Airfoil Selection

Aerospace Design

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Laminar vs Turbulent Flow

- Large scale aircraft at high speeds
  - Laminar flow is good, less drag than turbulent flow
  - ***Turbulent airfoils*** vs newer ***laminar airfoils***
- Smaller aircraft at lower speeds (UAVs)
  - Laminar flow is still good but can cause problems like ***laminar separation***
- Most airfoils experience both laminar and turbulent flow along their surface
- Three distinct types of flow in an airfoils ***boundary layer***
  - Laminar
  - Transitional
  - Turbulent

Laminar vs Turbulent Flow

- Reynolds Number

- Ratio of inertial and viscous forces

$$\mathrm{Re} = \frac{\rho V L}{\mu}$$

ρ, density
V, free stream velocity
L, characteristic length
μ, dynamic viscosity

- Two types of Re when talking about airfoils
  - ***Local Reynolds*** – the Reynolds number is a function of distance travelled over the airfoil, i.e. Re_{local} will be 0 at leading edge, maximum at trailing edge
  - ***Airfoil Reynolds*** – global Reynolds number for airfoil based on chord length, i.e. characteristic length

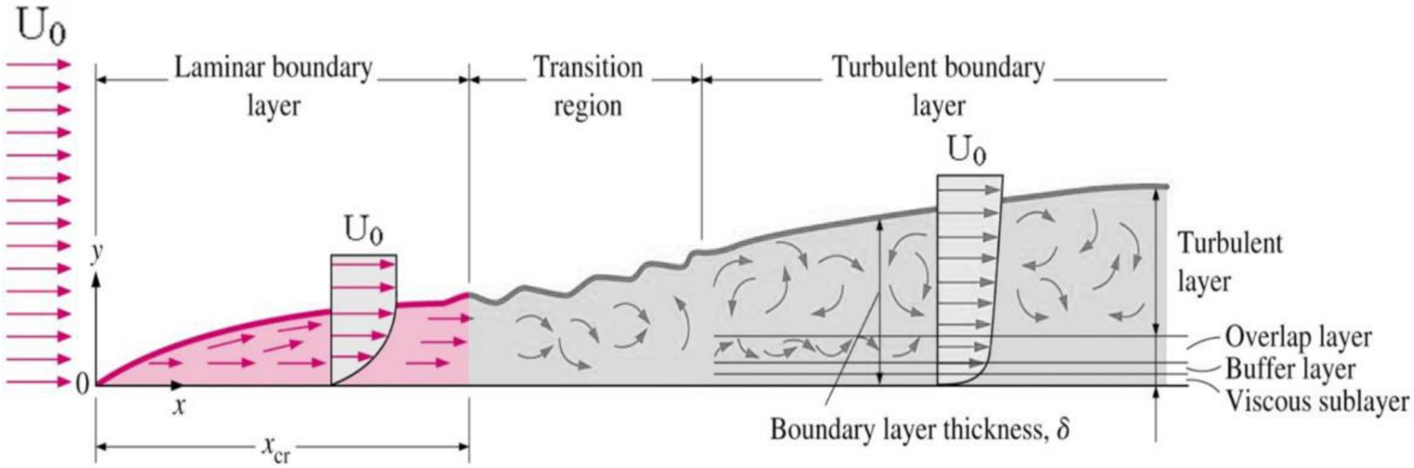
Laminar vs Turbulent Flow

- Typical Re values

Aircraft Type	Reynolds Number
Commercial aircraft	10,000,000 upwards
Light aeroplane	1,000,000 upwards
Sailplane at maximum speed	5,000,000 (wing root) 500,000 (wing tip)
Pylon racing model aeroplane at maximum speed	1,000,000 (wing root) 500,000 (wing tip)
Hang gliders, man-powered aircraft, ultra light aeroplanes	600,000 (wing root) 200,000 (wing tip)
Multi-task R.C. sailplanes (in speed task)	400,000
Multi-task R.C. sailplanes (when soaring)	100,000
Large model sailplanes (thermal soaring)	100,000
Large model sailplanes (penetrating)	250,000
A-1, A-2 sailplanes, Wakefields, Coupe d'Hiver, {etc.}	80,000 (maximum) 30,000 (minimum)
Indoor models, {peanut} scale, {etc.}	10,000

