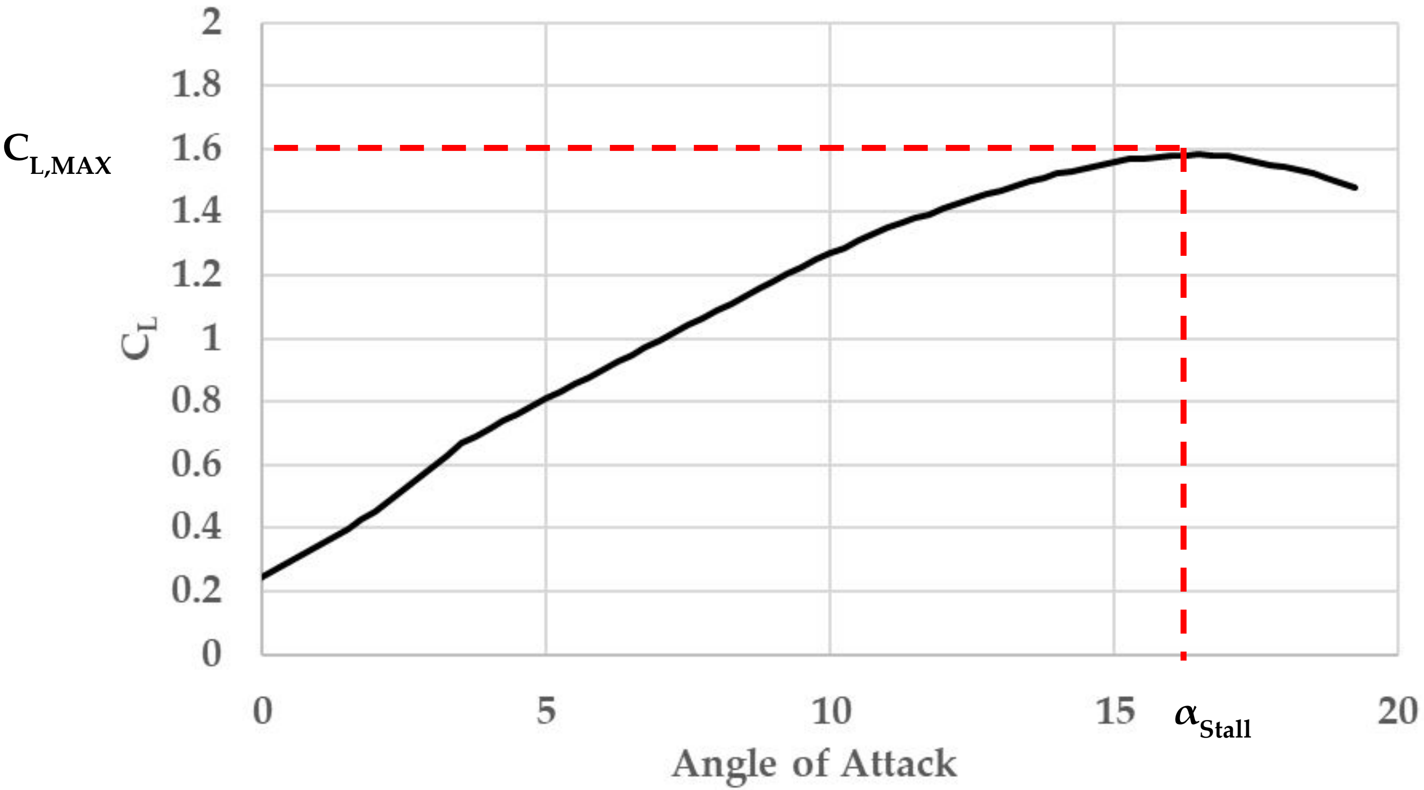
- Newton’s Second Law defines thrust, since thrust is a force (F = MA)
- High T/W -> high acceleration -> excess thrust

Bernoulli's Principle



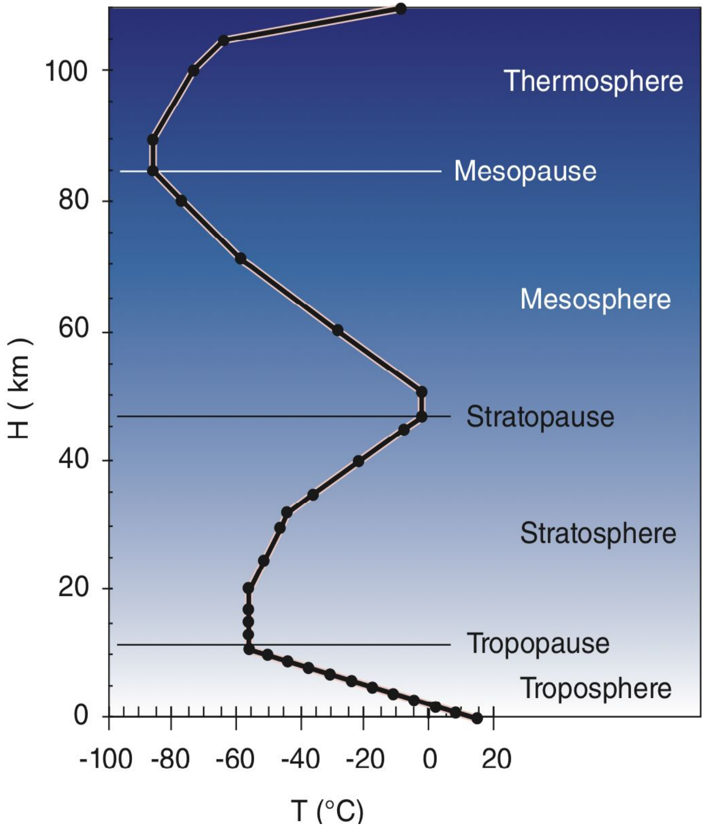
$$P + \frac{1}{2}\rho v^2 = \text{constant}$$

Lift vs AOA


2
1.8
$C_{L,MAX}$
1.6
1.4
1.2
C_L
1
0.8
0.6
0.4
0.2
0
0
5
10
15
α_{Stall}
20
Angle of Attack

Standard Atmosphere

- International Standard Atmosphere (ISA)
  - Empirical model created in 1950s
  - Provides Pressure, Temperature, and Density estimations in atmosphere
- All models are wrong, but some are useful
- Used for flight planning and performance estimations
- Deviations from this model are indicated with +- ISA



