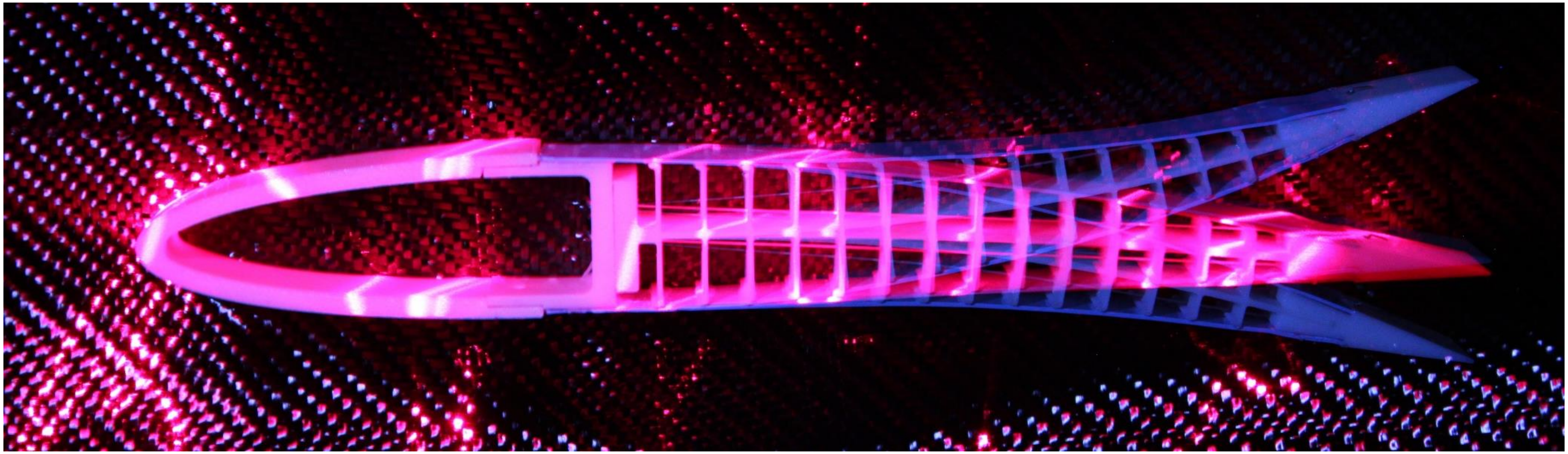
Aeronautics & Mechanics
AENG11301
Lecture 3

Aerofoils (known as Airfoils in the real world)



30/1/18

Dr Ben Woods

Department of Aerospace Engineering
University of Bristol

University of BRISTOL

DEPARTMENT OF aerospace engineering

Reminder! Matlab lab

- First one is this Friday 11am-1pm
- MVB 1.07
- 3 lab sessions, two exercises to be completed during lab
- 1 coursework to be done after

Outline for today

- Aerodynamic coefficients
- Aerofoil characteristics
  - Lift
  - Stall
- High lift devices

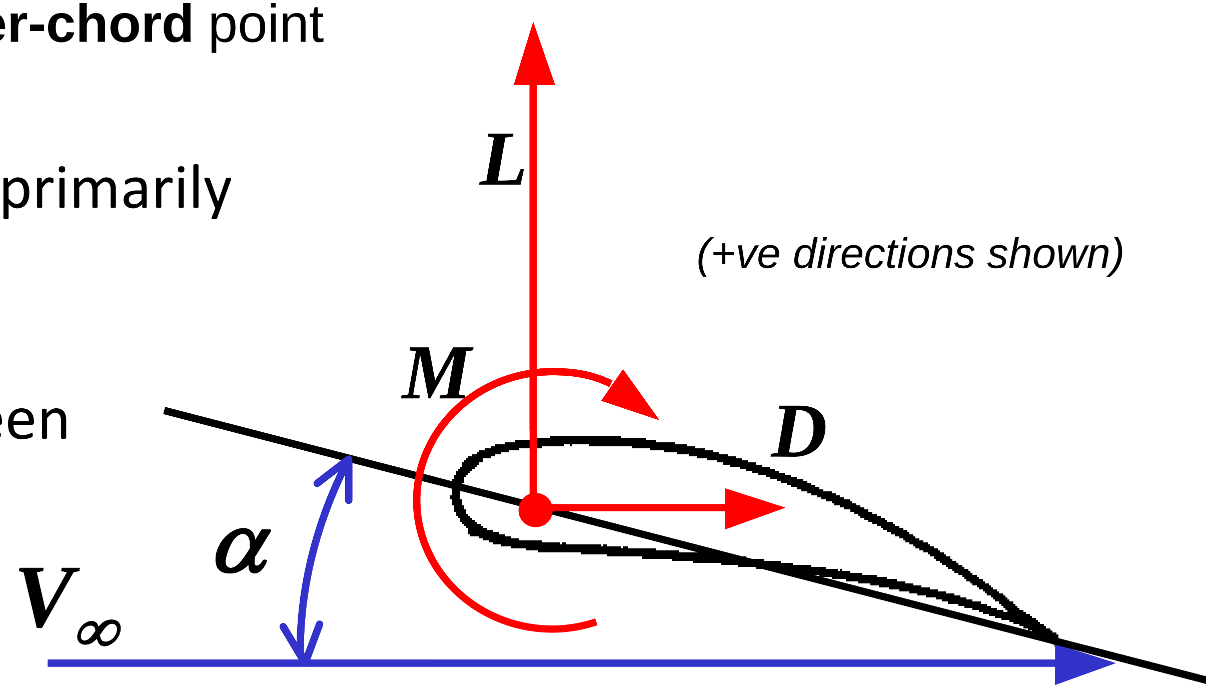
Aims for today

- Be able to interpret the lift coefficient and define what factors effect it.
- Be able to read a lift curve and understand how it changes with:
  - Wing thickness
  - Chamber
  - Flap extension
  - Leading edge devices

Review - Aerodynamic Forces

- Pressure distribution + friction give:
  1. **Lift** (L) acting *perpendicular* to the flow
  2. **Drag** (D) acting *parallel* to the flow
  3. **Pitching Moment** (M) acting about a defined axis
     - usually the leading-edge or the **quarter-chord** point

- Forces determined primarily by the **incidence** or **angle of attack**
  - angle (α) between chord line and flow direction



Equation for Lift

- From last lecture: $L \propto \alpha \rho_\infty V_\infty^2$
- Lift (L) is also proportional to a measure of area, which for airplanes is taken as the wing area (S)

- Taking these relationships we get the equation for lift:

$$\boxed{L = \tfrac{1}{2} \rho_\infty V_\infty^2 S C_L}$$

Where:
ρ_∞ = free stream air density
V_∞ = free stream velocity
S = wing area

- But what is C_L?

Aerodynamic Coefficients (1)

- engineers like to work in **non-dimensional** equations
  - Allows for more meaningful comparisons
- aerodynamic forces found to be proportional to:
  - velocity squared V^2
  - density ρ
  - wing area S
- leads to non-dimensional coefficients:
  1. **Lift Coefficient** (C_L)
  2. **Drag Coefficient** (C_D)
  3. **Pitching Moment Coefficient** (C_M)
     - with additional reference length (c)
- coefficients ~ independent of aircraft size and speed
- factor of ½ added for consistency with dynamic pressure $q = ½\rho V^2$

$$C_L = \frac{L}{\frac{1}{2}\rho_\infty V_\infty^2 S}$$

$$C_D = \frac{D}{\frac{1}{2}\rho_\infty V_\infty^2 S}$$

$$C_M = \frac{M}{\frac{1}{2}\rho_\infty V_\infty^2 Sc}$$

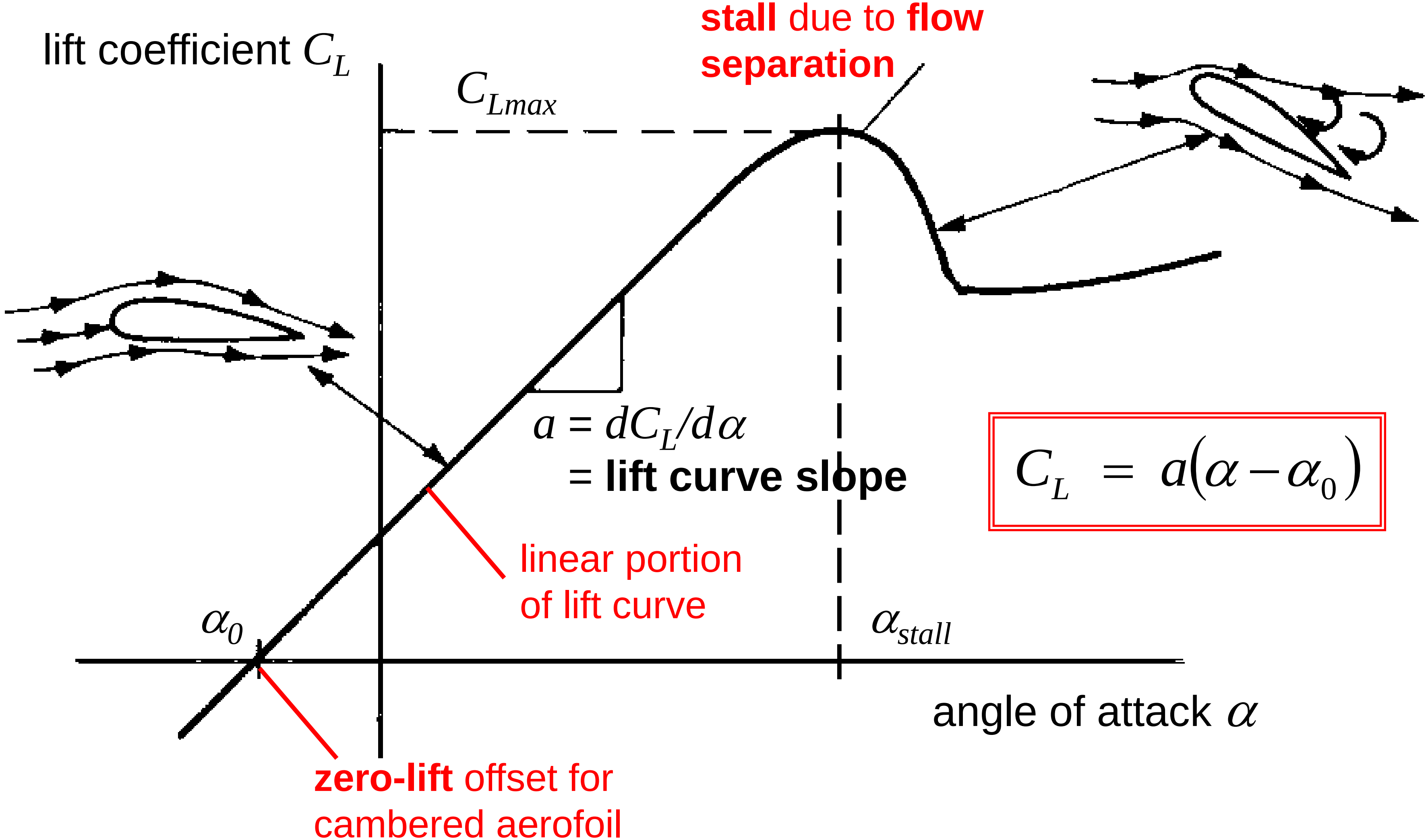
Aerodynamic Coefficients (2)

