# Lecture 3 - Drag



# Two types of drag



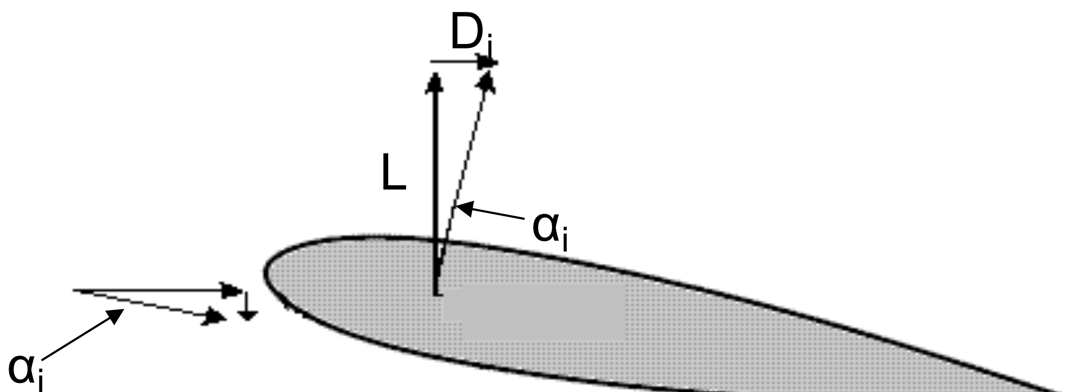
- **All types of drag can be included in these two groups:**
  - **Skin friction drag**
    - **Caused by viscous shearing forces tangential to body's surface**
    - **Influenced by Reynold's number and surface roughness**
      - **Laminar flow leads to lower skin friction coefficients than turbulent flow**
  - **Pressure Drag**
    - **Caused by pressure distribution normal to body's surface**
    - **Dependent on Reynold's number, projected frontal area.**
      - **Laminar flow can lead to an adverse pressure gradient that increases drag**
- **In general, both skin friction and form drag are difficult to predict, so experimental wind tunnel tests often are required to obtain accurate predictions**

Concorde

# Induced Drag



- **Induced angle of attack due to downwash tilts lift vector backward**
- **With respect to free stream AoA, a component of the lift vector is in the drag direction**




$$C_{D_i} = \left( \frac{C_L^2}{\pi A e} \right)$$

$$C_D = C_{D\min} + \left( \frac{C_L^2}{\pi A e} \right)$$

**Reduce Induced Drag by:**

- **Increasing Aspect ratio**
- **Optimizing span-wise lift distribution**
- **Disrupting tip vortices at wingtips**