- Laminar Flow

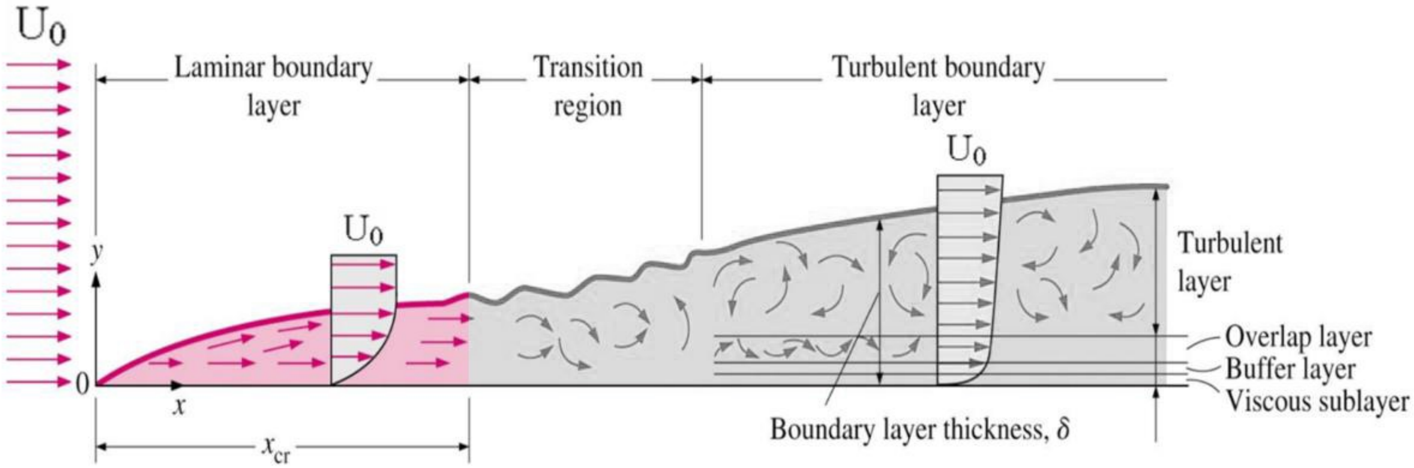
- Viscous forces outweigh inertial effects, ***low Reynolds***
- Layers of lamina of flow slide smoothly over one another
- Boundary layer tends to be thin, ***less form drag***
- Gradual increase in velocity means slow flow near surface



Laminar vs Turbulent Flow

- Laminar Flow

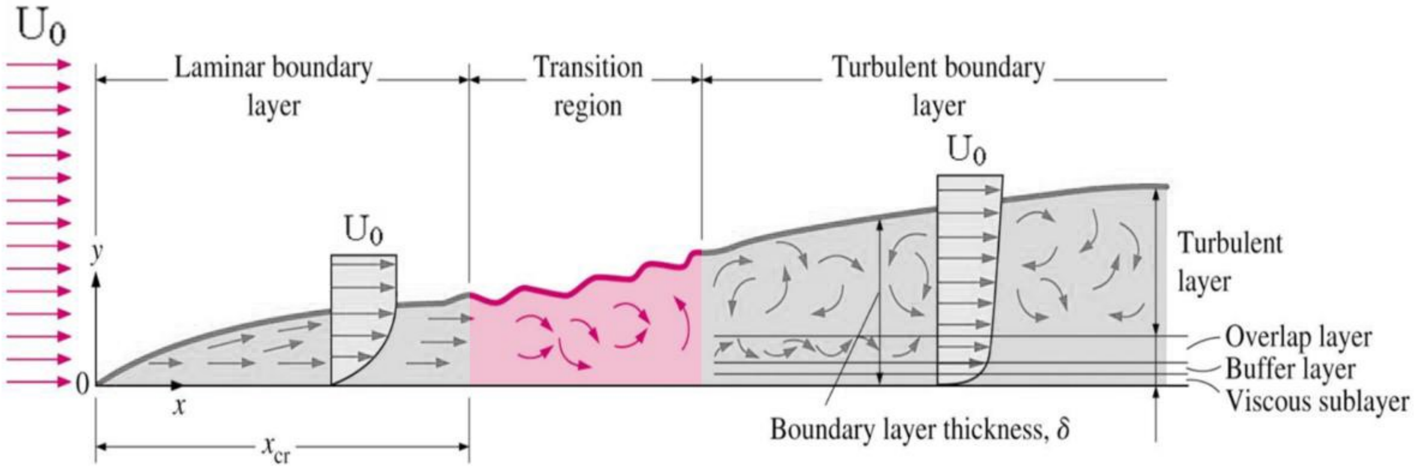
- Slow, smooth movement near surface means low friction (less energy dissipated as heat)
- However, smooth laminar flow means less traction and less velocity passed to lower layers from free stream
- ***Slow lower layers can easily come to stop***