- coefficients are then functions of three further non-dimensional parameters
  1. **Incidence angle (a.k.a. angle of attack)** (α)
     – governs basic changes in flow pattern
  2. **Mach Number** (M_∞)
     – $M_\infty = V_\infty / a$, where (a) is **speed of sound**
     – **compressibility** effects at high speed only ($M_\infty > \sim 0.4$)
  3. **Reynolds Number** (Re)
     – ratio of inertia forces to viscous forces
     – effect of viscosity (μ) on flow pattern
     – important below a critical value ($Re < Re_{crit}$)

$$\boxed{Re = \frac{\rho V_\infty c}{\mu}}$$

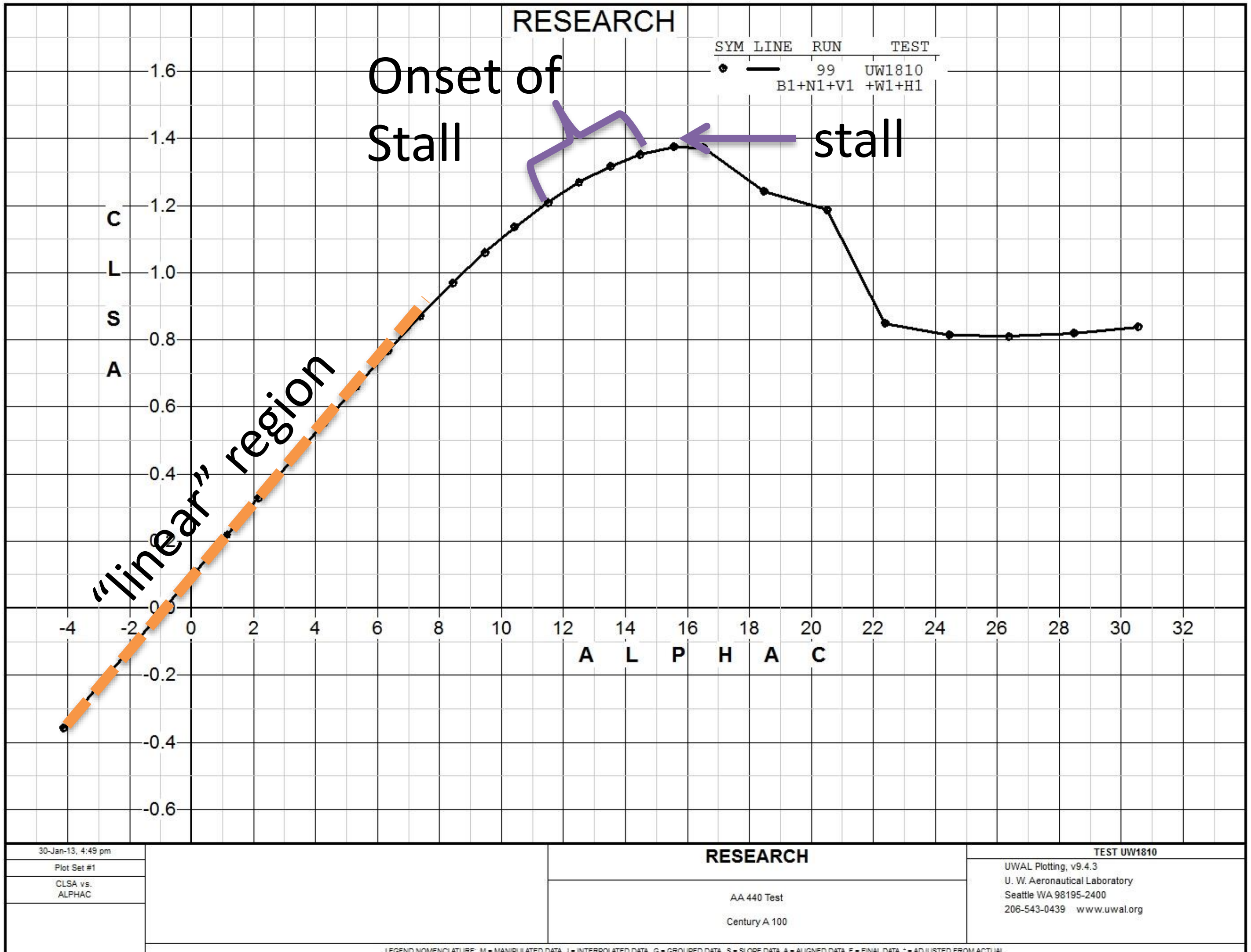
- Re important for low speed, M_∞ for high speed
- matching both M_∞ and Re in wind tunnel tests rather difficult

Typical Aerofoil Lift Characteristics (1)



$$C_L = a(\alpha - \alpha_0)$$

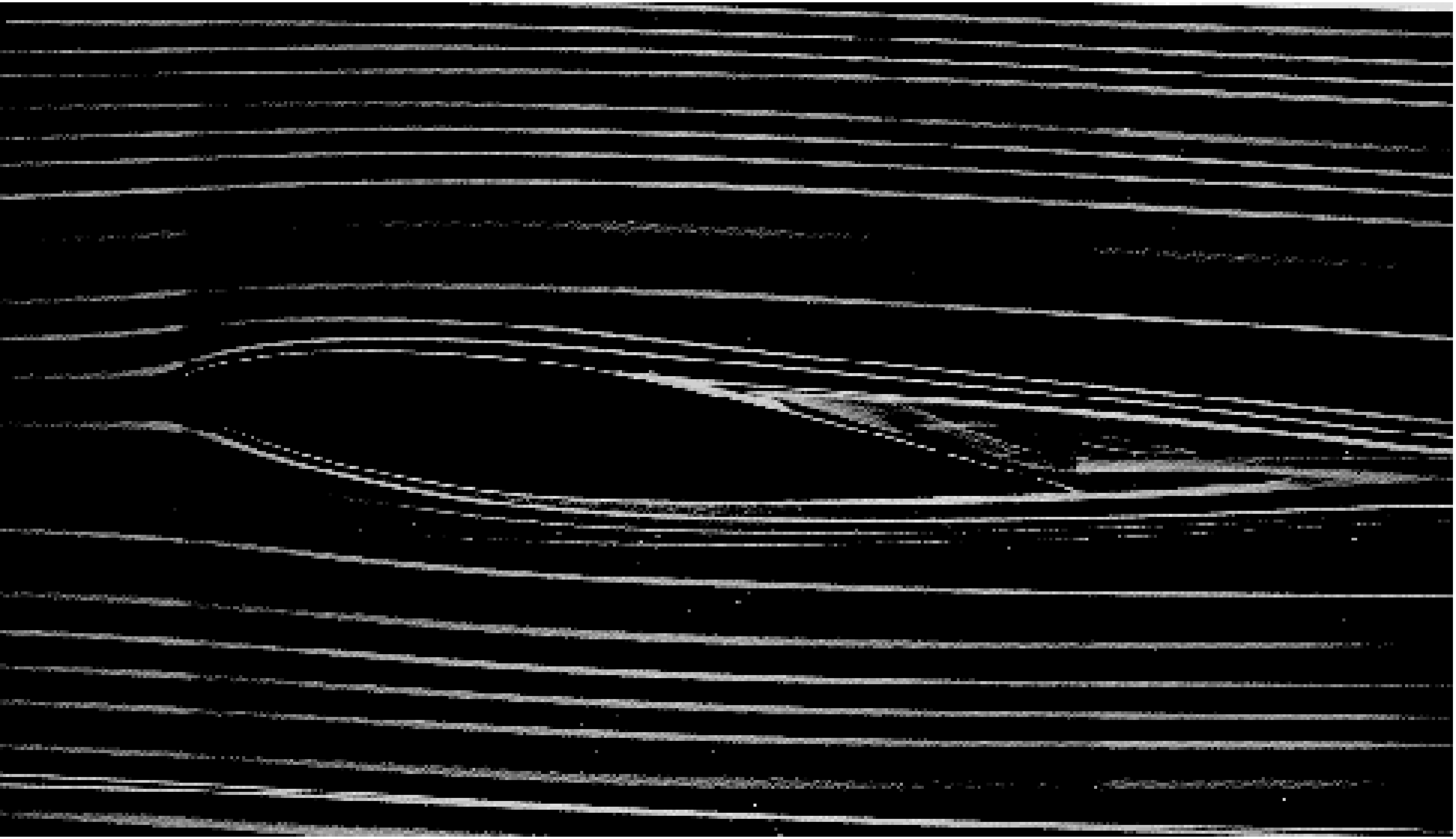
Lift Curve


RESEARCH
SYM LINE RUN TEST
99 UW1810
B1+N1+V1 +W1+H1
Onset of Stall
stall
"linear" region
CLSA
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.0
-0.2
-0.4
-0.6
-4 -2 0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
ALPHAC
30-Jan-13, 4:49 pm
Plot Set #1
CLSA vs. ALPHAC
RESEARCH
AA 440 Test
Century A 100
TEST UW1810
UWAL Plotting, v9.4.3
U. W. Aeronautical Laboratory
Seattle WA 98195-2400
206-543-0439 www.uwal.org
LEGEND NOMENCLATURE: M = MANIPULATED DATA, I = INTERPOLATED DATA, G = GROUPED DATA, S = SLOPE DATA, A = ALIGNED DATA, F = FINAL DATA, * = ADJUSTED FROM ACTUAL