# Drag Equations



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

$$C_D = C_{D_P} + \frac{C_L^2}{\pi A e}$$

$$D = \frac{1}{2}\rho V^2 S C_{D_p} + \frac{1}{2}\rho V^2 S C_{D_i}$$

**Parasite Drag** **Induced Drag**

**If flying straight, then lift equals weight (L = W).**

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

$$\downarrow$$

$$C_L = \frac{2W}{\rho V^2 S}$$

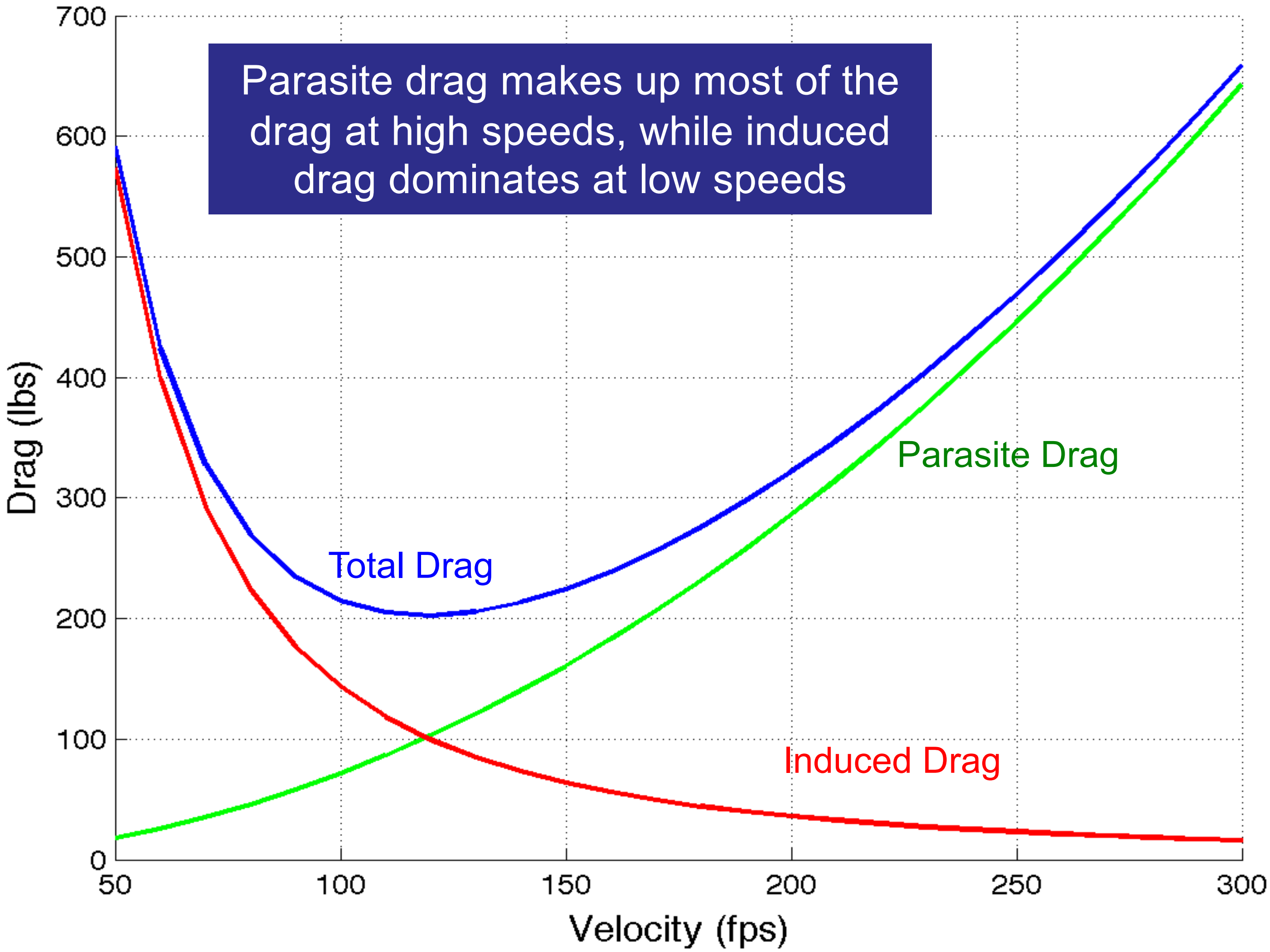
$$\downarrow$$

$$C_{D,i} \propto \frac{1}{V^4}$$

If L=W, parasite drag is proportional to $V^2$, while induced drag is proportional to $1/V^2$

# Drag vs. Velocity when L=W






**Aircraft data: W= 3200 lbs, S = 300 ft$^2$ , $C_D$=0.02+0.05*$C_L^2$, ρ=0.00238 slug/ft$^3$**

# Interference Drag



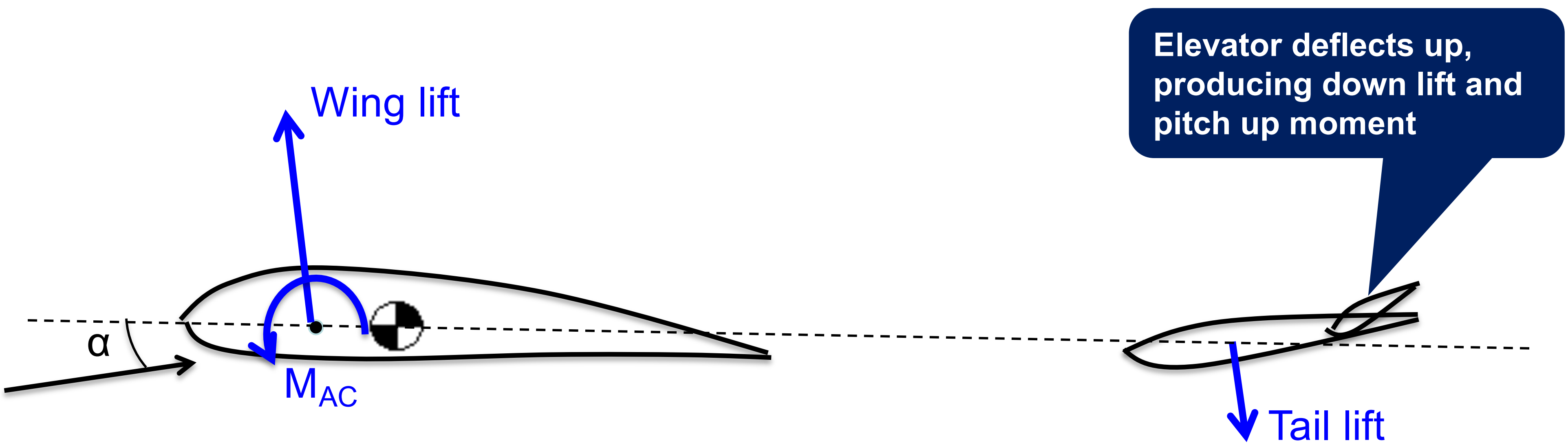
- When two objects are placed in proximity, their boundary layers and pressure distributions interact with each other
- The net drag is higher than the sum of each components' drag by itself
- Interference drag mitigated by smoothing out sharp angles and blending components whenever possible
- Placement of wings and other components also impact interference drag

# Trim Drag



- **Drag due to control surface deflections that are needed to balance aircraft moments**