Laminar vs Turbulent Flow

- Transition

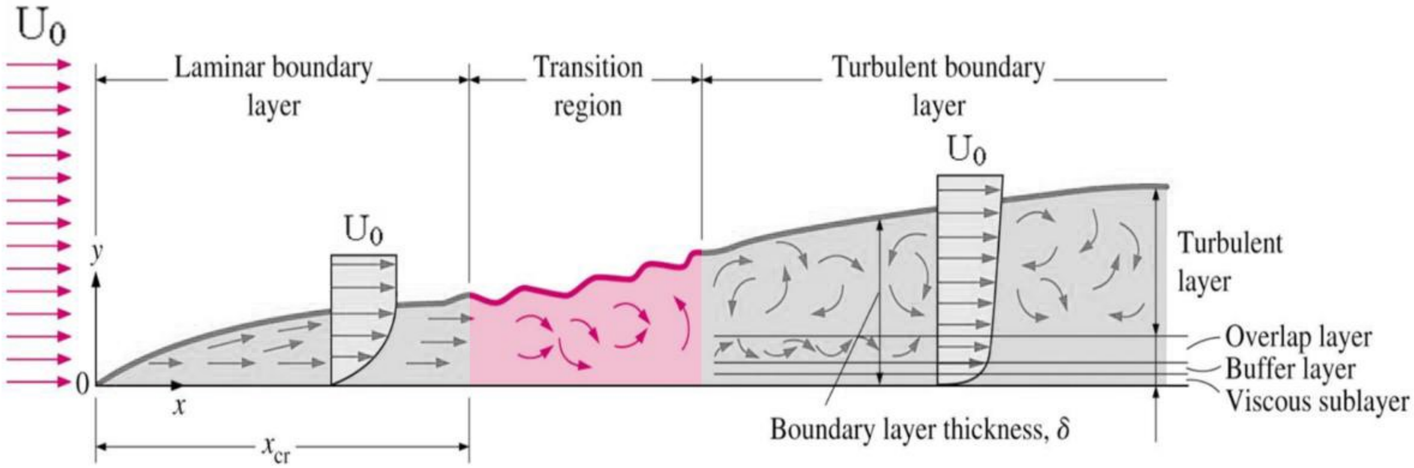
- Initially, small bumps disturb laminar boundary layer but large viscous effects overcome this
- As flow travels along skin local Reynolds goes up
- At some point small disturbances no longer damp out and boundary layer starts to transition to turbulent