Pitot-Static System - Airspeed

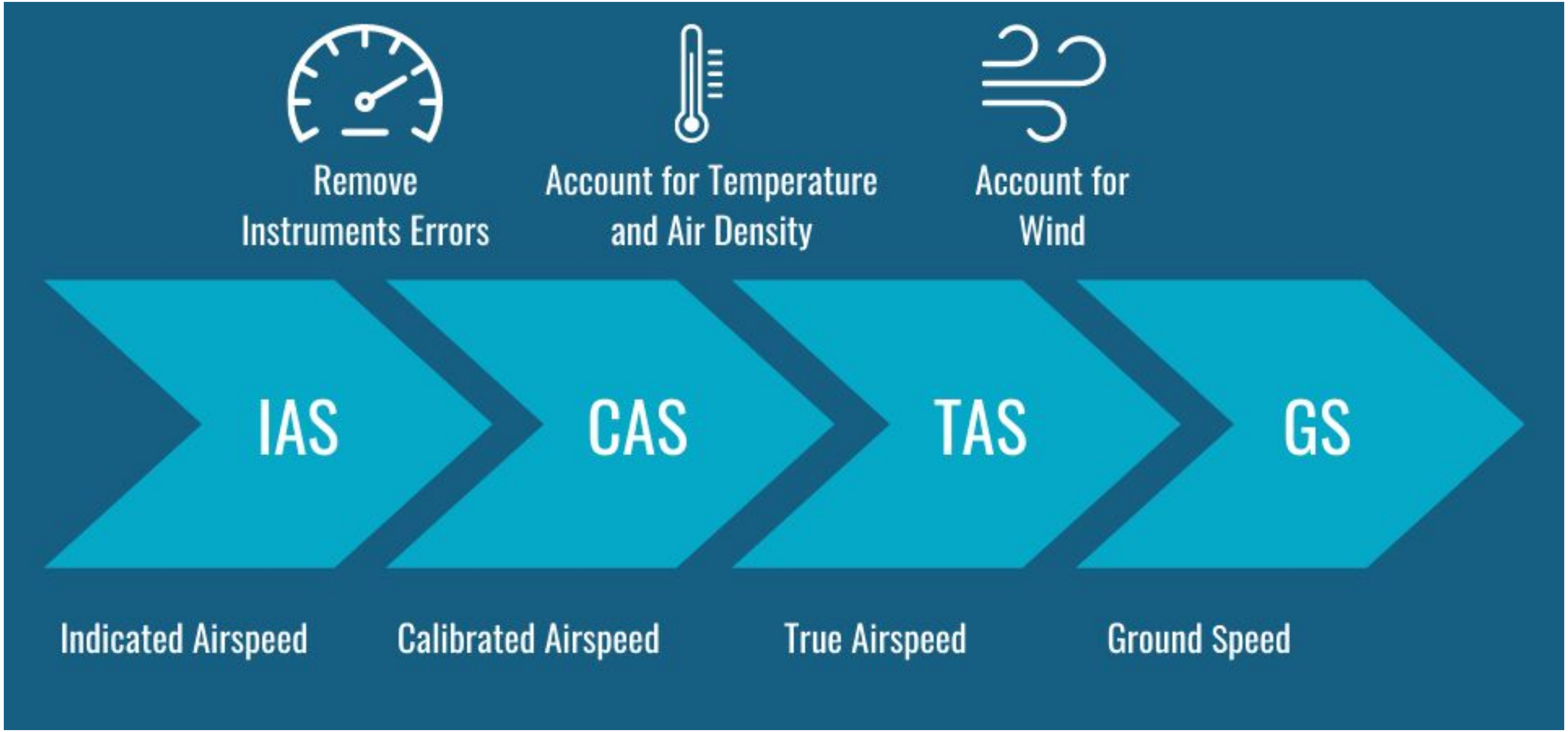
- Pitot tube measures Total Pressure (P_T)
- Static port measures Static Pressure (P_S)
- The difference gives Dynamic Pressure (q)

$$(\mathbf{P_T} - \mathbf{P_S}) = q = \frac{1}{2}\rho V^2$$

- If we know density, velocity can be calculated
- There is no direct way to measure density in flight, but the ideal gas law can be used to find it

$$\rho = \frac{P_S}{RT}$$

Airspeed

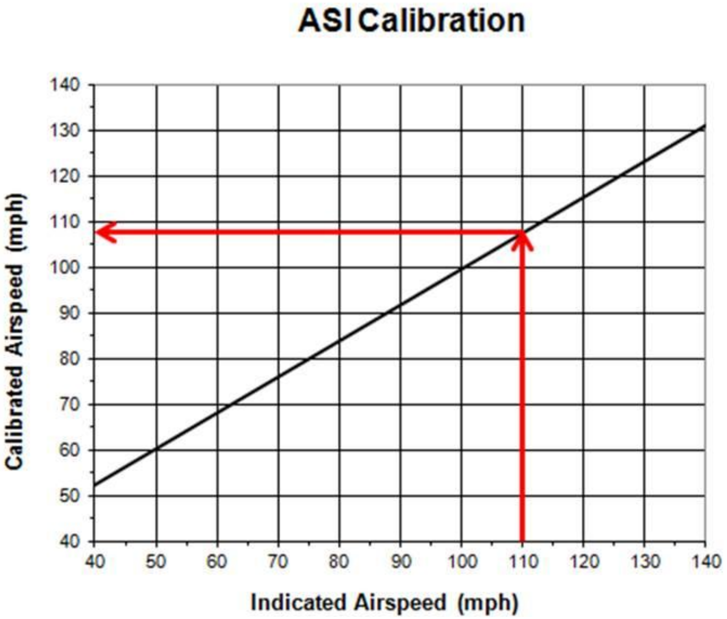

Remove
Instruments Errors
Account for Temperature
and Air Density
Account for
Wind
IAS
CAS
TAS
GS
Indicated Airspeed
Calibrated Airspeed
True Airspeed
Ground Speed

Indicated Airspeed (IAS)

- Displayed directly from the airspeed indicator
- Airspeed indicator measures dynamic pressure

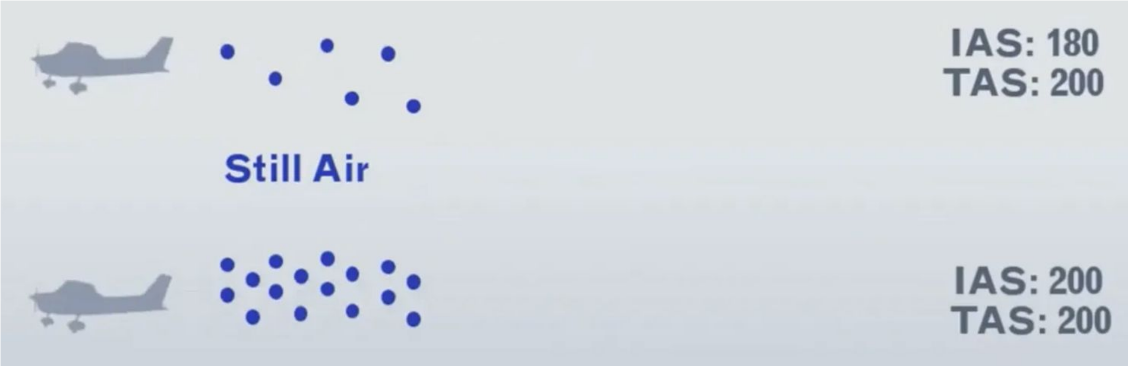
Calibrated Airspeed (CAS)

- IAS corrected for instrument and positional errors
  - Error greater when flaps are used



True Airspeed (TAS)