- **CG locations strongly influence trim drag**
  - **CG too far forward may result in increased trim drag, as more down-lift on tail would be required to balance the moments about CG (leads to increased induced drag at tail and wing)**



# Designing for Drag Reduction



Lancair 360

- **Reducing Skin Friction**
  - **Laminar airfoils can be used, but not always very realistic depending on the materials and construction tolerances being used**
  - **Wetted area should be minimized, usually by having the fuselage taper in the back. However, useful volume of fuselage is sacrificed**
  - **Can consider optimum fineness ratio for fuselage. However, this usually isn't very realistic either. Most aircraft fuselages are longer to provide sufficient moment arms for tail control surfaces**

# Designing for Drag Reduction



- **Reducing form drag**
  - **Make as streamlined as possible**
  - **Retractable landing gear (added complexity)**
  - **Shorter wings lower cross-section and reduce parasite drag (leads to increased induced drag)**
  - **Avoid flow separation**

### F-104 Starfighter (1958)

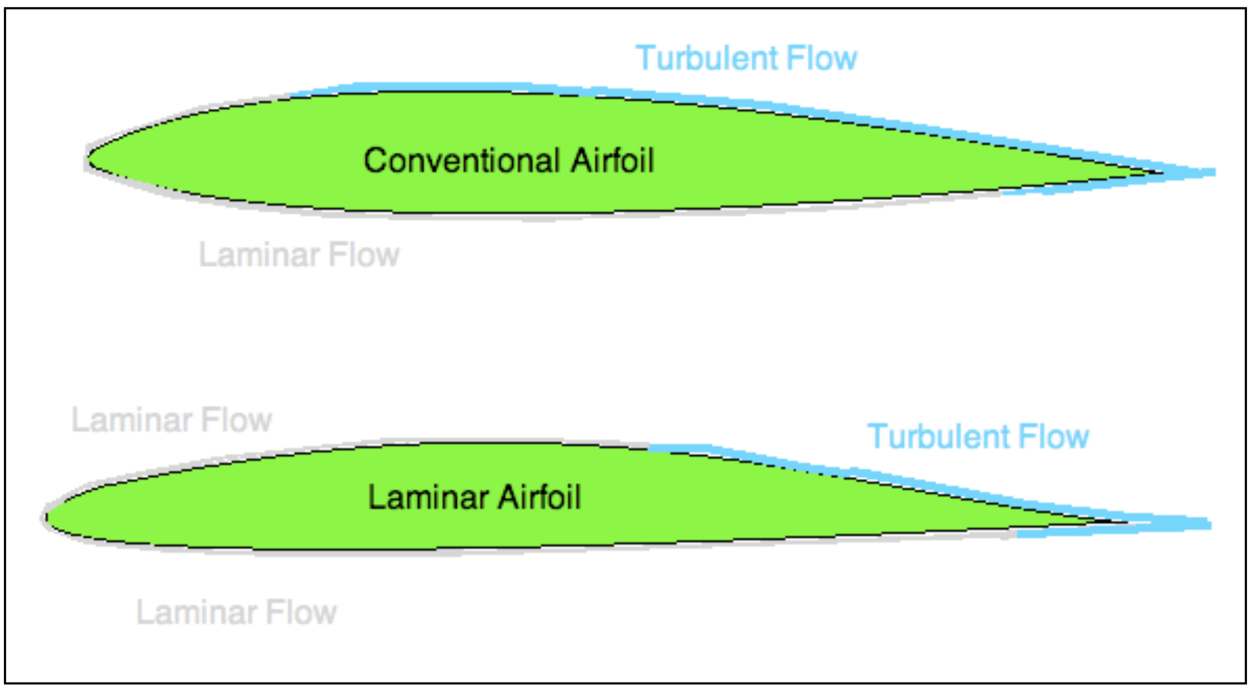
- **Wingspan:** 21 ft 9 in (6.36 m)
- **Wing area:** 196.1 sq ft (18.22 m²)
- **Loaded weight:** 20,640 lb (9,365 kg)
- **Aspect ratio:** 2.45
- **Maximum speed:** 1,328 mph
- **Rate of climb:** 48,000 ft/min
- **Wing loading:** 105 lb/sq ft (514 kg/m²)
- **Thrust/weight:** 0.54 with max. takeoff weight (0.76 loaded)
- **Lift-to-drag ratio:** 9.2