Laminar vs Turbulent Flow

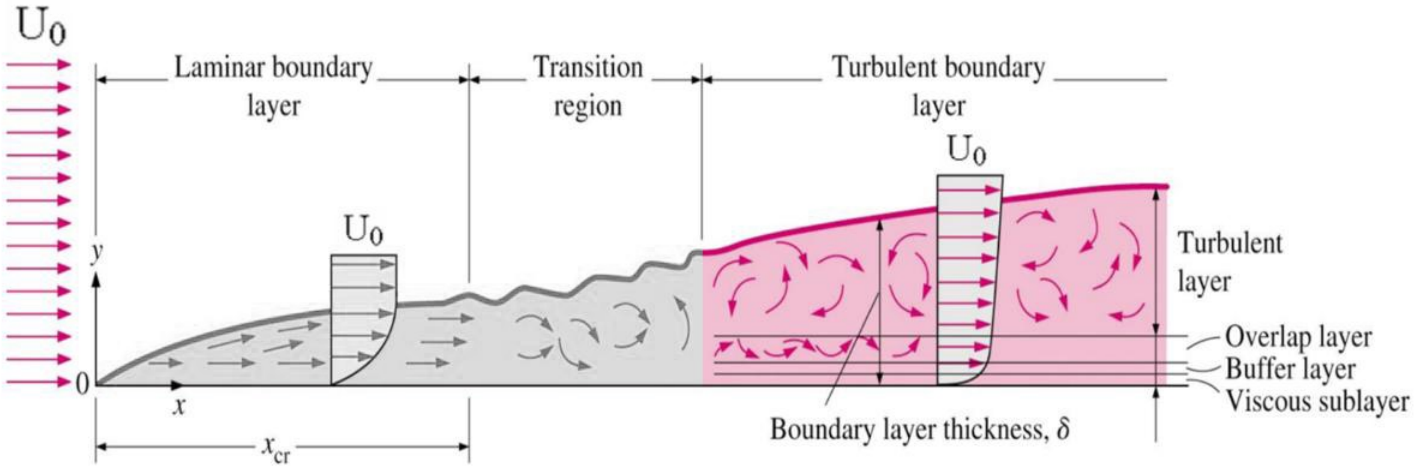
- Transition

- These effects can be delayed in one of two ways
  - Very smooth surface finish
  - Favorable pressure gradient accelerating flow in stream wise direction



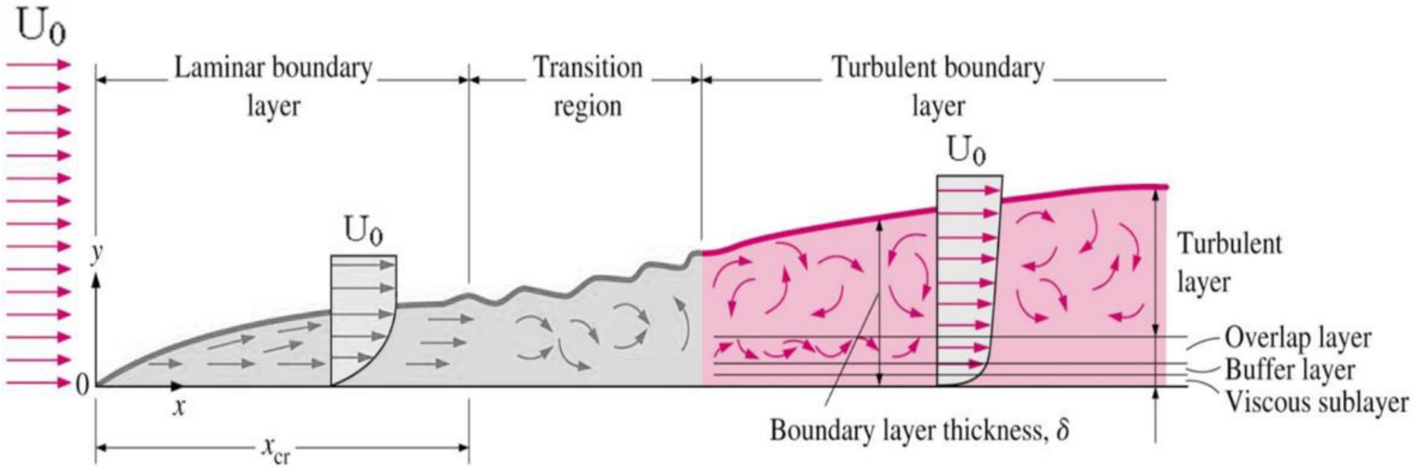
- Turbulent Flow

- No smooth lamina, particles move up and down in boundary layer
- Energy gets dissipated and therefore more friction is created
- Boundary layer tends to be thicker causing more profile drag