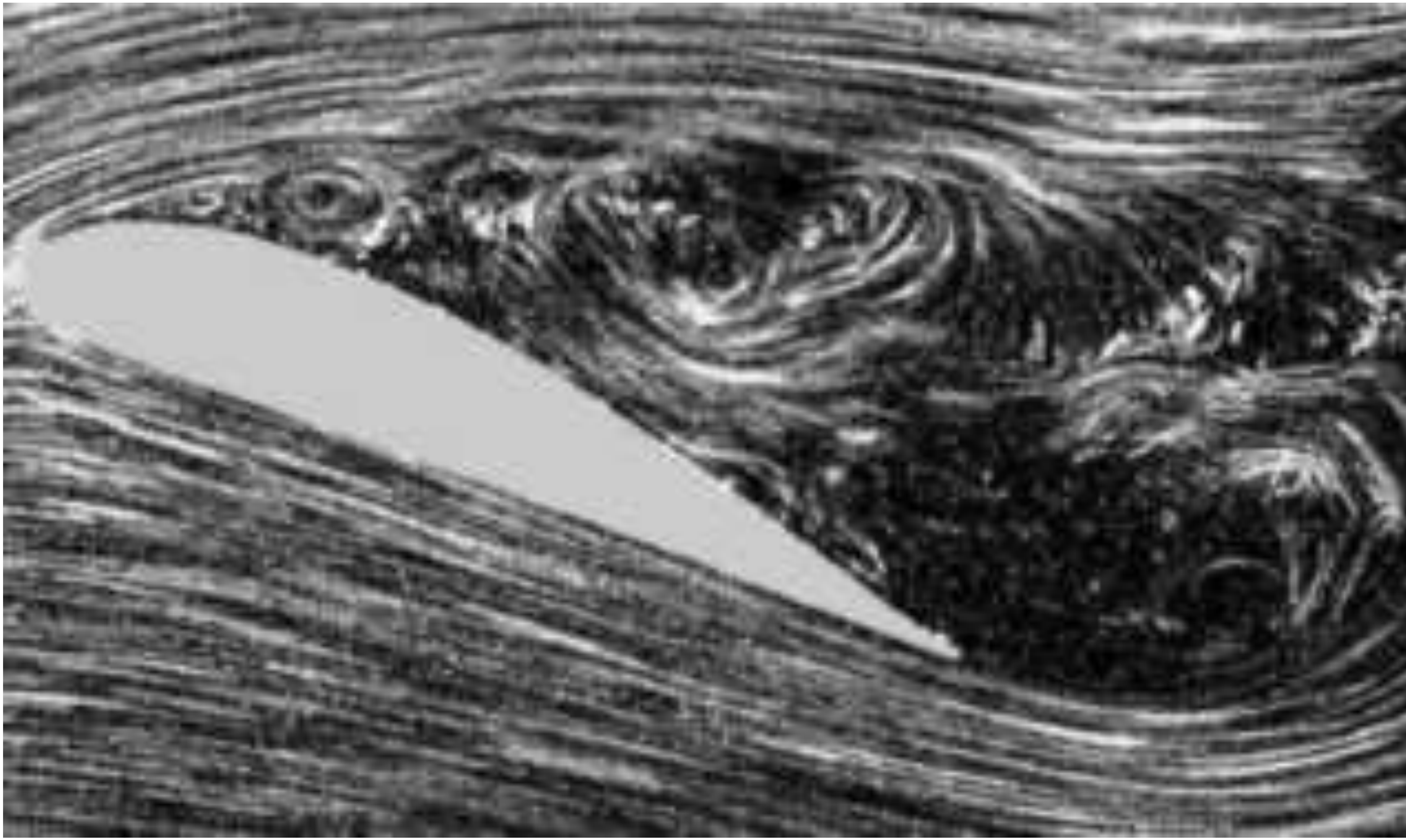
N.A.C.A.

Flow about the same airfoil section in the small smoke-tunnel at approximately one-sixth of the Reynolds Number of the flow shown previously

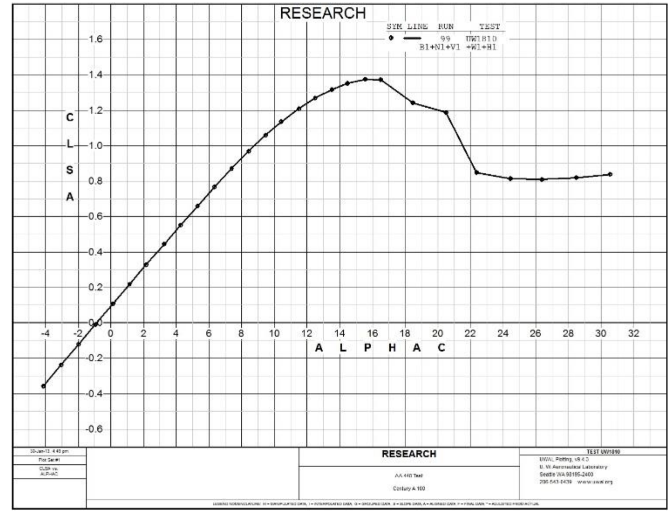
Onset of Stall



Stall



Let’s work through a problem together…



At cruise, an airplane weighs 3500kg
The wing area is 12 m^2
Speed is 600 km/hr
Altitude is 12,000 m (ρ = 0.31 kg/m^3)

What is the lift coefficient, C_L?
What angle of attack does it fly at?

Answer:

$$L = \tfrac{1}{2}\rho_\infty V_\infty^2 S C_L$$

L = W

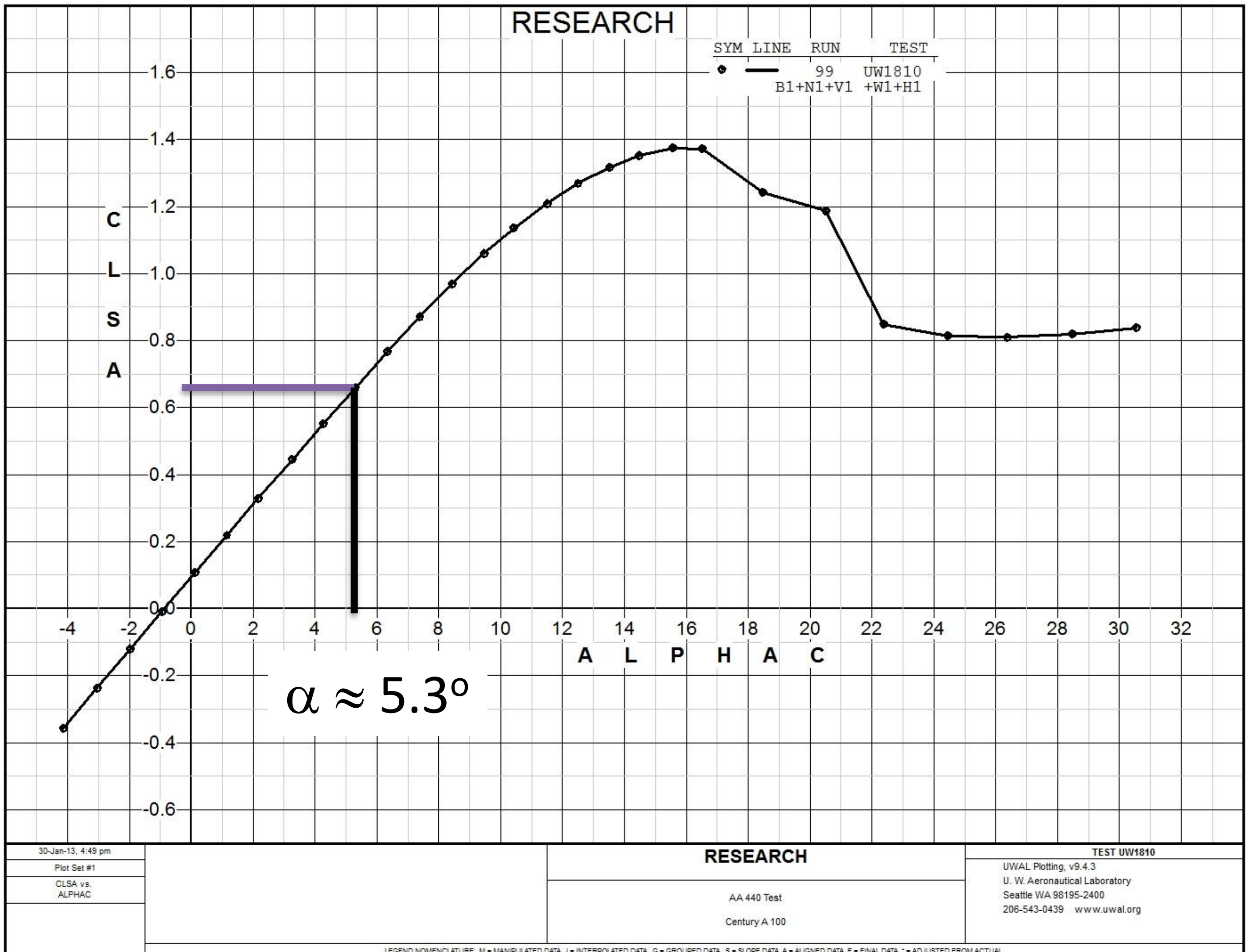
$$C_L = \frac{2W}{\rho S V^2}$$

$$= \frac{2 * 3500\text{kg} * 9.81\text{m}/s^2}{0.31\text{kg}/m^3 * 12m^2 * [600\text{km/hr} * 0.278\ (\text{km/hr} \rightarrow \text{m/s})]^2}$$

$$= 0.663$$

For angle of attack, we can use the lift graph…

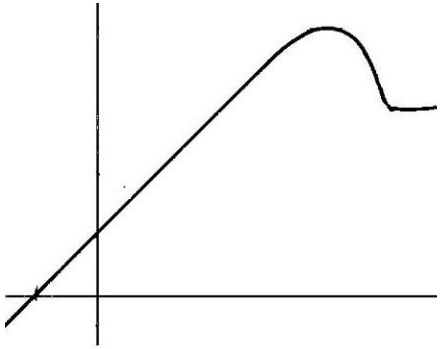
Lift Curve



RESEARCH
SYM LINE RUN TEST
99 UW1810
B1+N1+V1 +W1+H1
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
C
L
S
A
-4
-2
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
A L P H A C
α ≈ 5.3°
30-Jan-13, 4:49 pm
Plot Set #1
CLSA vs. ALPHAC
RESEARCH
AA 440 Test
Century A 100
TEST UW1810
UWAL Plotting, v9.4.3
U. W. Aeronautical Laboratory
Seattle WA 98195-2400
206-543-0439 www.uwal.org
LEGEND NOMENCLATURE: M = MANIPULATED DATA, I = INTERPOLATED DATA, G = GROUPED DATA, S = SLOPE DATA, A = ALIGNED DATA, F = FINAL DATA, * = ADJUSTED FROM ACTUAL

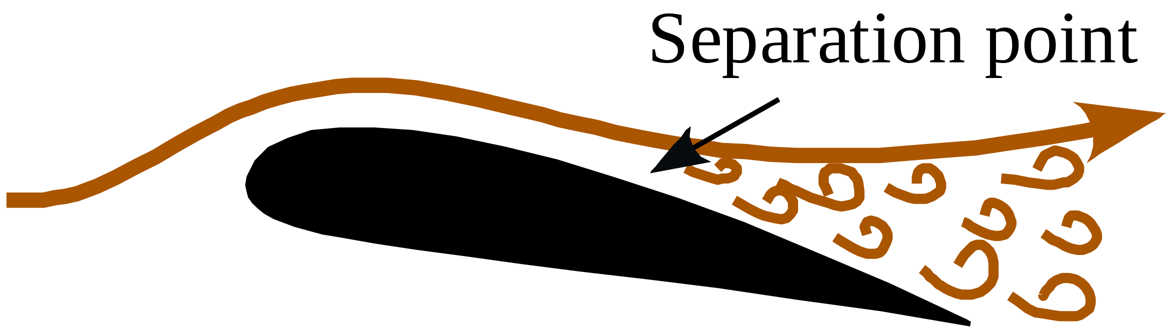
Typical Aerofoil Lift Characteristics (2)

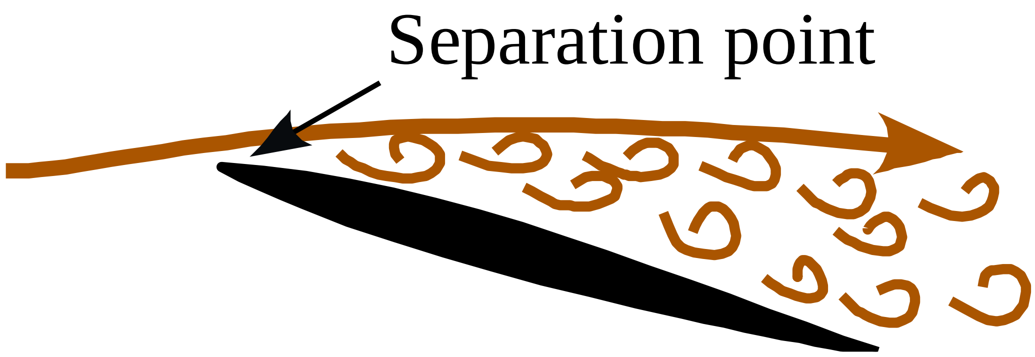
- aircraft usually operate in linear part of **lift-curve**
  - constant slope $dC_L/d\alpha$
  - lift-curve slope $a \approx 2\pi$ /rad (or ≈ 0.11/deg) for 2D aerofoil
  - slope less for 3D wing (*more later* …)
  - linear region extends into negative incidence range
- positive camber gives constant increment in lift
  - corresponds to negative **zero-lift incidence** α_0