**Photo Courtesy USAF**

# Laminar Airfoils

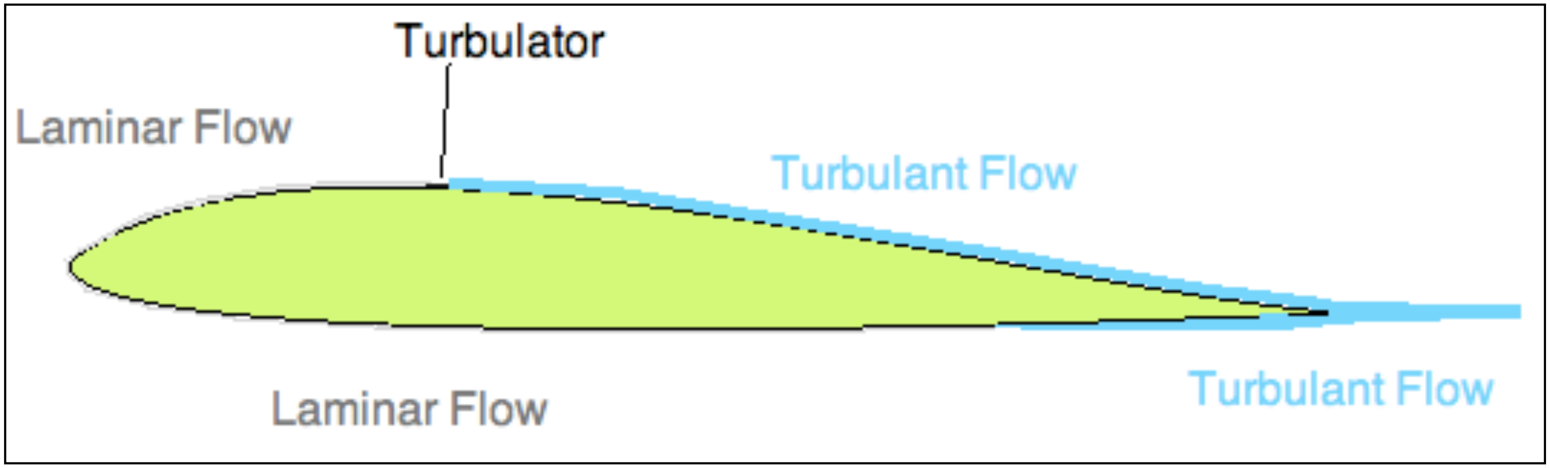


- **Laminar airfoils are shaped to prevent or delay the onset of turbulent flow in order to reduce skin friction**
- **Laminar airflow is difficult to produce**
  - **Airfoil must be very smooth to promote laminar flow**
- **For laminar airfoils, favorable pressure conditions only exist for a narrow $C_L$ and AoA range, leading to a "drag bucket" on the drag polar**