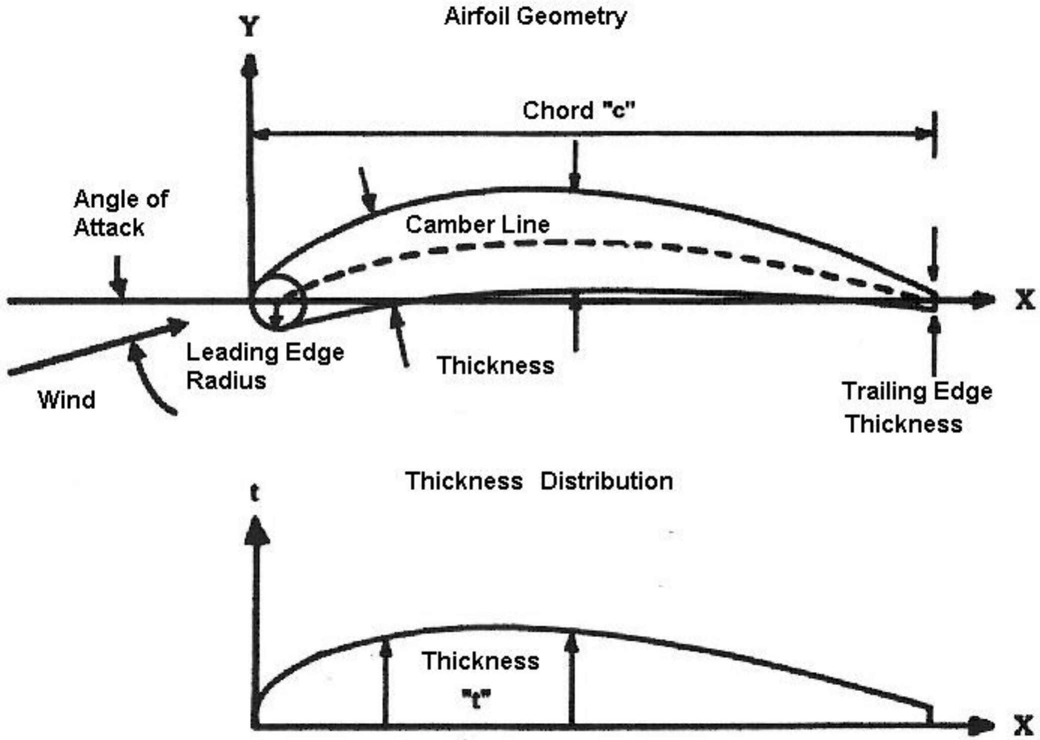


- Turbulent Flow

- However, mixing causes more traction and therefore more velocity is passed into lower layers
- ***Lower layers have higher velocity and are less likely to stop***



- Airfoil Geometry



- Parasite drag is affected by the thickness distribution
- Lift, pressure drag and induced drag is affected by the camber line