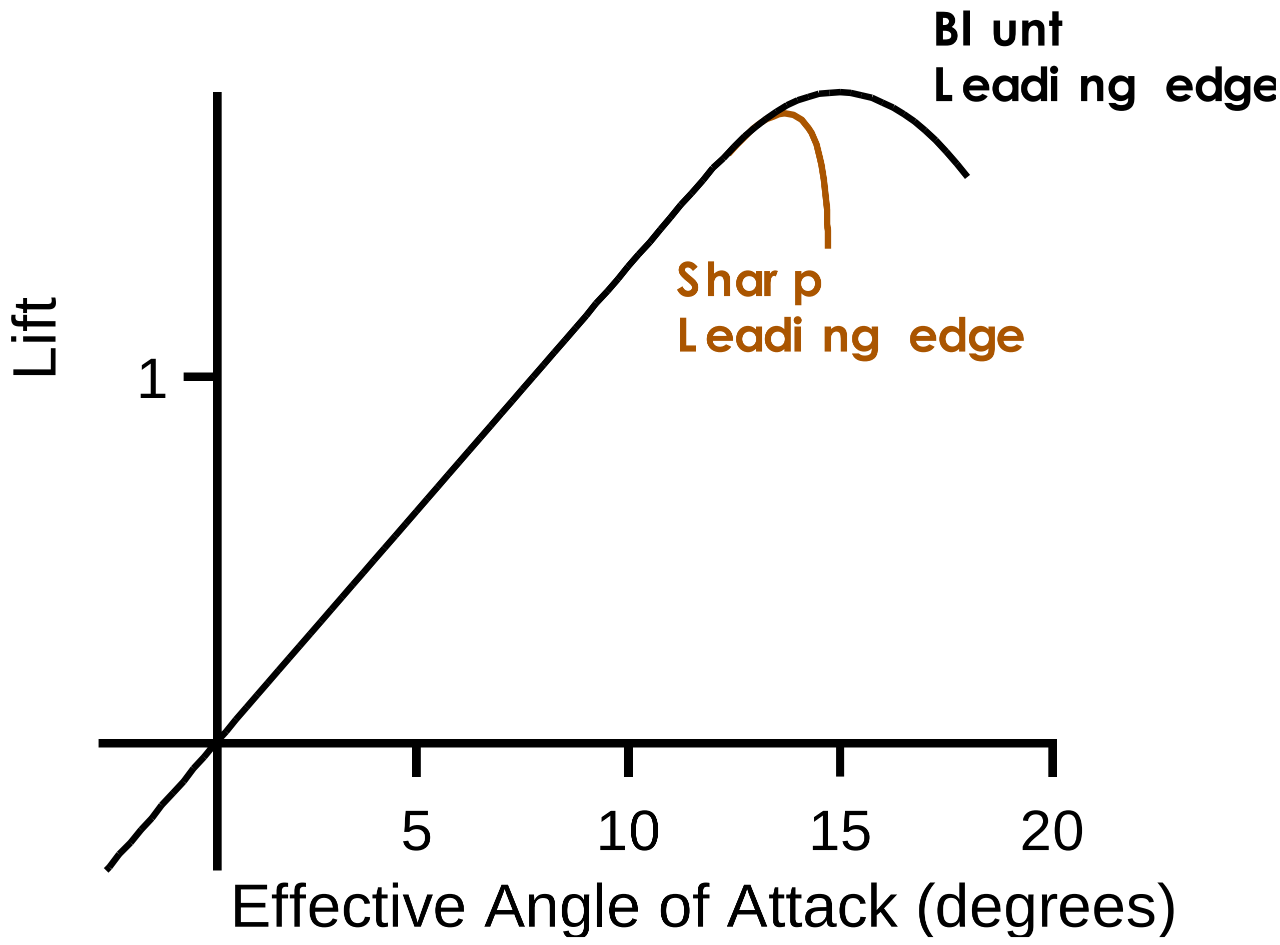
- maximum lift C_{Lmax} limited by **stall** onset
  - fundamental limit to **flight envelope**
  - due to occurrence of **flow separation**
- C_{Lmax} and post-stall lift loss very dependent on:
  - aerofoil section – ‘thick’ vs ‘thin’ governs type of separation
  - Reynolds Number – governs onset of separation
  - Mach Number – **shock**-induced separation at high speed