# Turbulators

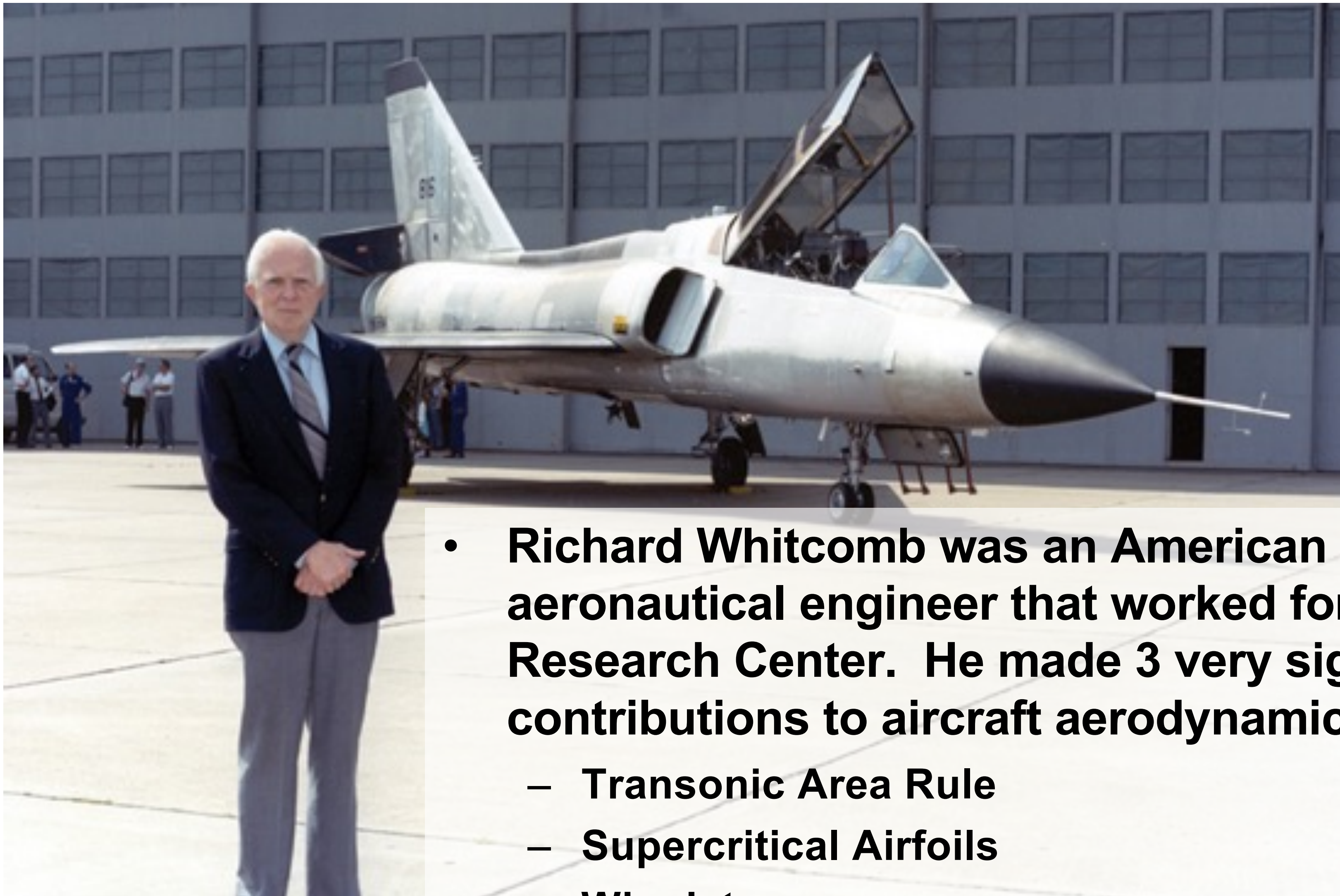





- **Although laminar flow leads to reduced skin friction drag, laminar flow tends to separate easier than turbulent flow**
  - **Flow separation is usually a lot worse than skin friction drag**
- **Some aircraft intentionally trip the flow to initiate turbulent flow. This thickens the boundary layer and helps delay or prevent flow separation**

# Richard Whitcomb (1921-2009)






- Richard Whitcomb was an American aeronautical engineer that worked for Langley Research Center. He made 3 very significant contributions to aircraft aerodynamics:
  - Transonic Area Rule
  - Supercritical Airfoils
  - Winglets

# Winglets



- **Winglets alter the structure of the trailing vortex system**
- **Sidewash velocity produces an angle of attack acting on the winglet**
  - **Outward flow from beneath the wing, inward flow on top**
  - **Lift force acting on winglet can have a forward component that counteracts some of the drag**

Photo by D. Nehrener

Airbus A319 wingtip fence

# Vought V-173 “Flying Pancake” (1942)



- **Very unorthodox design: disc-shaped body serves as the lifting surface**
  - **A disc wing such as this has a very low aspect ratio, which typically leads to very high induced drag**
  - **Large propellers were used to cancel the effect of the wingtip vortices by rotating in the opposite direction. This allowed the wing to be much smaller, which has improved maneuverability and increased structural strength**


# Compressibility



- **Critical Mach Number:**
  - **Mach number of the aircraft at which the local Mach number at some point of the wing becomes 1.0**
  - **Mach numbers above the critical mach number result in shock waves forming on the wing**
- **Divergence Mach No.**
  - **Mach number at which the aerodynamic drag of a wing increases rapidly as the Mach No. continues to increase**
  - **Usually close to but always greater than the critical mach number**