- Section Aerodynamic Coefficients

$$c_l = \frac{l}{qc}$$

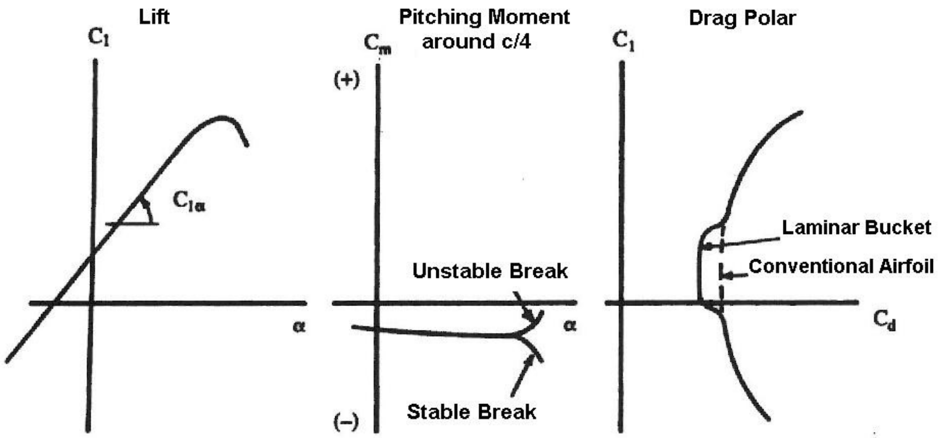
$$c_d = \frac{d}{qc}$$

$$c_m = \frac{m}{qc^2}$$

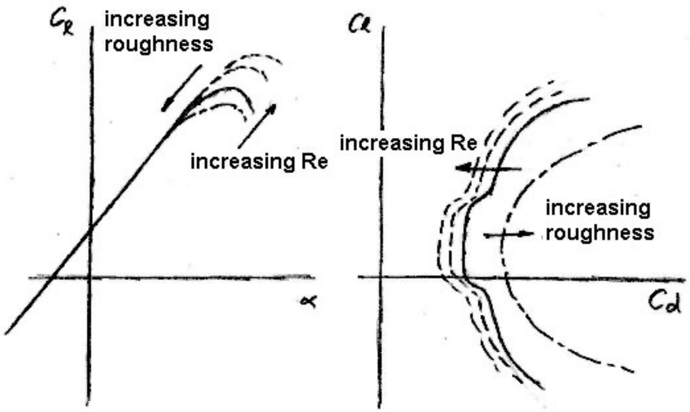
c_l, section lift coefficient
l, lift force per unit span
c_d, section drag coefficient
d, drag force per unit span
c_m, section pitch moment coefficient
m, pitch moment per unit span
c, section chord
$q = \frac{1}{2}\rho V^2$, dynamic pressure

- c_m is usually defined about the quarter chord for subsonic flows and about the mid chord for supersonic flows

- Section Aerodynamic Coefficients

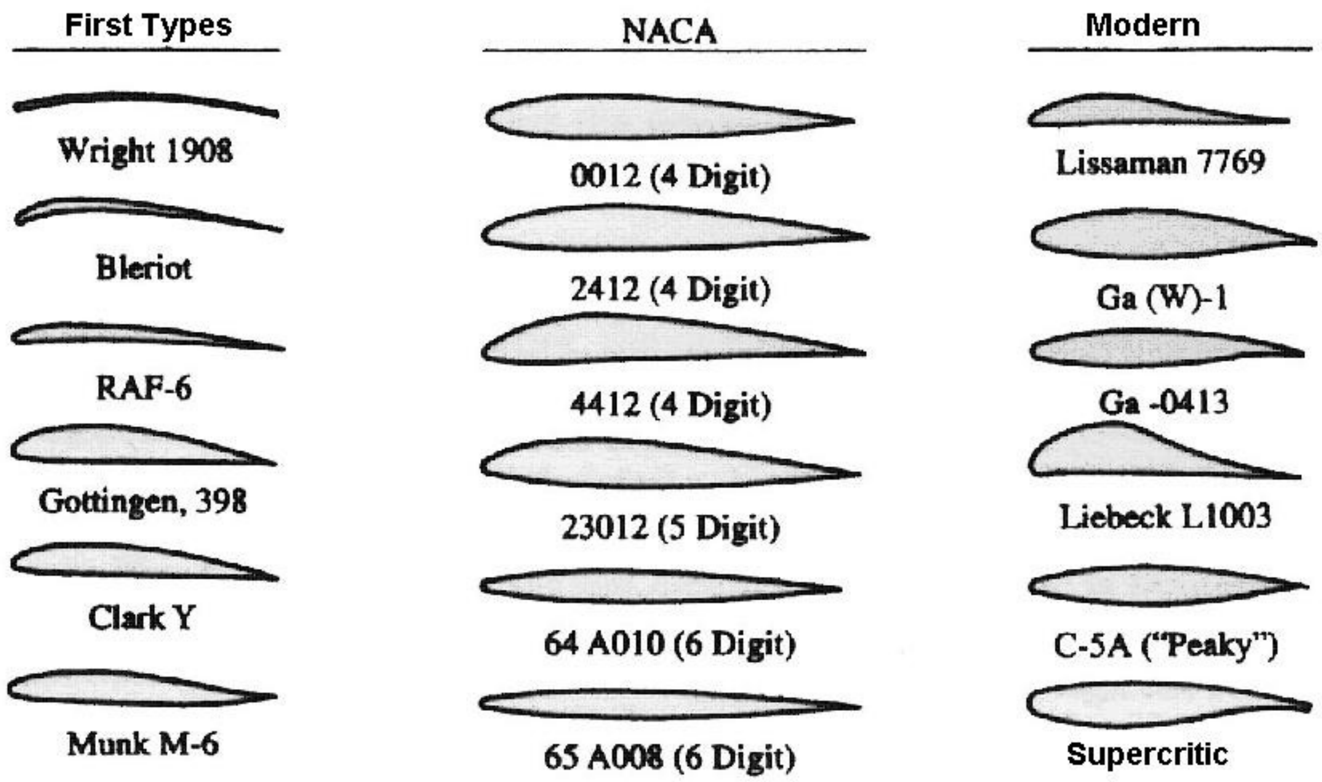


- It is important to know the Reynolds number of the operation of the aircraft and the skin roughness of the wing in order to chose an airfoil