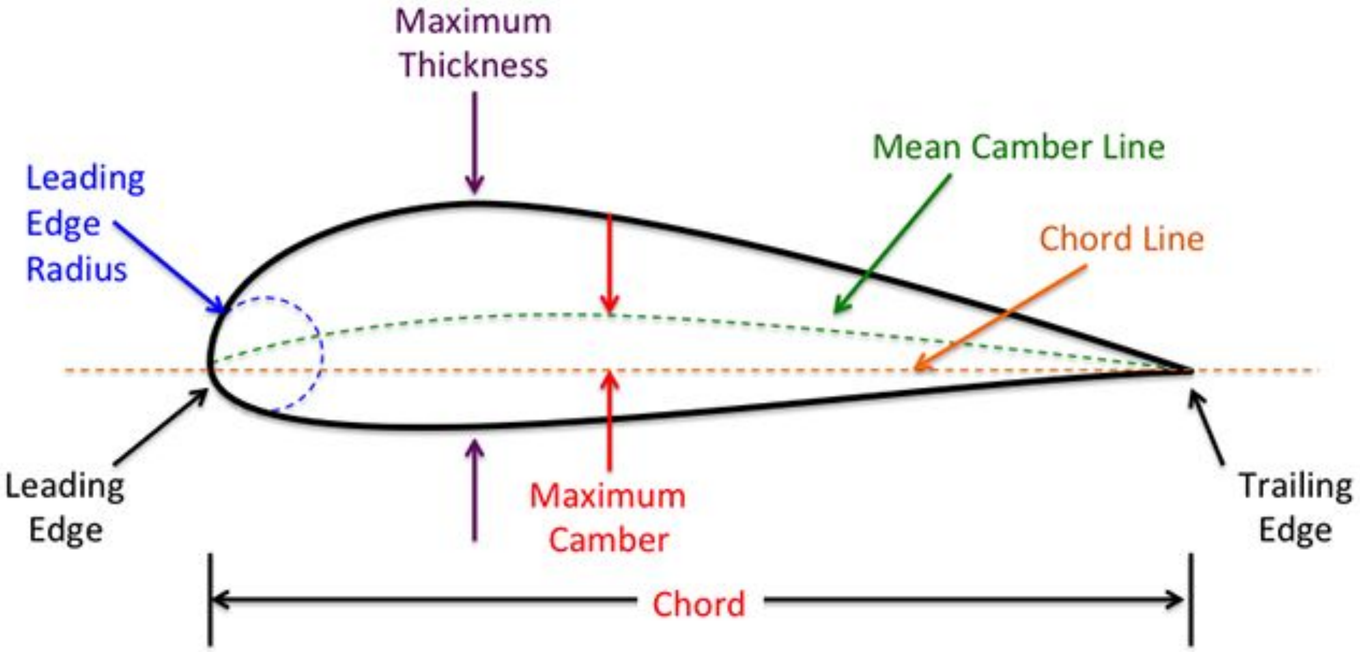
- Speed of aircraft relative to the air it's flying through
  - Pressure decreases with higher altitude
  - Less air molecules enter the pitot tube
    - During climb, IAS less than TAS
- Performance charts are based off of TAS
  - Used when filing a flight plan



Groundspeed

- Movement of airplane relative to the ground
- TAS corrected for wind

Airfoil Breakdown



Common Airfoils

NACA 4-digit Series

X X X X

Maximum % camber (percent of chord length)

Location of max camber from leading , X/10 (fraction or percent of chord length)

Maximum % thickness (percent of chord length)

Example: NACA 2412

Max camber is 2% of chord length

Max camber is at 4/10 or 40% of chord length

Max thickness is 12% of the chord length

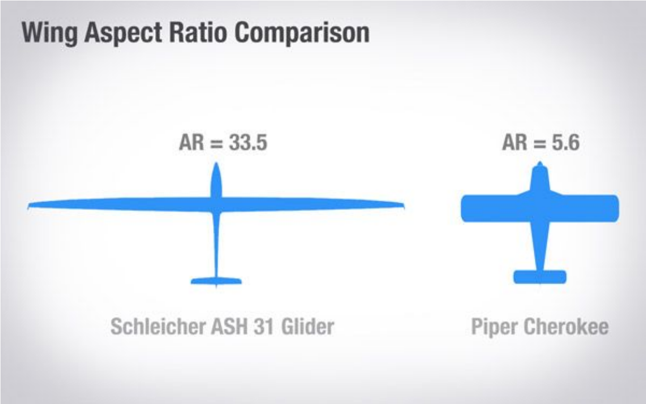
Wing Design

Aspect Ratio - wing span to wing chord

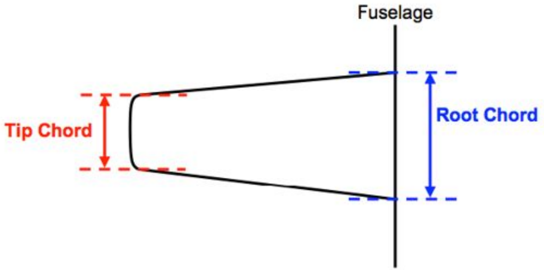
- Increase AR: increase weight and bending moment, decrease induced drag and downwash
- Low AR leads to high wing loading and high stall speeds

Taper ratio - tip chord to root chord

- Adding taper:
  - Decrease in drag
  - Increase in lift
  - Saves weight



$$Taper\ Ratio\ (\lambda) = \frac{Tip\ Chord}{Root\ Chord} = \frac{c_t}{c_r}$$



Wing Planforms

Rectangular Wing

- Stalls first at the wing root
- Favored for low cost, GA airplanes

Straight-Tapered Wing

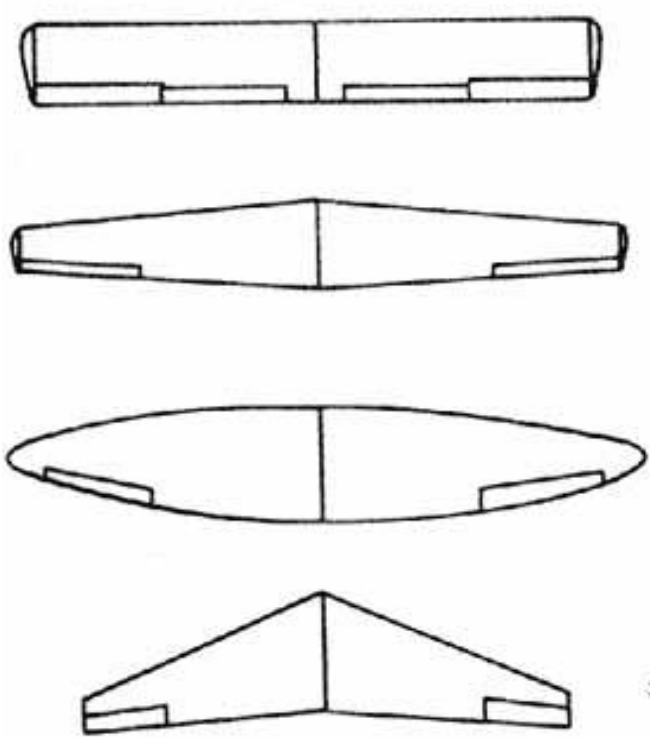
- Ideal for weight and stiffness
- Higher efficiency