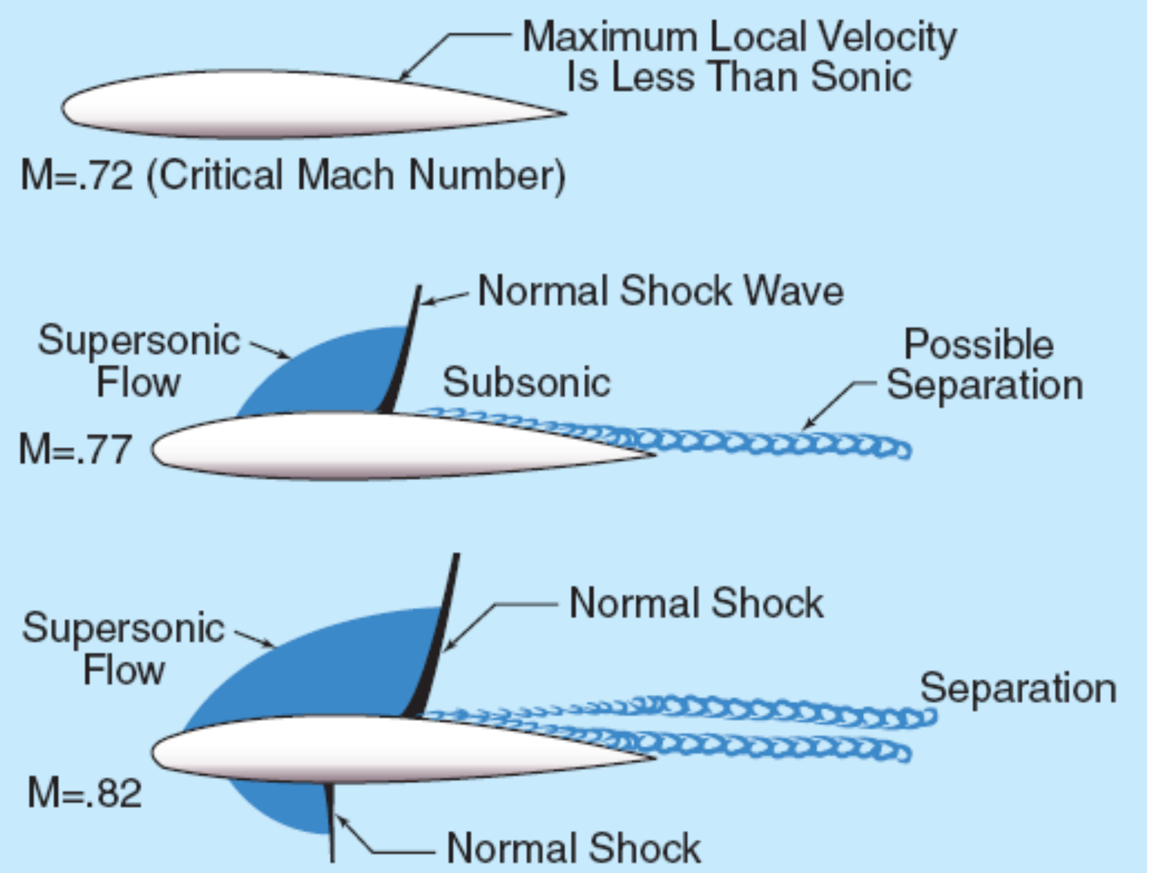



Image Courtesy of FAA

# Transonic Area Rule




- **At higher speeds, shock waves form on the aircraft body and cause wave drag**
- **Shockwaves can be reduced if the cross-sectional area of the aircraft changes gradually across its length, and it turns out this effect is largely independent of the aircraft shape**
- **One way to follow this area rule is to reduce the fuselage cross-section where the wing is placed (Coke bottle shape)**

# Transonic Area Rule



**Early version of the F-102 Delta Dagger with its straight fuselage design. Aircraft performance was disappointing – designed to fly Mach 1.2 but could not exceed Mach 1**


**Later variants of the Delta Dagger followed the transonic area rule**

# Transonic Area Rule

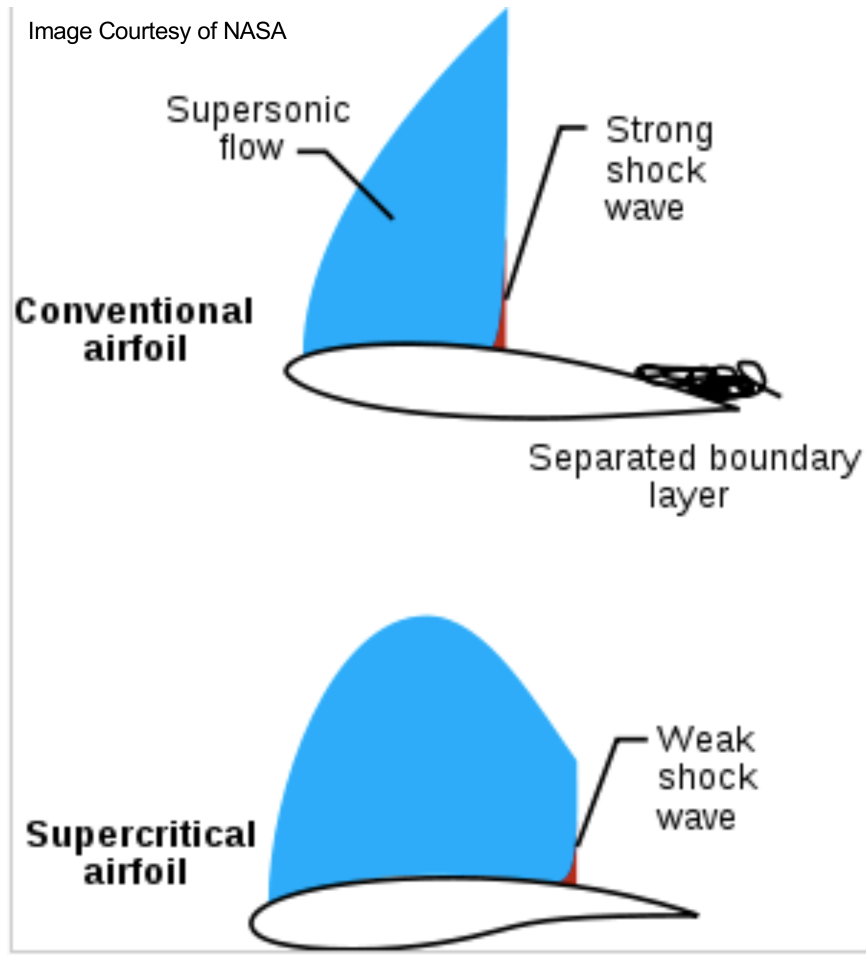


- **Not all aircraft follow the Area rule by narrowing the fuselage at the wing location. This would not make much sense for passenger aircraft that desire large fuselage volume**
- **Instead, anti-shock bodies can be added to the aircraft to help keep the changes in cross-sectional area smooth**


# Supercritical Airfoil



- **At transonic speeds, drag for a given lift coefficient can be reduced if using a supercritical airfoil**
- **Airfoil shape results in a more rearward location and decrease in the strength of the shock wave**
- **Onset of boundary layer separation is also delayed to a higher Mach number**
- **Lift is lost due to reducing the upper surface curvature, but this is made up for by the supersonic flow on the upper surface, and by the large camber on the rear portion of the airfoil**