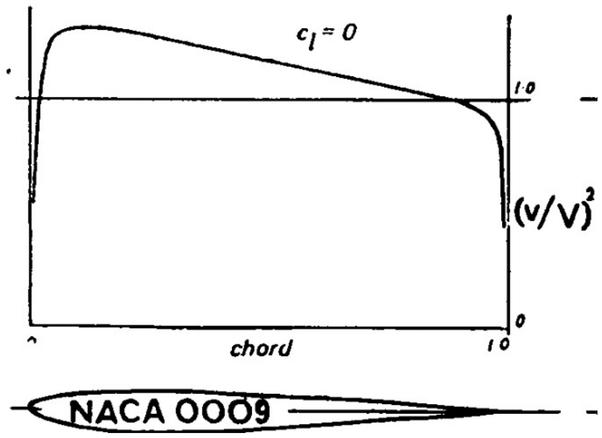
Types of Airfoils

- Typical Airfoil Geometries



- Turbulent Airfoils

- Conventional airfoils (or turbulent) have been around since beginning
- Flow similar to that discussed
  - Flow is laminar after stagnation point
  - Begins transition near critical local Re ($5 - 50 \times 10^5$)
  - Remainder of flow is turbulent



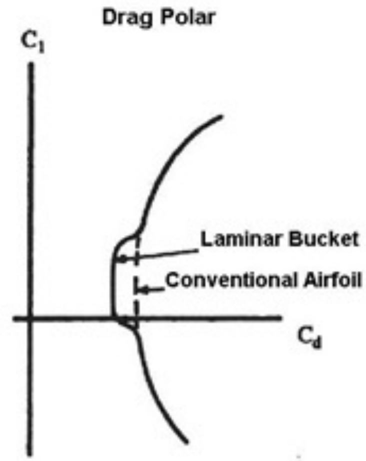
Types of Airfoils

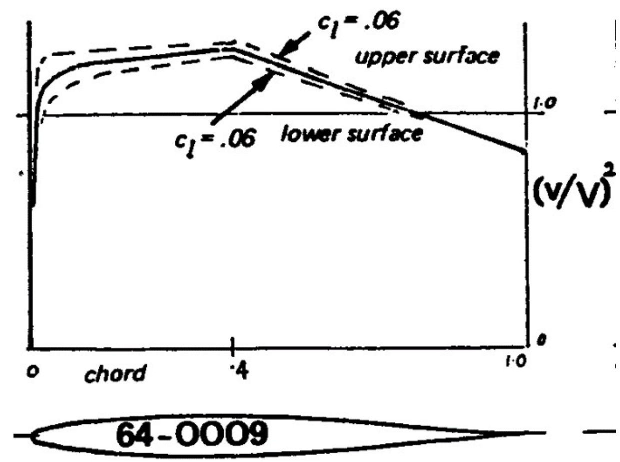
- Turbulent Airfoils

- On conventional aircraft, transition begins quickly due to any surface roughness and high velocity (higher Reynolds)
- As angle of attack increases more lift is generated
- At some point flow becomes detached and lift decreases, ***stall***
- ***NACA 4-Series and 5-Series***

- Laminar Airfoils

- New generation of airfoils designed to preserve laminar flow over larger portion of airfoil
- If boundary layer is accelerated in stream wise direction then transition will be delayed
- Transition happens well beyond Re_x which similar turbulent airfoils would see transition
- Drag polar curve shows a ***drag bucket*** region, where the airfoil should operate at to ***minimize drag***