Stall

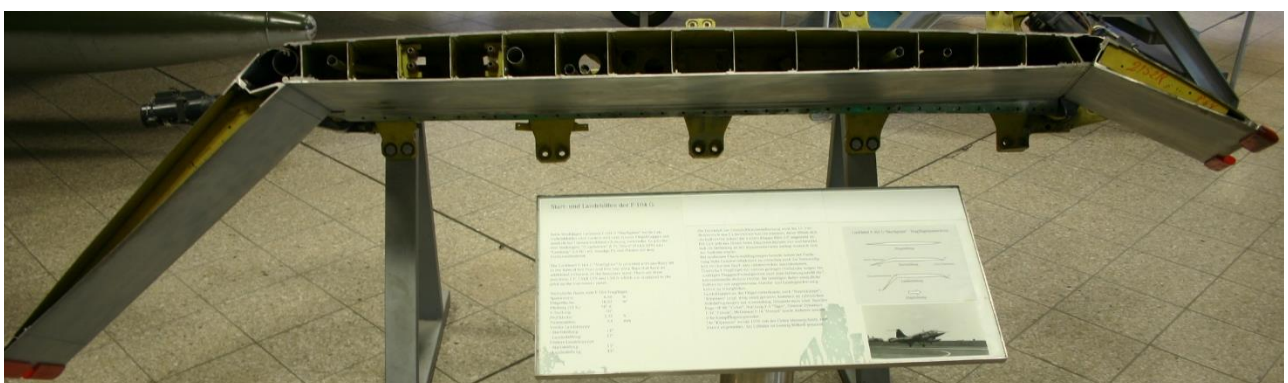




Stall Characteristics

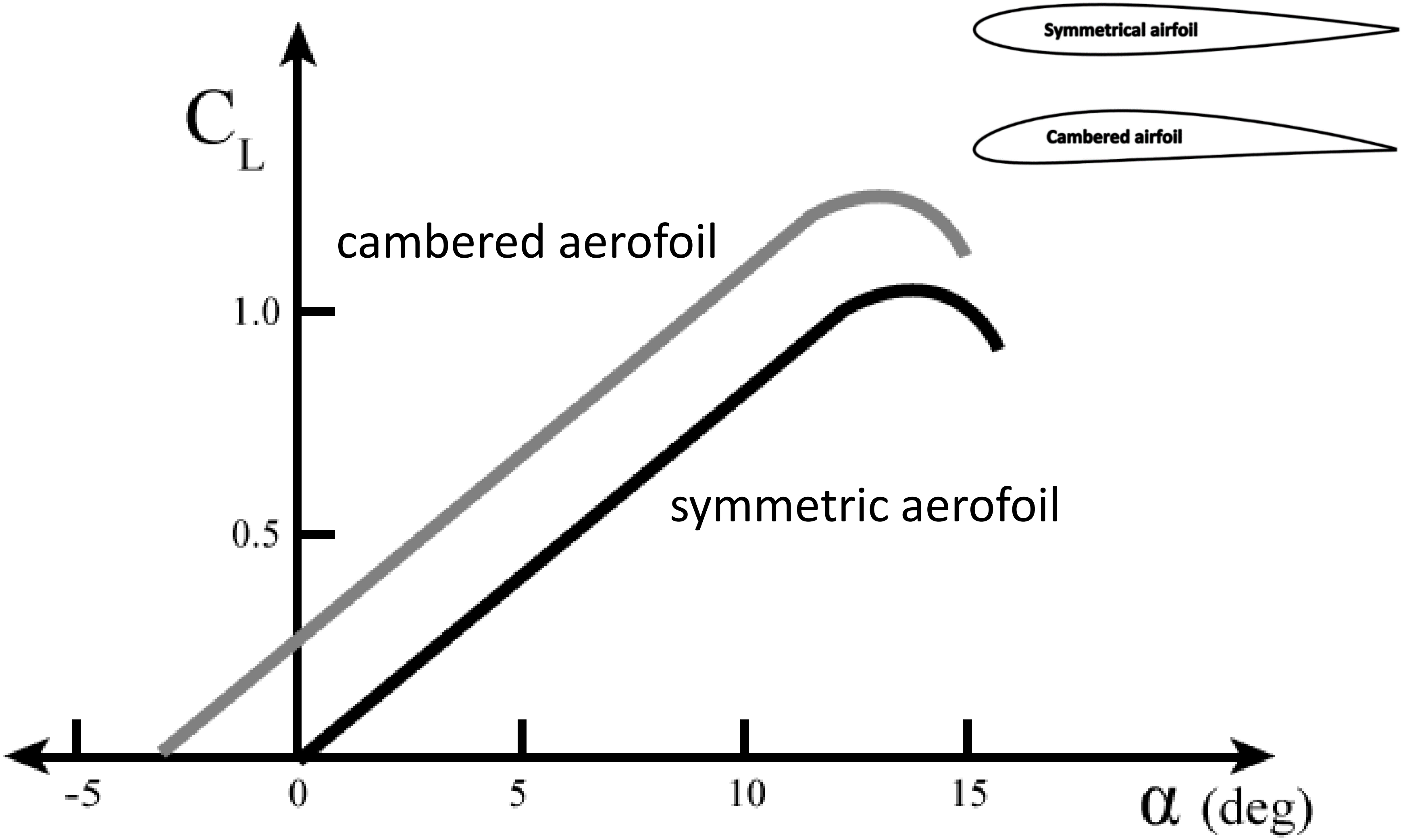


Sharp Aerofoil



Blunt Aerofoil

Effect of Camber



Note difference in **zero-lift angle of incidence** α_0

Reynolds Number

$$\boxed{Re = \frac{\rho V_\infty c}{\mu}}$$

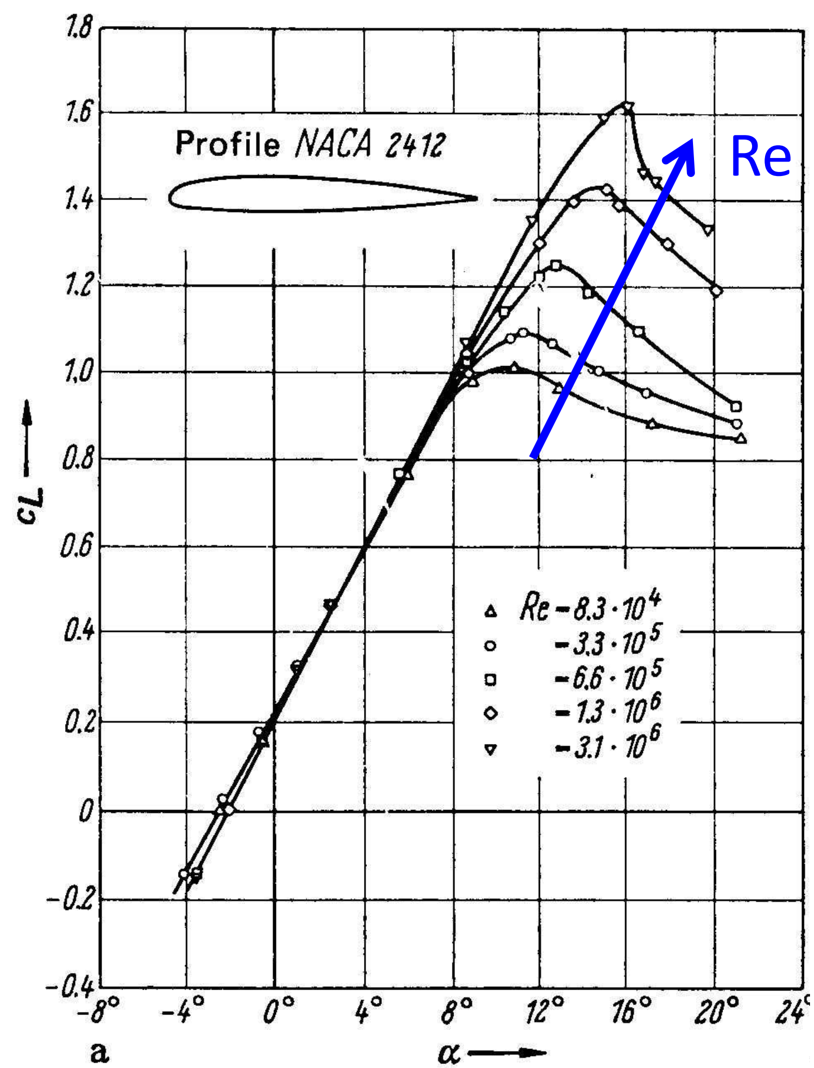
Relates inertial forces to viscous forces

747-400	2×10^8
PA-16	5×10^6
Eagle	1×10^5
House Fly	8,000

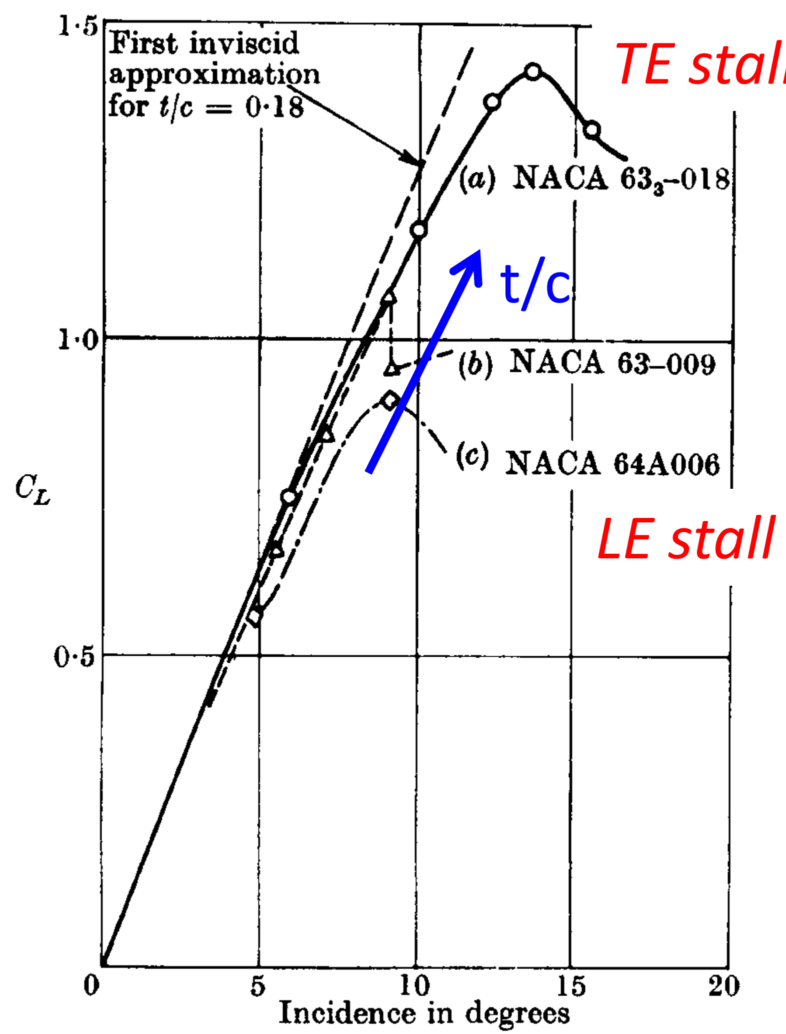
Where μ is dynamic viscosity and for air at sea level = 1.7894×10^{-5} kg/(ms)

Stall Characteristics

- Reynolds Number Re



- thickness (t/c)



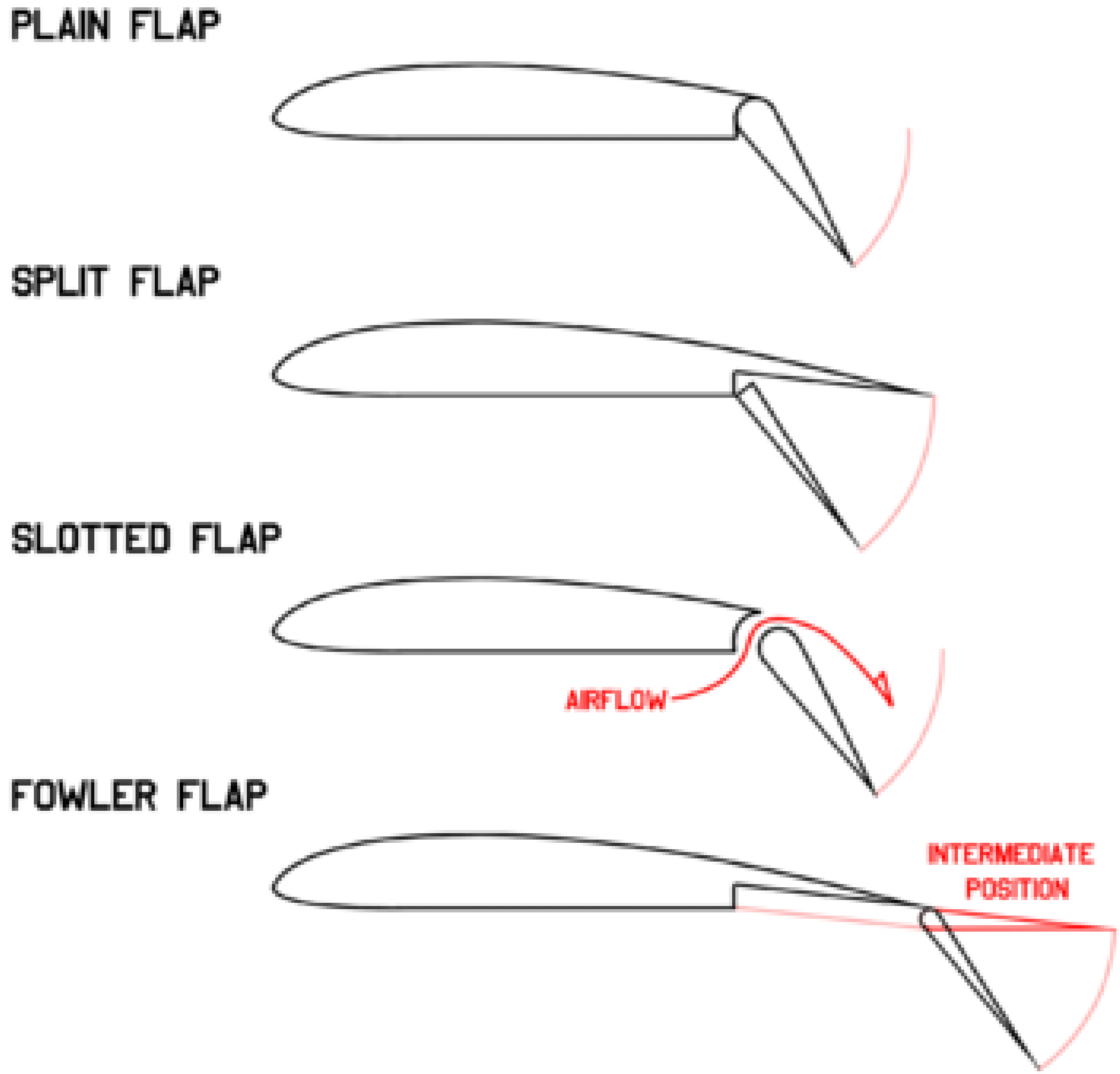
Why is C_{Lmax} Important ?

- the lift coefficient C_L required to support an aircraft of weight W varies with speed V
- for steady level flight

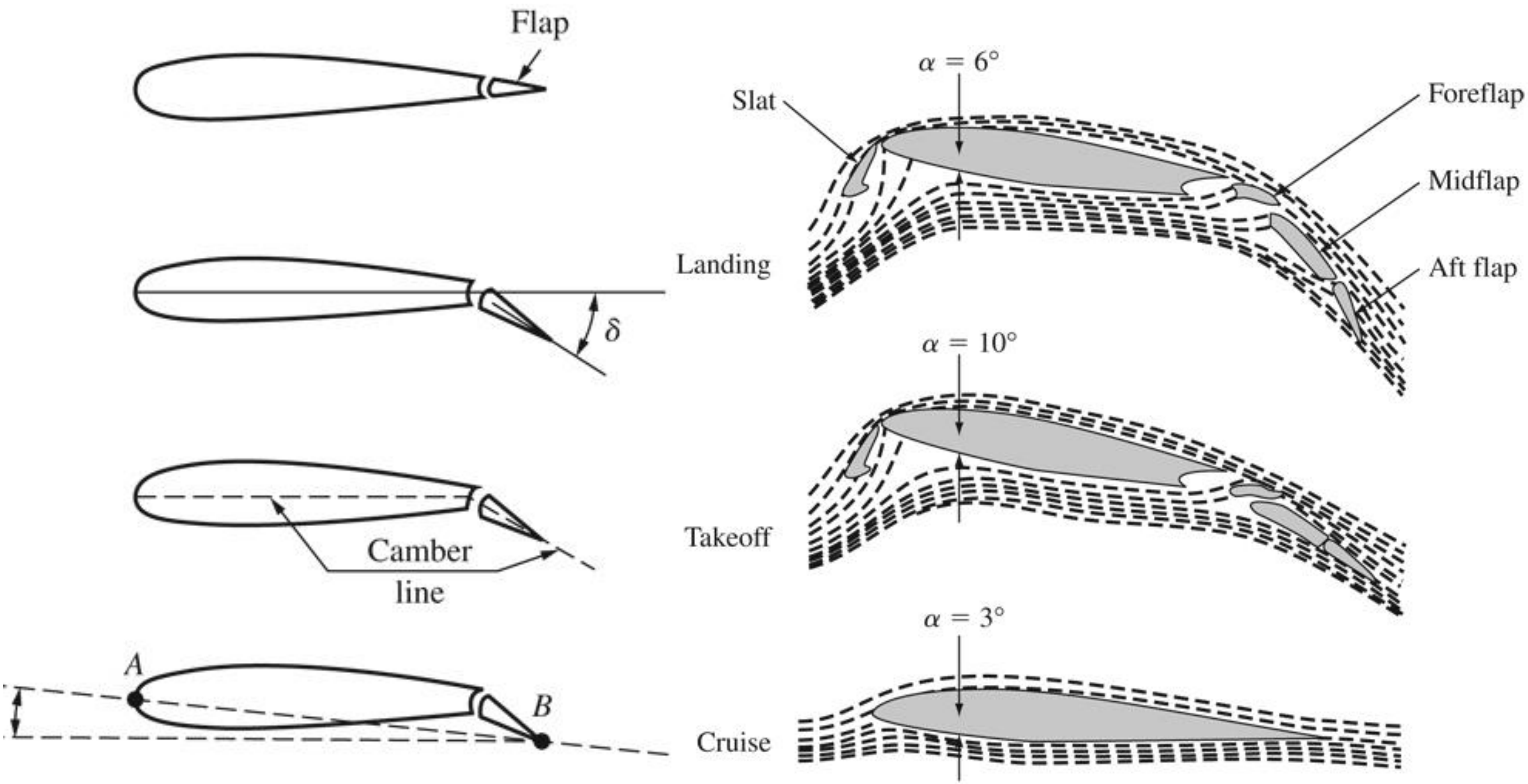
$$\boxed{W = L = \tfrac{1}{2}\rho V^2 S C_L} \Rightarrow \boxed{V = \sqrt{\frac{W}{\tfrac{1}{2}\rho S C_L}}}$$