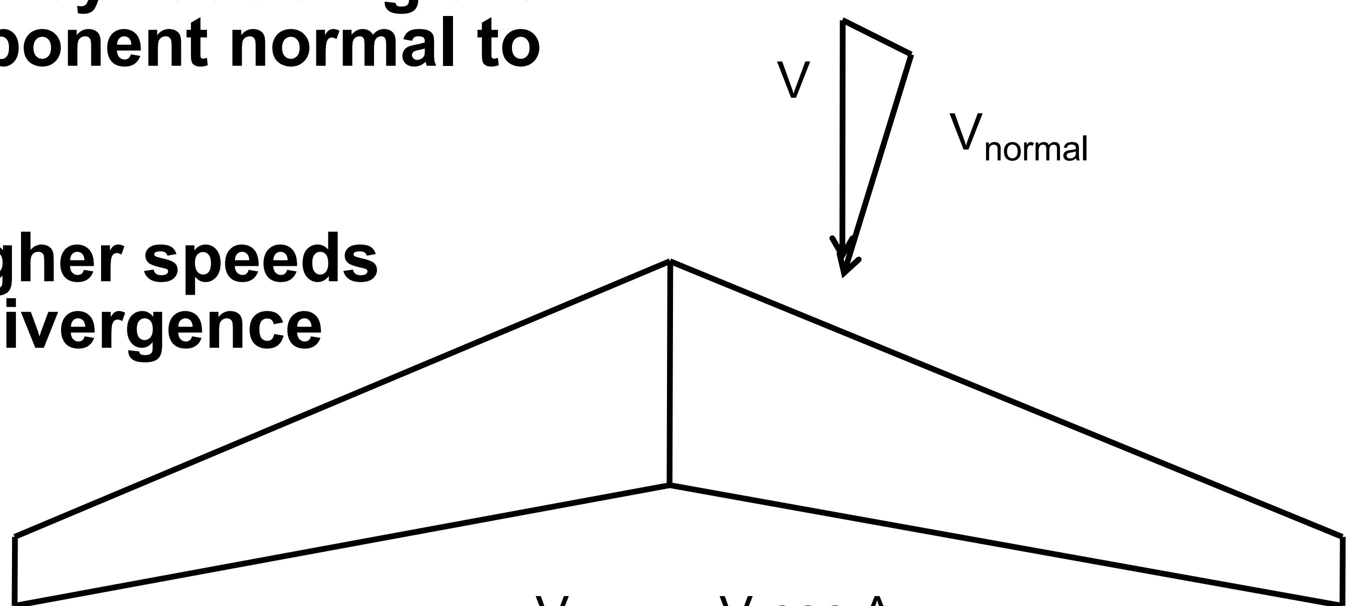
# Wing Sweep for Transonic Aircraft



- **Critical mach number is dependant on airspeed normal to leading edge**

- **Wing sweep increases critical mach number by reducing the velocity component normal to leading edge**