Elliptical Wing

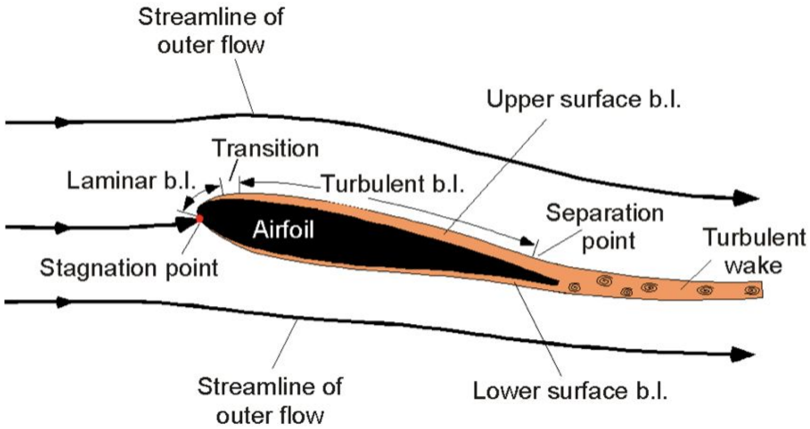
- Lowest induced drag
- Gives little warning of complete stall

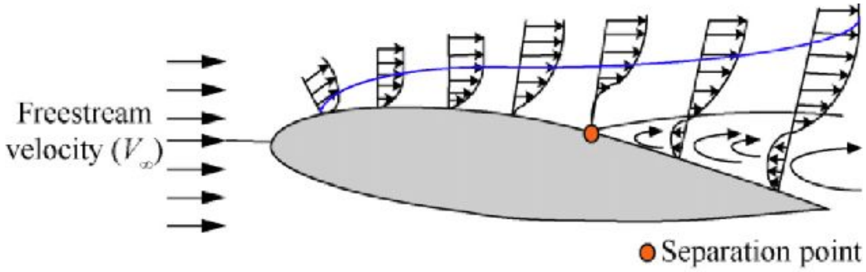
Swept Wing

- Higher Mach
- Delay wave drag



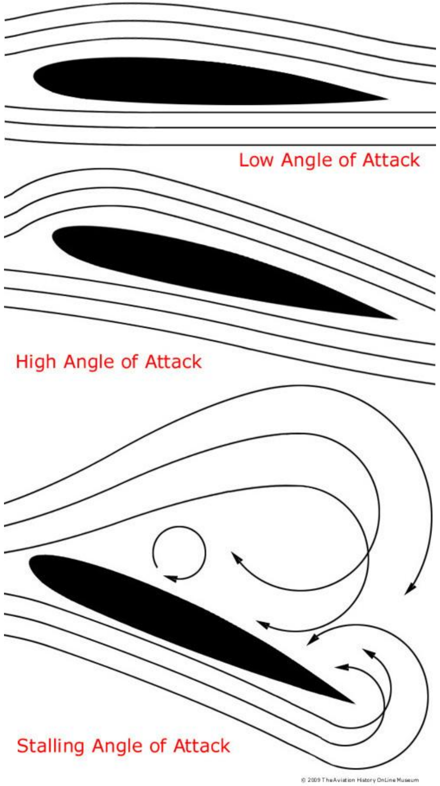
Boundary Layers





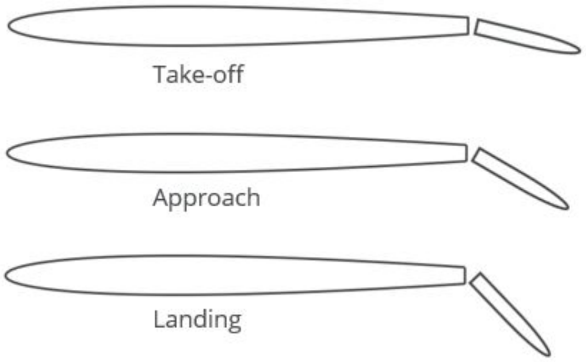
Stalls

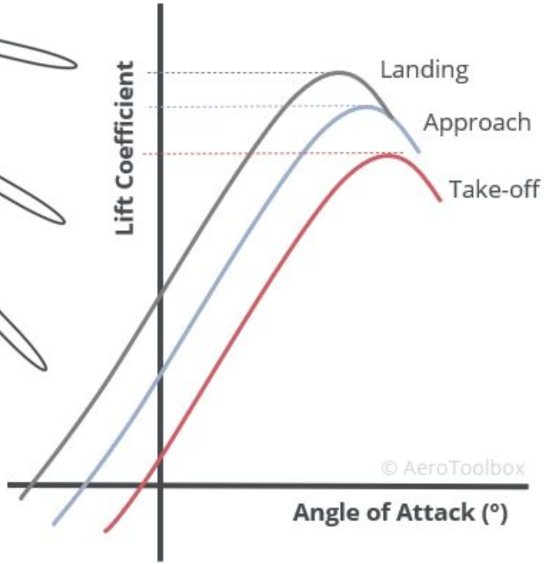
- Wing exceeds critical AoA
- Tip stall vs. root stall
  - Affected by Reynolds number and effective AoA
- Vortex generators energize the boundary layer
- Flaps delay onset of stall

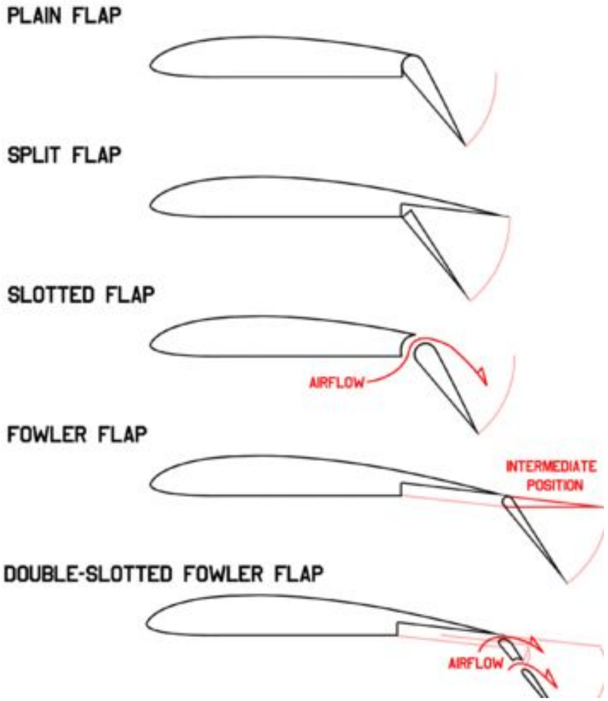


Flaps

- Increases airfoil camber and wing area
- Lowers stall speed for the same C_L
- Common types of flaps