- and hence minimum flight speed $V_{min} \propto 1/\sqrt{C_{Lmax}}$
- low minimum speed needed for take-off & landing
  - approach speed typically ~ $1.3V_{min}$
- cambered high lift aerofoils inefficient in cruise
  - need variable geometry – vast array of complex devices used
  - leading-edge devices and trailing-edge flaps

Flaps


PLAIN FLAP
SPLIT FLAP
SLOTTED FLAP
AIRFLOW
FOWLER FLAP
INTERMEDIATE
POSITION

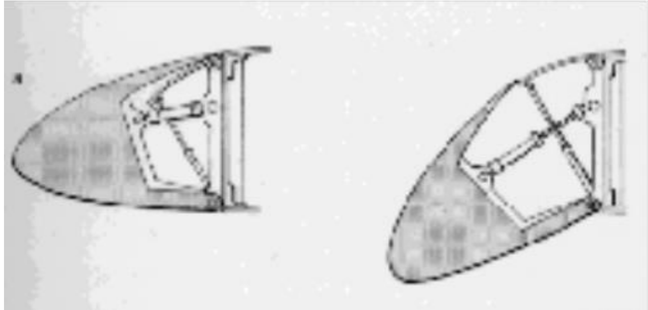
What do flaps do?

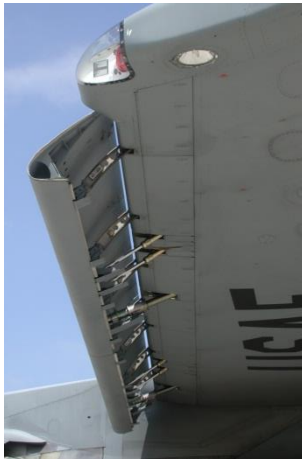


Increases camber and effective angle of attack, which increases lift

Leading Edge Devices

Drooped leading edge

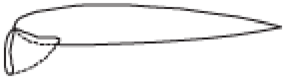




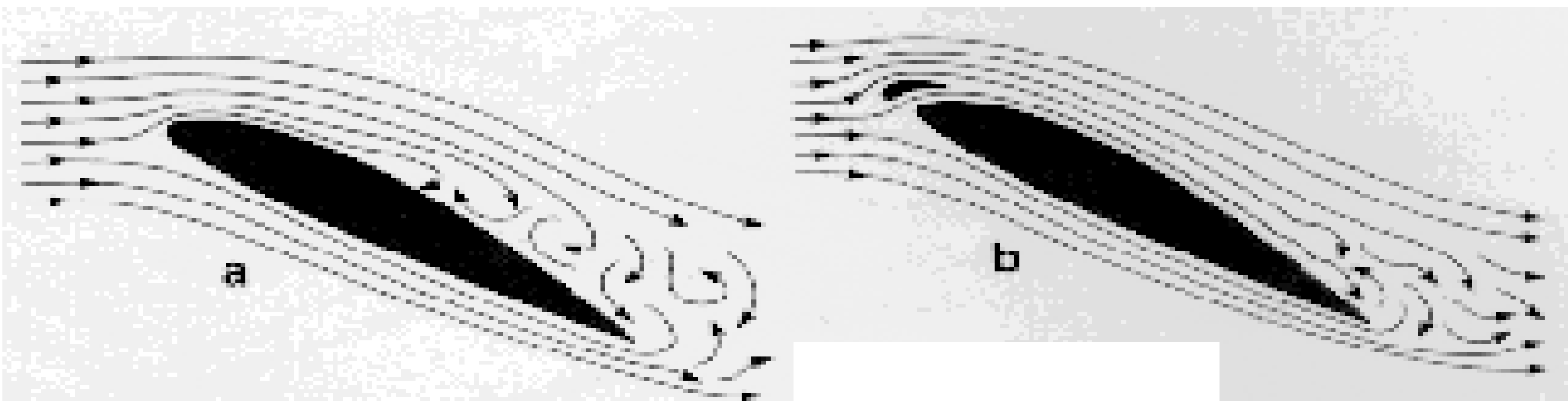
Slat

Slot

Krueger flap

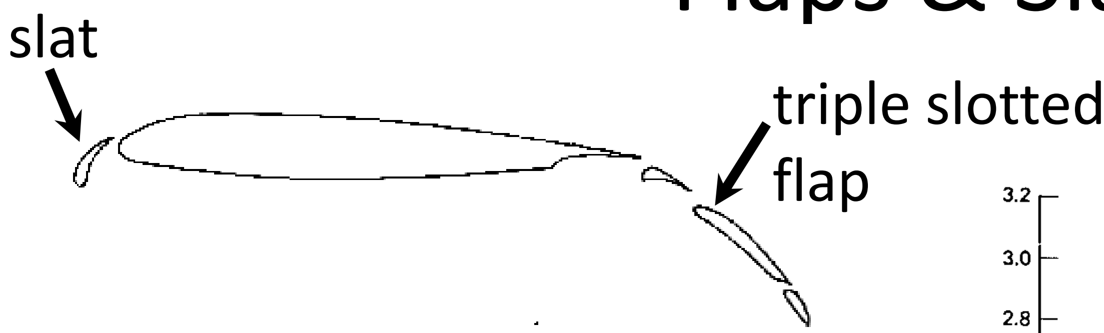


What do leading edge devices do?