- **Allows for higher speeds before drag divergence occurs**

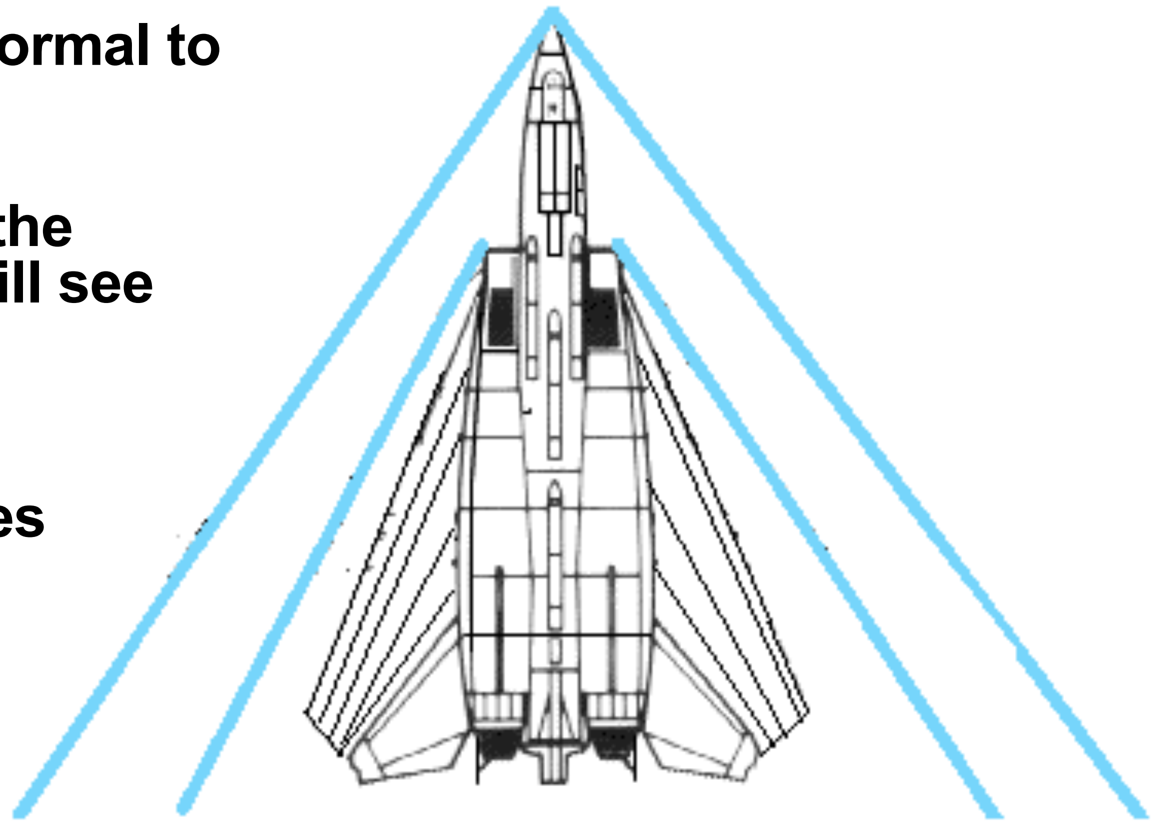



$V_{normal} = V \cos \Lambda$

# Swept Wings and Supersonic Aircraft



- **Airflow behind the shock is reduced such that the component of the flow normal to the shock is subsonic**
- **If the aircraft lies within the cone-shaped shock, it will see subsonic flow**
- **As Mach No. increases, the shock angle increases**
  - $$\sin\mu = \frac{1}{M}$$
  - **At Mach 2, aircraft sweep angle would need to be 60°**



# Swept Wings and Supersonic Aircraft



- **Aircraft with high wing sweep suffer in performance at low speeds**
  - **Loss in maneuverability**
  - **High stalling angle**
- **Some aircraft like the F-14 employ variable sweep wings to improve performance at different flight conditions**

**F-14 Tomcat**
Max Speed: Mach 2.34
Wing Sweep: 20-68 deg

**Photo Courtesy US Navy**

# Ground effect



- **Ground proximity prevents trailing vortices from fully forming, leading to a reduction in induced drag**

- **With the downwash reduced, the 'Wing in Ground' effect increases the effective angle of attack, making the wing more effective at producing lift**

Image Courtesy of Flarecraft


Russion A-90 Orlyonok Image from of Wikimedia Commons Mike79Russia

# Drag Estimation



## Component build-up method

- Estimate parasite drag on each aircraft component exposed to flow
- Add them up to estimate parasite drag for entire aircraft

$$C_{D_P} = \sum_{i=1}^{\#comp} \frac{K_i Q_i C_{f_i} S_{wet_i}}{S_{ref}} + C_{D_{Misc}} + C_{D_{L\&P}}$$

$S_{ref}$: reference area (wing area)

$C_f$: skin friction coefficient

K: form factor

Q: interference factor

$C_{D,misc}$: additional miscellaneous drag terms

$C_{D,L\&P}$: Leakage and protuberance

# Drag Estimation



- **Empirical equations can be used to estimate the various drag terms**
  - **Skin friction can be estimated with Raymer eq. 12.27**

$$C_f = \frac{0.455}{\left(\log_{10}\mathrm{Re}\right)^{2.58}\left(1+0.144M^2\right)^{0.65}}$$

  - **Raymer eq. 12.30 estimates the form factor for wings, tails, canards, etc**

$$K = \left[1 + \frac{0.6}{(x/c)_m}\left(\frac{t}{c}\right) + 100\left(\frac{t}{c}\right)^4\right]\left[1.34M^{0.18}\cos(\Lambda_m)^{0.28}\right]$$

  - **Raymer eq. 12.12 can be used to estimate form factor for smooth surfaces like fuselages**

$$K = \left(1 + \frac{60}{f^3} + \frac{f}{400}\right) \qquad f = \frac{l}{d}$$

  - **Interference Factors are harder to estimate, but values range from 1 to 1.25 depending on the surface.. Usually wings have a negligible interference so we can assume a value of 1. Tail surfaces are vary from 1.03 to 1.08**

# Drag Estimation



- **To get total drag coefficient, we combine the parasite drag with the induced drag**

$$C_{D_{total}} = C_{D_P} + C_{D_i}$$

- **Since both wing and tail can produce lift, both surfaces can contribute to induced drag**

$$C_{D,i} = \frac{C_{L_w}^2}{\pi A_w e_w} + \frac{S_t}{S_w}\frac{C_{L_t}^2}{\pi A_t e_t}$$

Where did the $S_t/S_w$ term come from?

- **With total drag coefficient, the drag force can now be computed**

$$D = \frac{1}{2}\rho V^2 S_{ref} C_{D_{total}}$$

# References



1. McCormick, B.W., *Aerodynamics, Aeronautics and Flight Mechanics*, 2nd edition, Wiley & Sons, 1995
2. E. Field, MAE 154S, Mechanical and Aerospace Engineering Department, UCLA, 2001
3. Raymer, D.P., *Aircraft Design: A Conceptual Approach*, AIAA Education Series