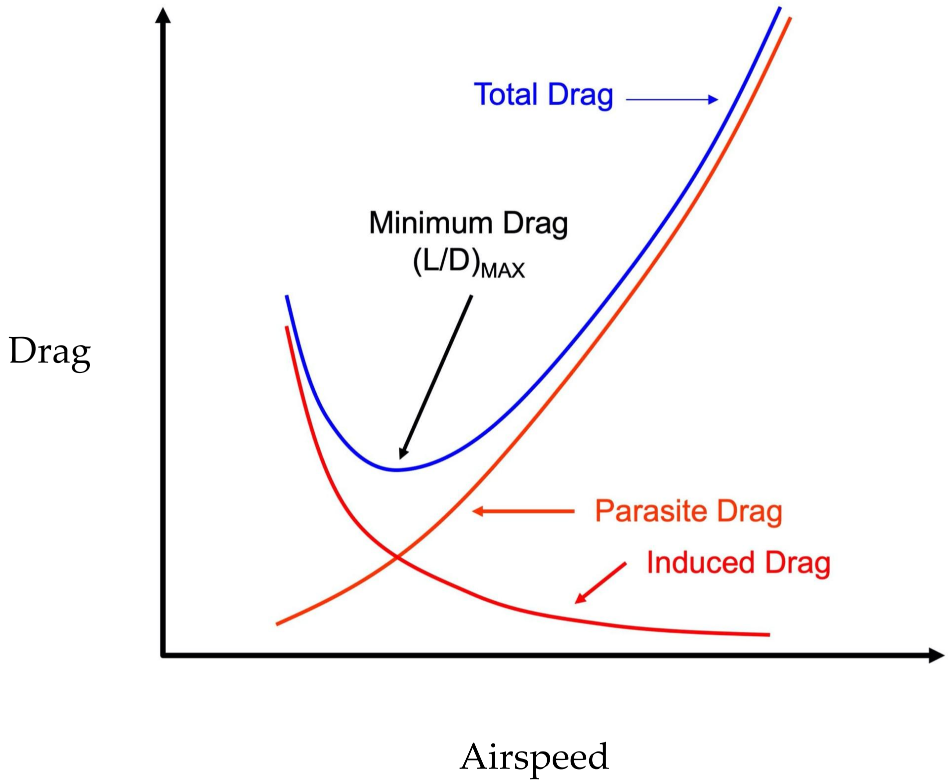


Drag

1) Parasitic Drag
   - Pressure (Form) Drag
   - Interference Drag
   - Viscous (Skin Friction) Drag
2) Induced Drag
   - Drag from Lift generation

$$C_D = C_{D0} + KC_L{}^2$$

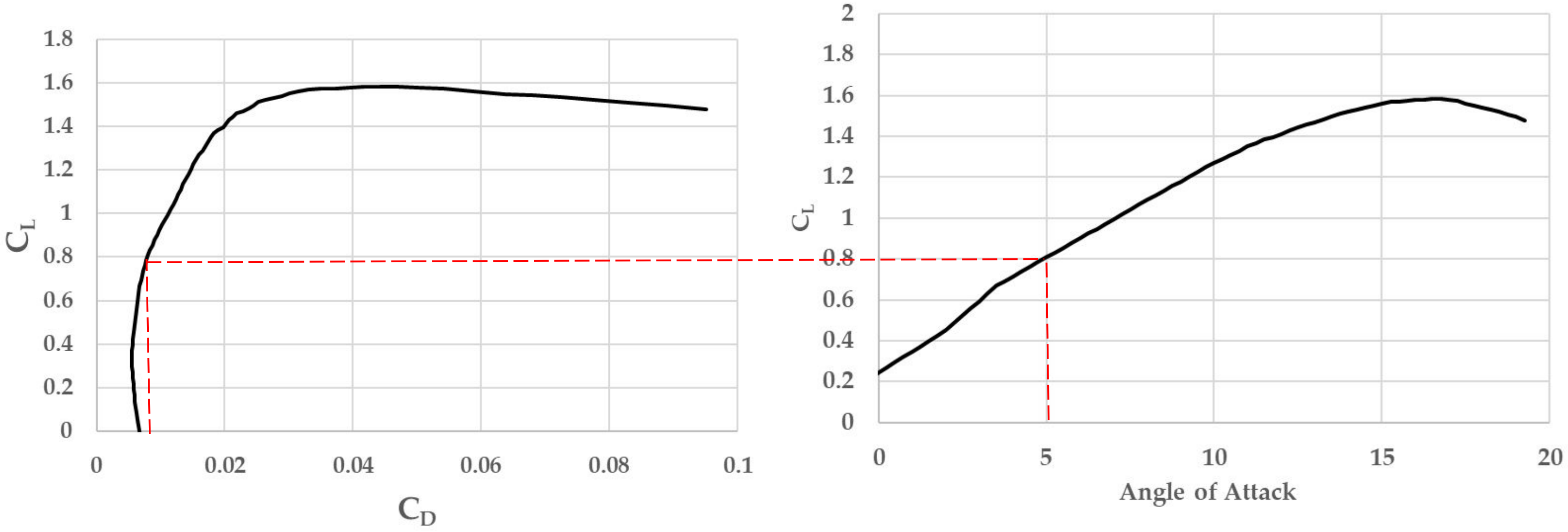
Parasitic — Induced



Drag Polar

$$C_D = C_{D0} + KC_L{}^2$$

- In Steady Level Flight (Lift = Weight & Thrust = Drag), there is a **unique relationship** between $\mathbf{C_L}$, $\mathbf{C_D}$, $\boldsymbol{\alpha}$, **Velocity, and Weight**
- The Drag Polar is a tool that offers insight to this