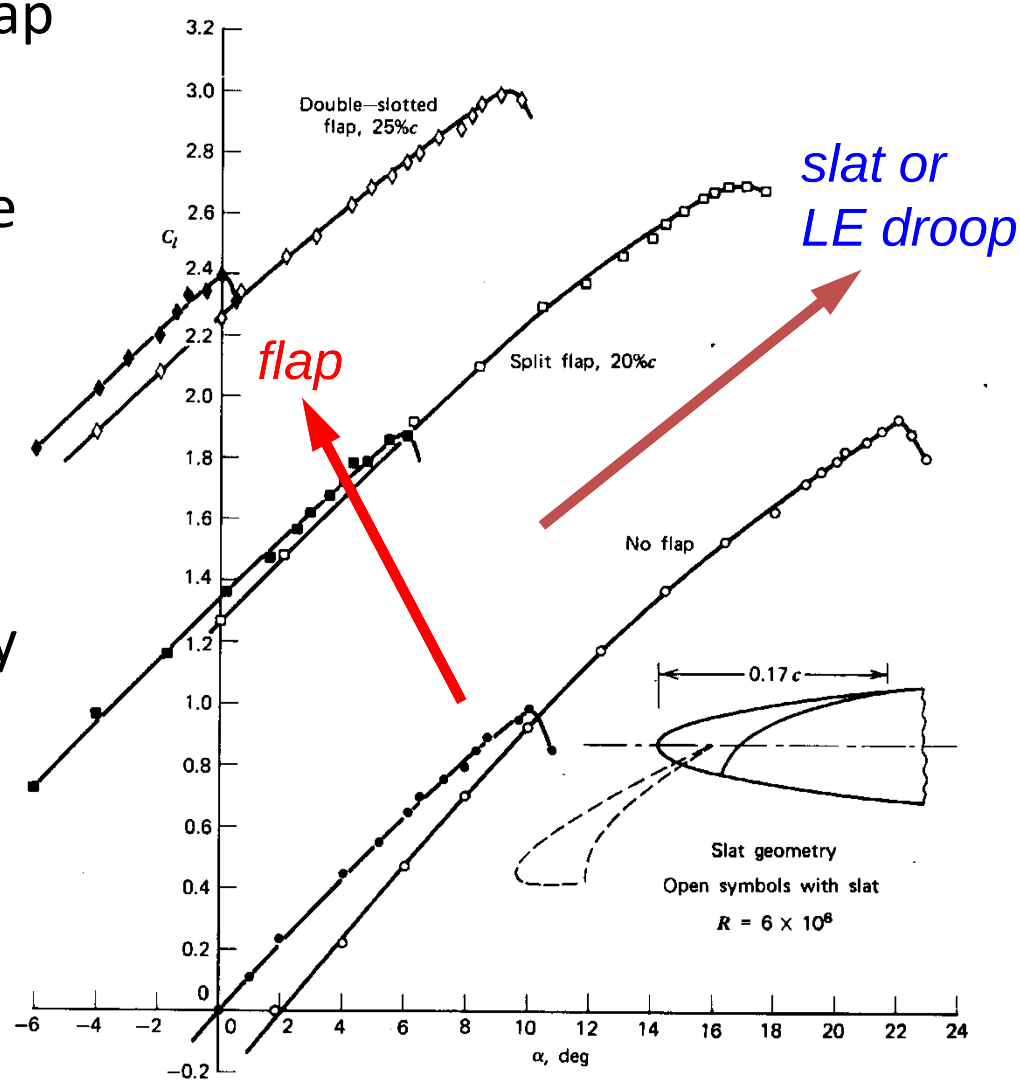


Increases angle at which stall occurs

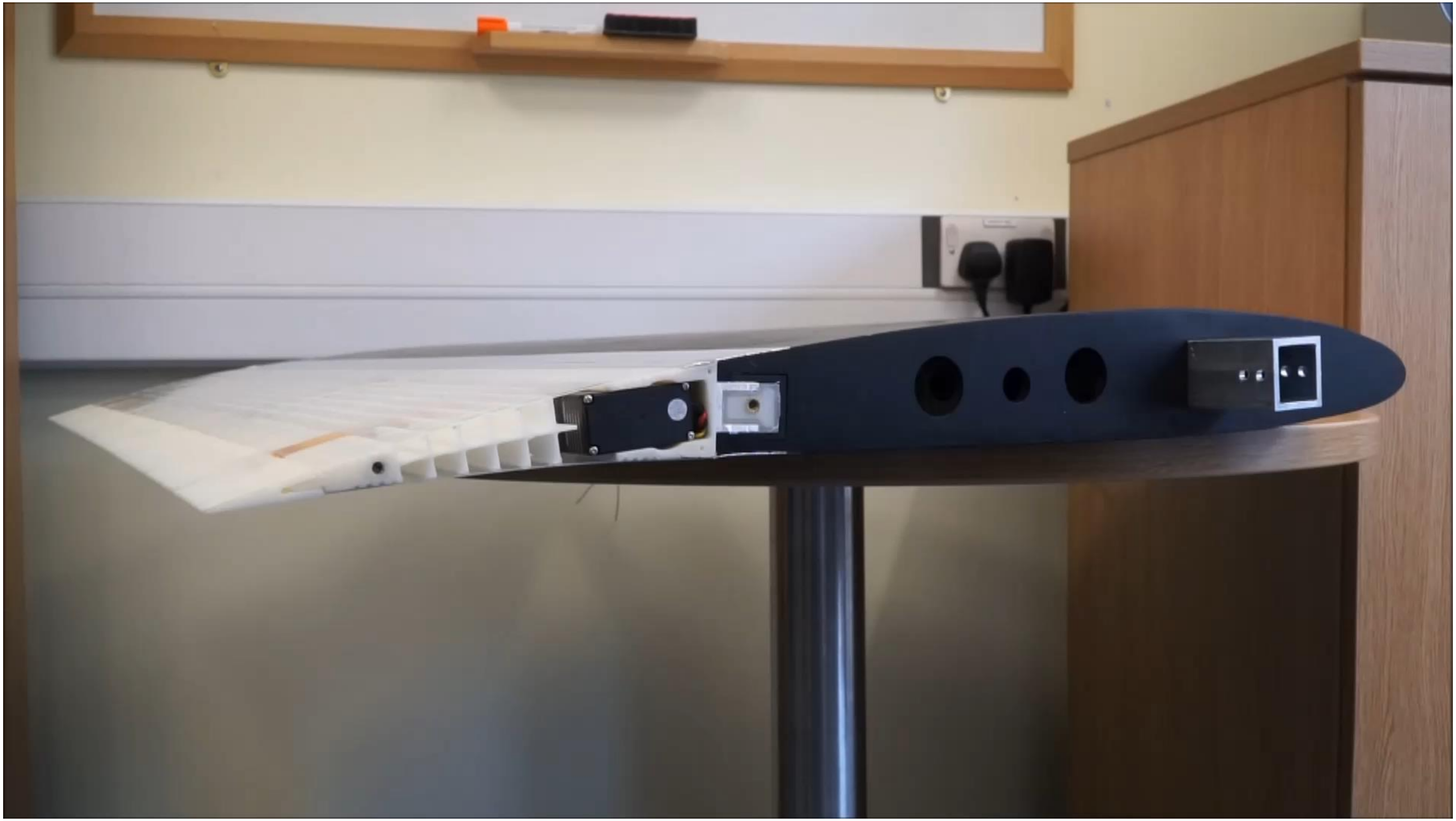
Flaps & Slats



- trailing-edge flaps increase camber
  - increased lift
  - lower stall angle
  - increased C_{Lmax}
- leading-edge devices delay onset of separation
  - reduced lift
  - much later stall
  - increased C_{Lmax}
- both increase drag



Is there a better way?!

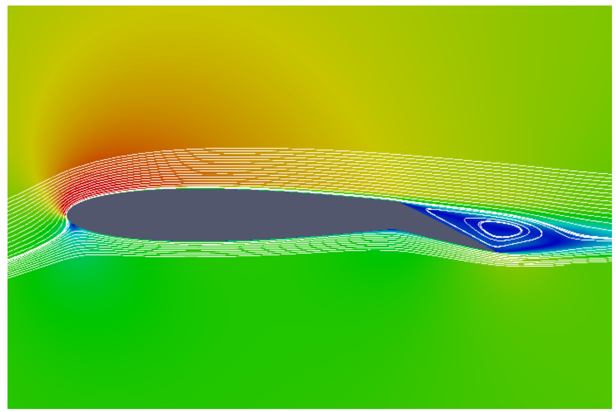


Fish Bone Active Camber morphing aerofoil
Tested here at UoB as part of a 4th year FYP

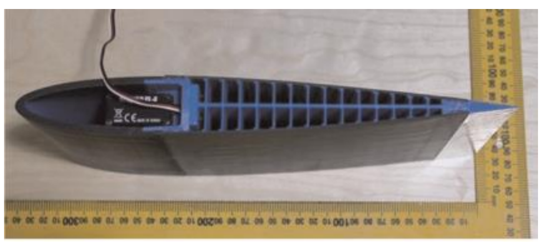
That drag though…

- While traditional flaps and slats are very effective and reliable, using them creates a significant drag penalty
- What if we could do the same thing, but more *efficiently*?

=



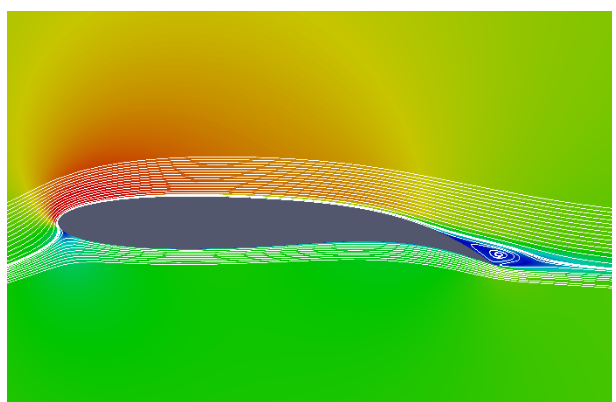
CFD results

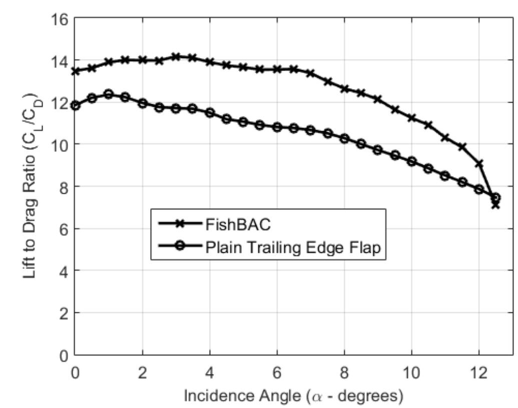


(a)

FishBAC

=





Wind tunnel data shows the FishBAC provides a 20-25% increase in C_L/C_D

Summary

- Lift coefficient determined by:
  - Shape
  - Angle of attack
  - Reynolds number
  - Mach number

$$Re = \frac{\rho V_\infty c}{\mu}$$

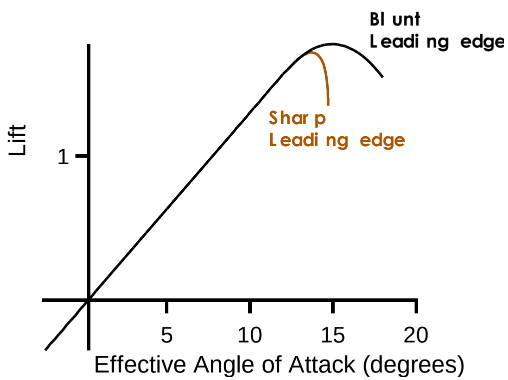
$$C_L = a(\alpha - \alpha_0)$$

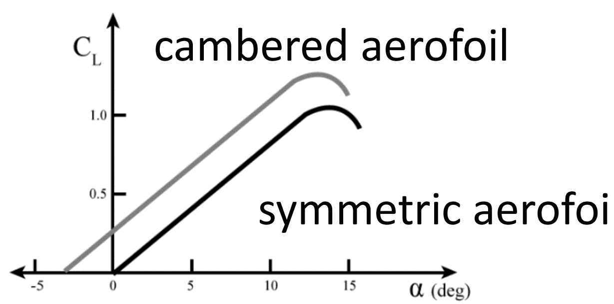
$$C_L = \frac{L}{\frac{1}{2}\rho_\infty V_\infty^2 S}$$

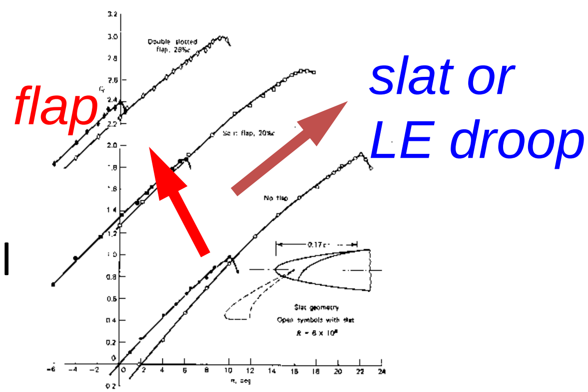
$$C_D = \frac{D}{\frac{1}{2}\rho_\infty V_\infty^2 S}$$