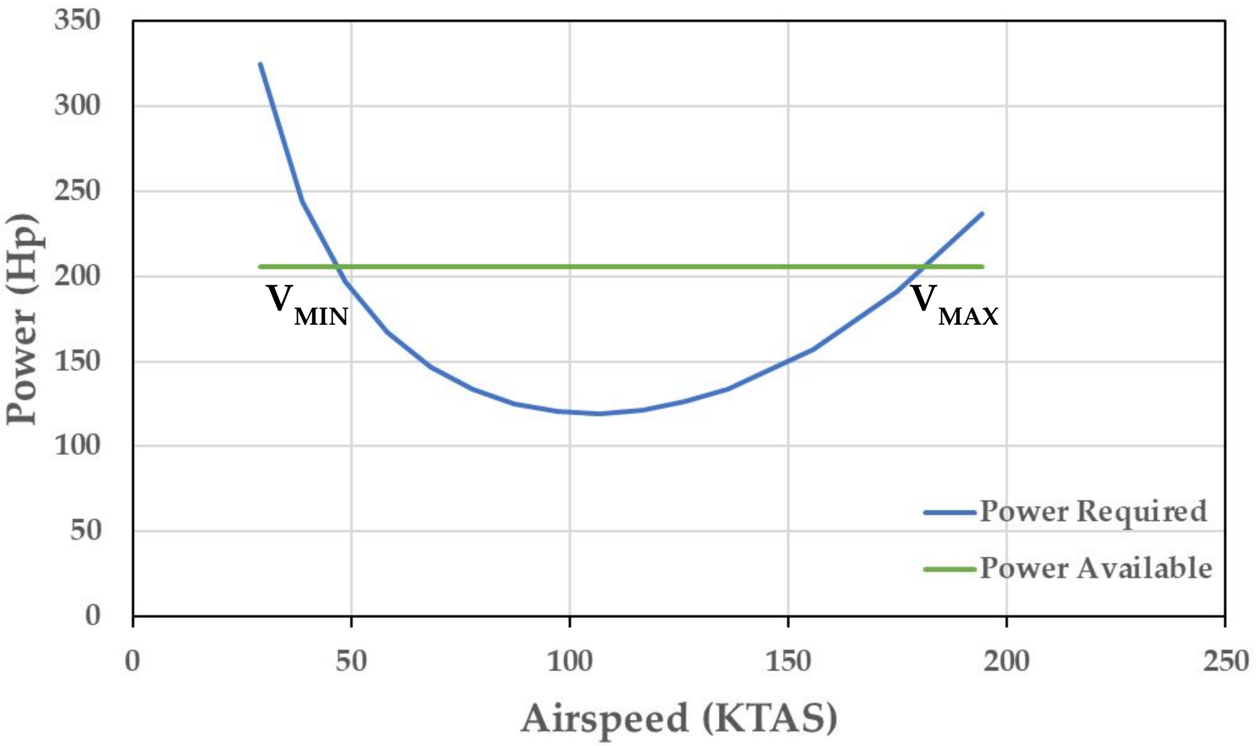


Power Available and Required Curves

- By assuming steady level flight, we can plot the power required (Drag*Velocity) and the power available from the engine.
- The intersection of these curves are the minimum and maximum flight speed

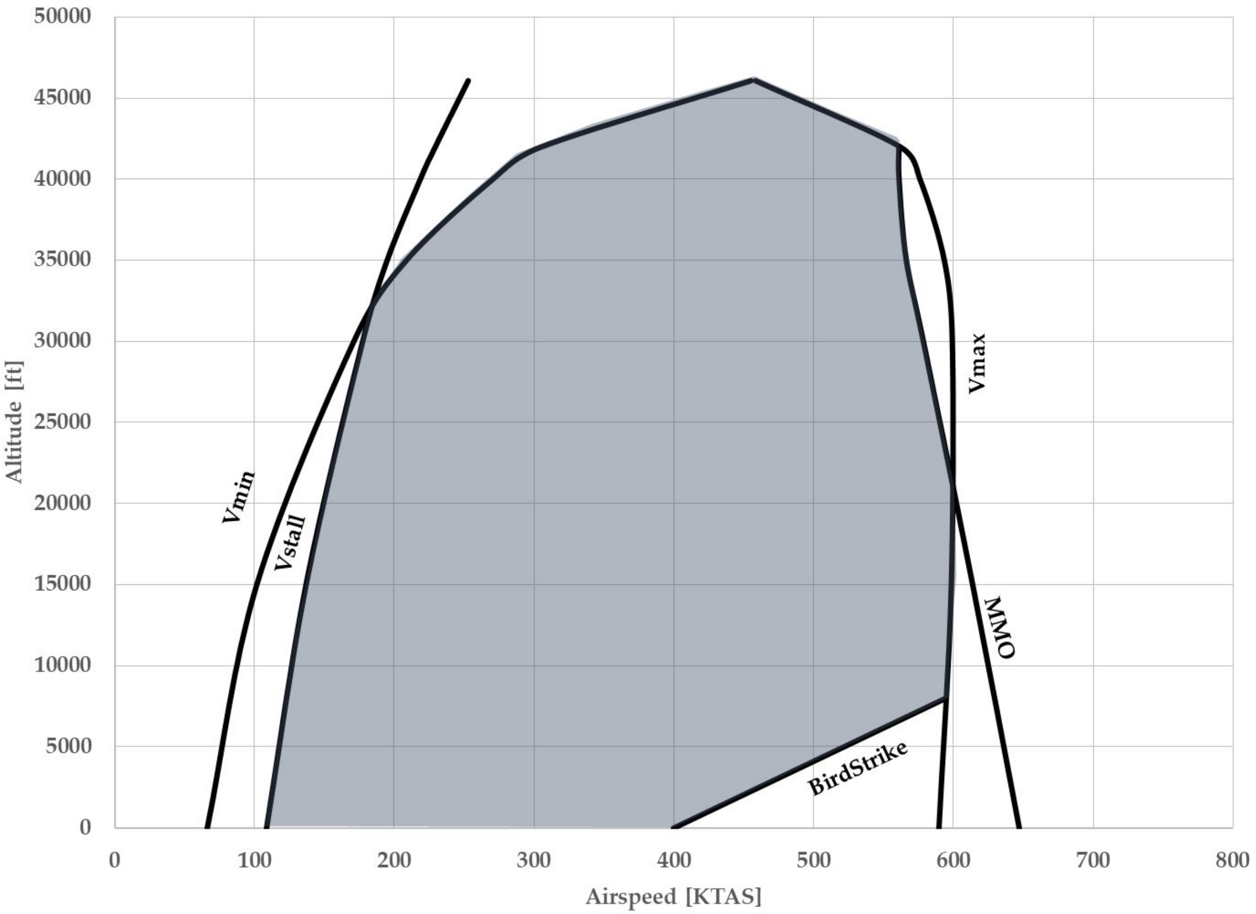
$$D = \frac{1}{2}\rho V^2 S C_{D0} + \frac{2KW^2}{\rho S V^2}$$

Notice drag force is dependent on density & thus altitude



Flight Envelope

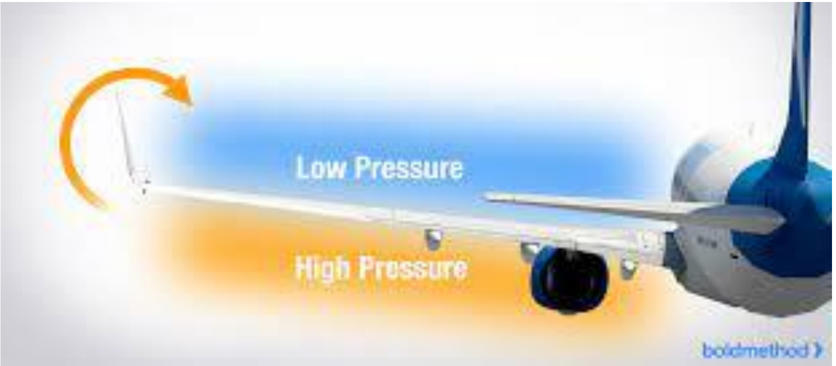
- By iterating power curves at many different altitudes, we can build a flight envelope with Vmin and Vmax
- Other constraints are introduced such as Vstall, Mach Limits, Flutter Limits, etc.
- Flight envelopes are verified with Flight Test



CAL POLY SAN LUIS OBISPO

Wingtip Vortices

- High pressure air seeks to equalize with the low pressure air above the wing
- The downward component of the vortex pushes the wing down
- Reducing lift at the tips and across the wing
- Larger c_L values increase the strength of the vortices
- Major component of induced drag

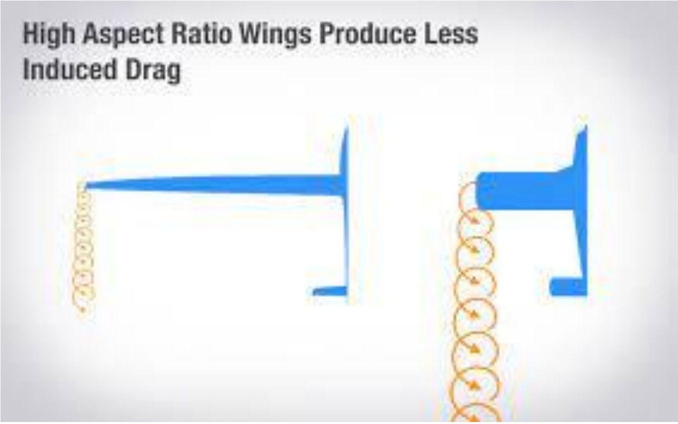


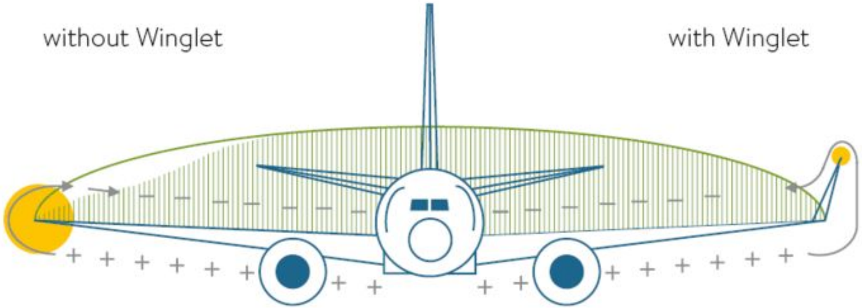
$$C_D = C_{D0} + \frac{c_L^2}{\pi AR e}$$

Reducing Wingtip Vortices

- High Aspect Ratio
  - Longer wings have more lift producing area
  - Thinner, smaller tips produce weaker vortices

- Winglets -
  - Additional lift generating wingspan
  - Reduces the size of the vortex
  - Potentially can generate thrust





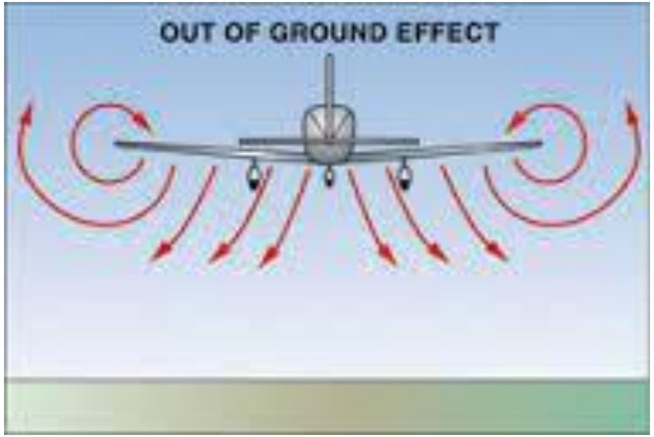
Ground Effect

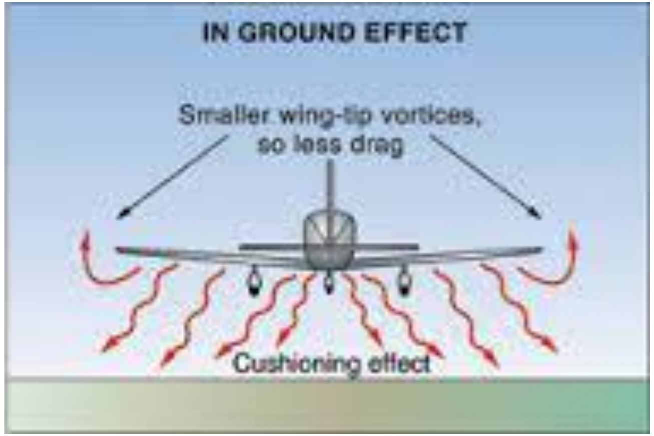
- Reduction in induced drag -

  Tip vortices become elliptical increasing the effective aspect ratio

- Increase in Lift (Cushion Effect) -

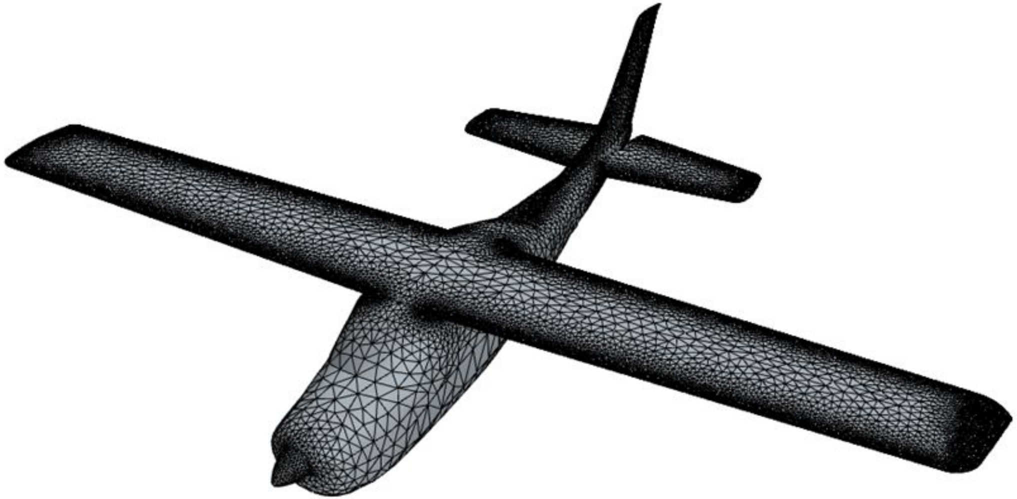
  Air is compressed between the two surfaces, creating higher pressure on the bottom of the wing