$$C_M = \frac{M}{\frac{1}{2}\rho_\infty V_\infty^2 Sc}$$

- Lift curve effected by: wing thickness, chamber, + high lift devices





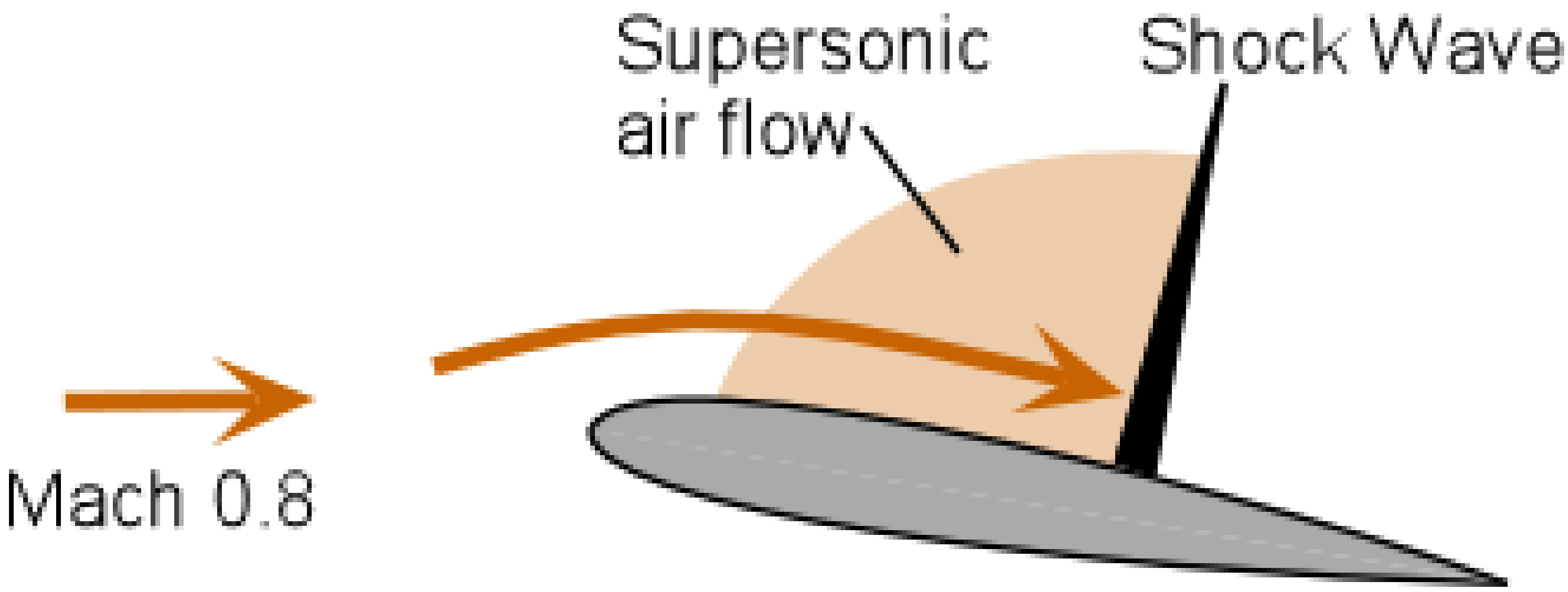


Follow-up materials

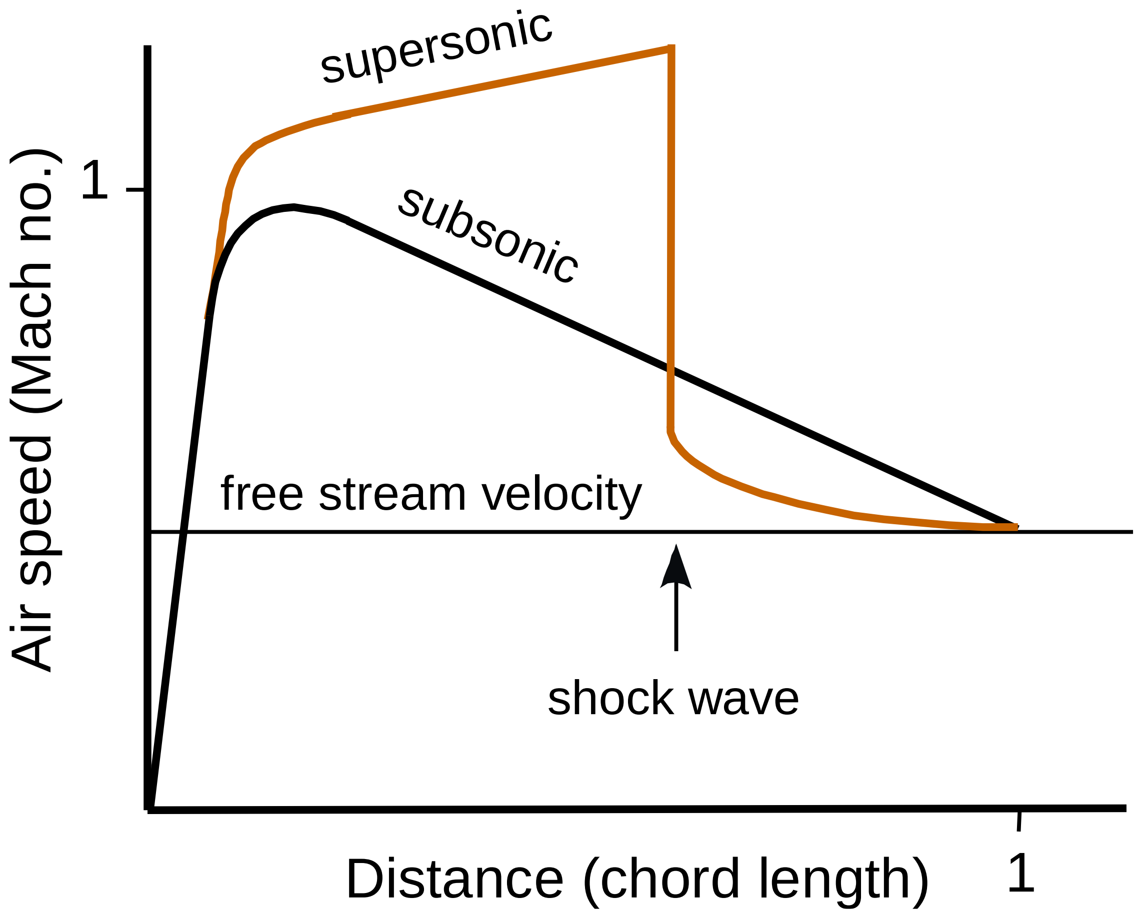
To help with exam:

- Introduction to Flight – 5.3-5.4

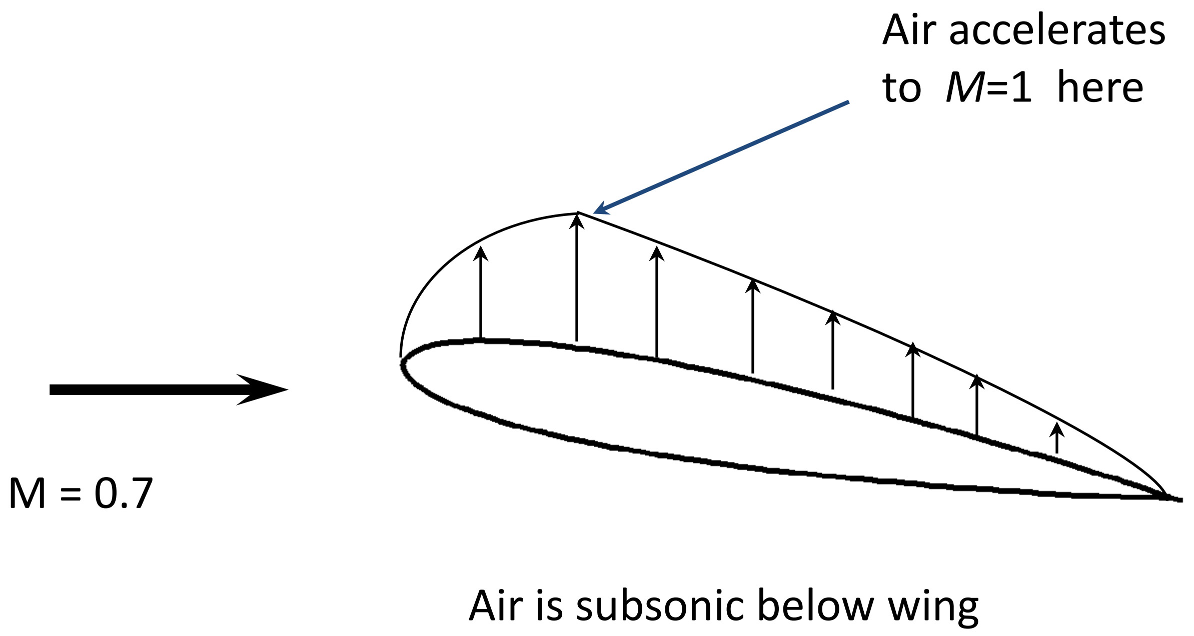
Airfoil at Mach 0.8



Different pressure distributions

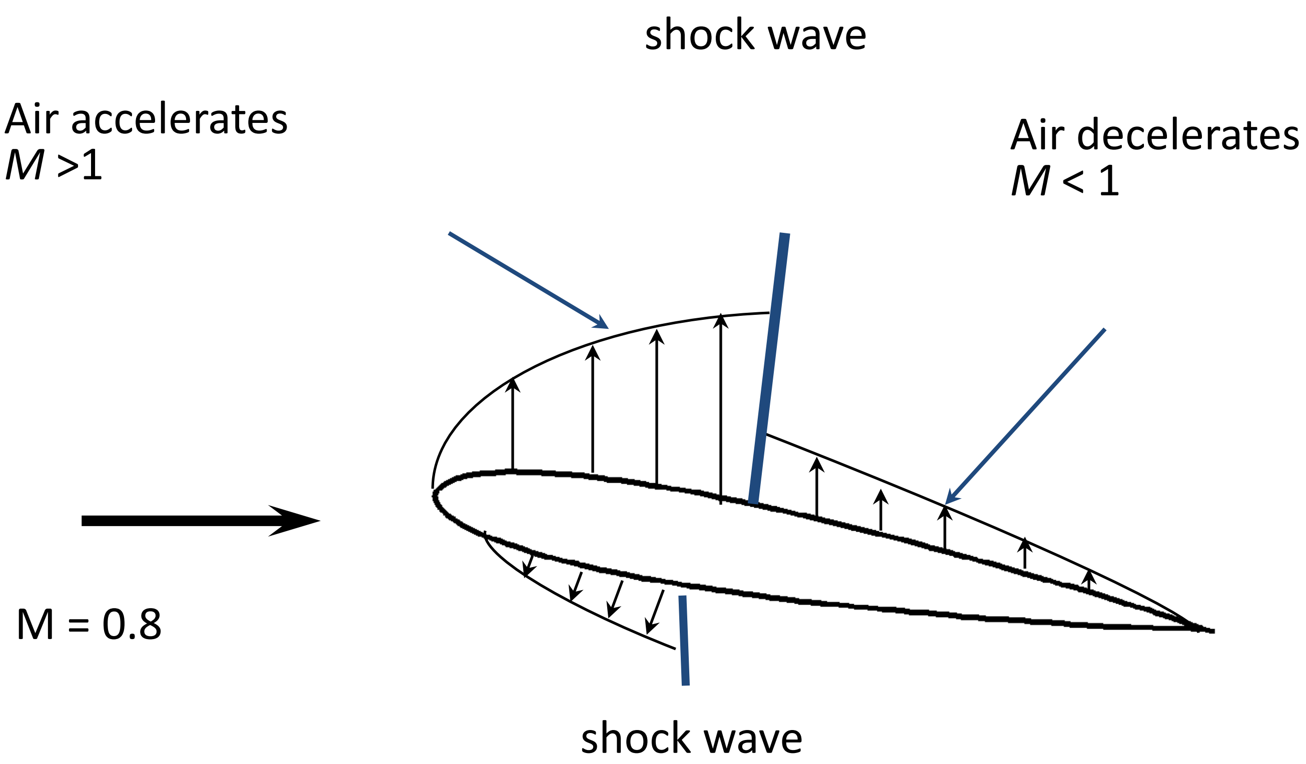


Airfoil at Critical Mach



In this example the critical Mach number is 0.7

Airfoil above Critical Mach

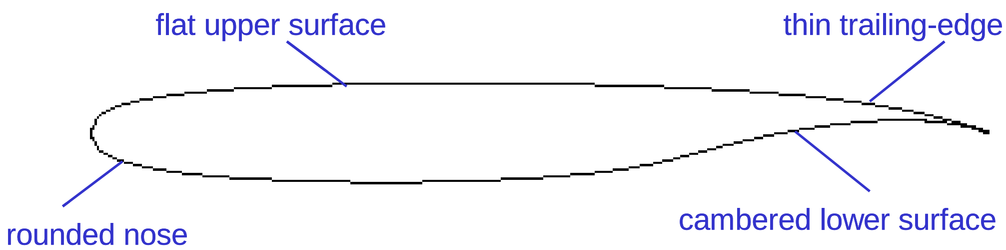


F-4 Phantom


The Military Aircraft Archive:
http://www.milair.simplenet.com

Supercritical Airfoils

- significant lower surface curvature



- rather similar to modern laminar flow sections
  - good structural shape!