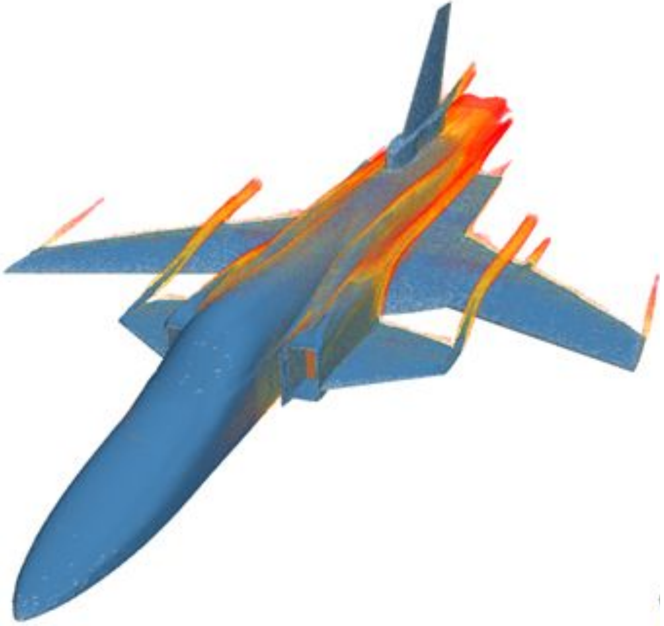


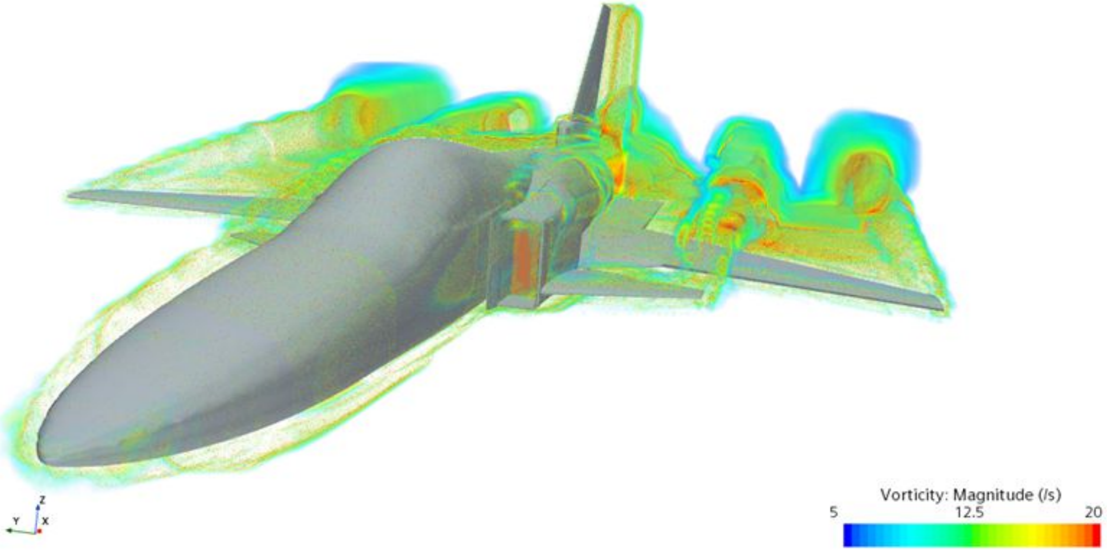
CFD - Computational Fluid Dynamics

- Application of aerodynamic theory using the power of computers
- Implementation of simplified navier stokes equations
- Breaks 3-D models into millions of little pieces and solves the surrounding flow field

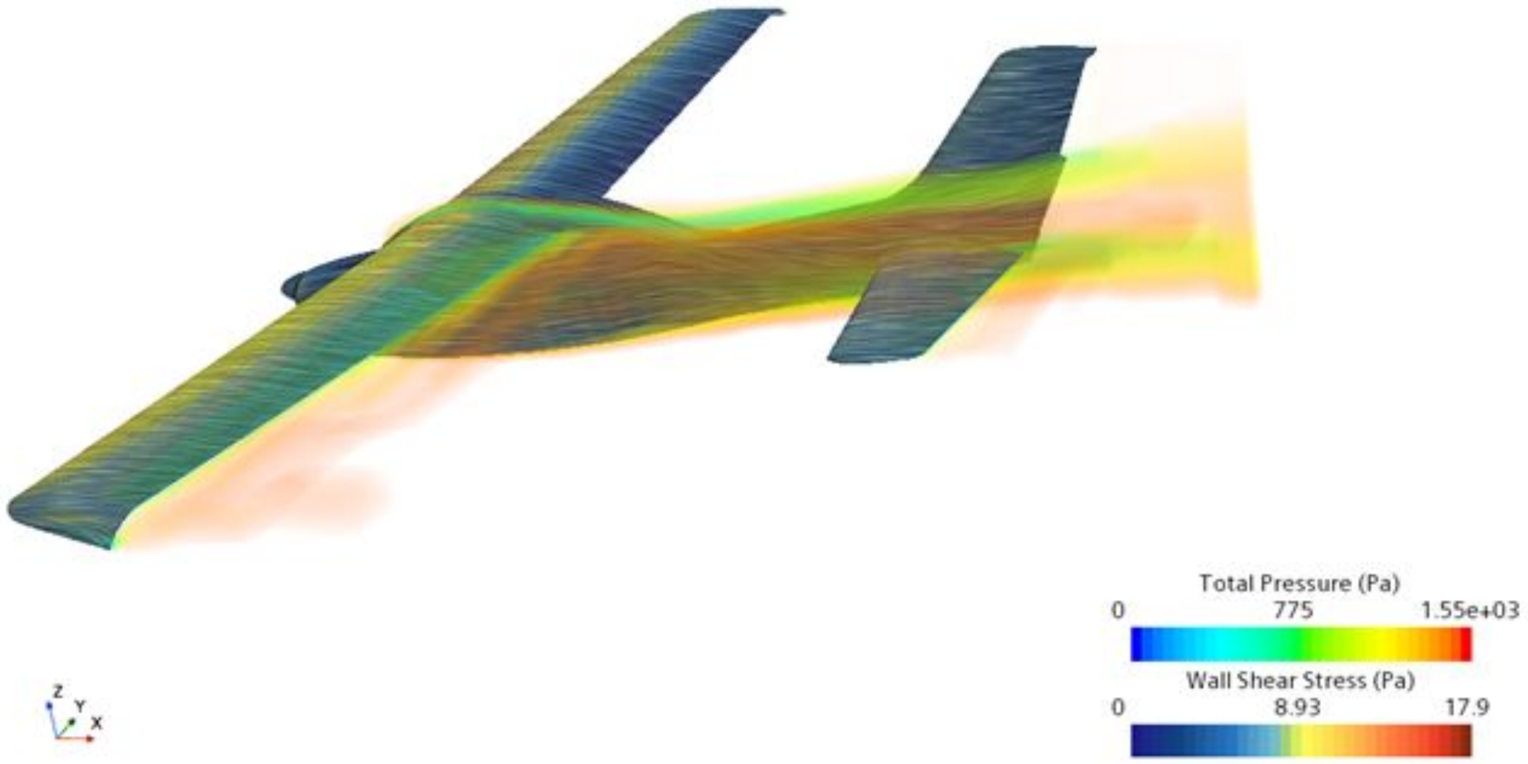


CFD





CFD


Total Pressure (Pa)
0
775
1.55e+03
Wall Shear Stress (Pa)
0
8.93
17.9
Z
Y
X

Thank you!

Questions?