- Laminar Airfoils

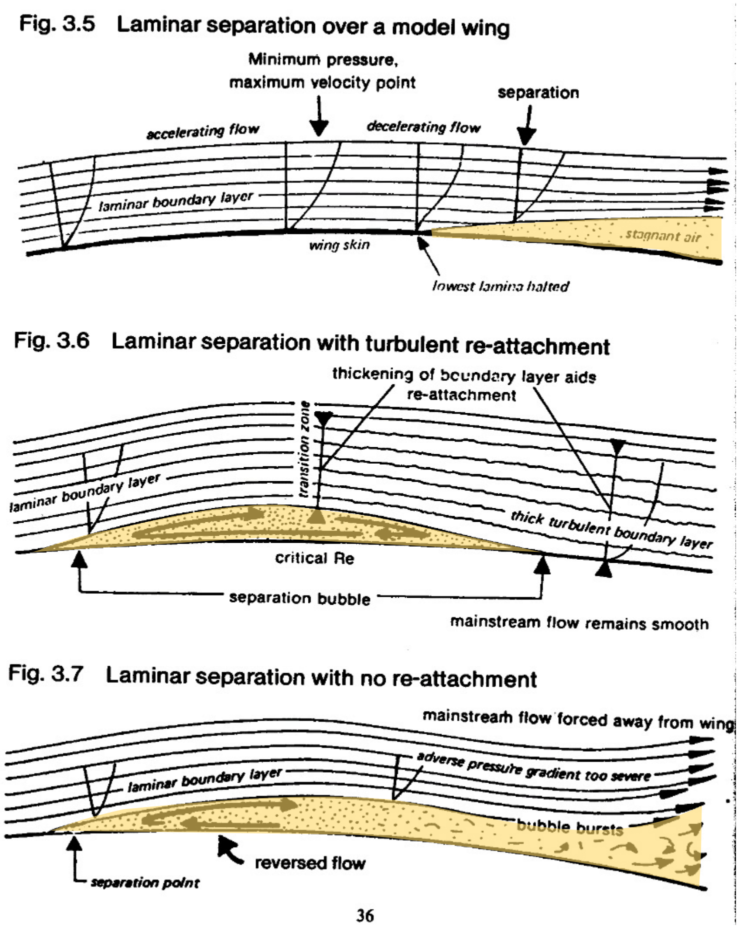
- More laminar flow means ***less skin friction drag***
- Thinner boundary layer means ***less profile drag***
- This is achieved in two main ways
  - Much more ***accurate*** and ***smooth construction***
  - ***Favorable pressure gradient*** ensures gradual acceleration over large percentage of chord
- When airfoil operating Reynolds are low we get a phenomena called ***laminar separation***
  - Low velocity
  - Low chord length (UAVs)
- This can occur at a much smaller angle of attack than stall
- ***NACA 6-Series***

- Laminar Separation

- Laminar flow is not effective at passing energy (velocity) into lower layers of boundary layer
- This can result in lower layers coming to a complete stop
- When this happens the flow can detach from the wing

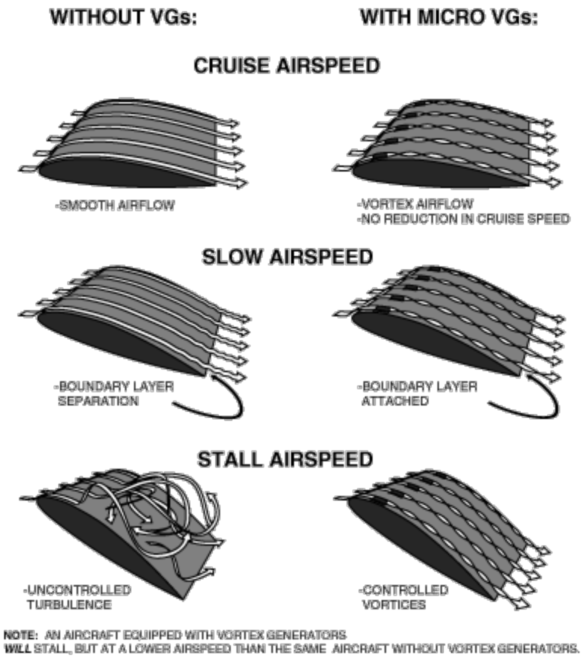
- Laminar Separation

- After detaching the separation may disturb air enough to cause transition to turbulent
- This may then energize lower layers and cause re-attachment
- If the bubble becomes too severe, the flow completely separates and wing stalls



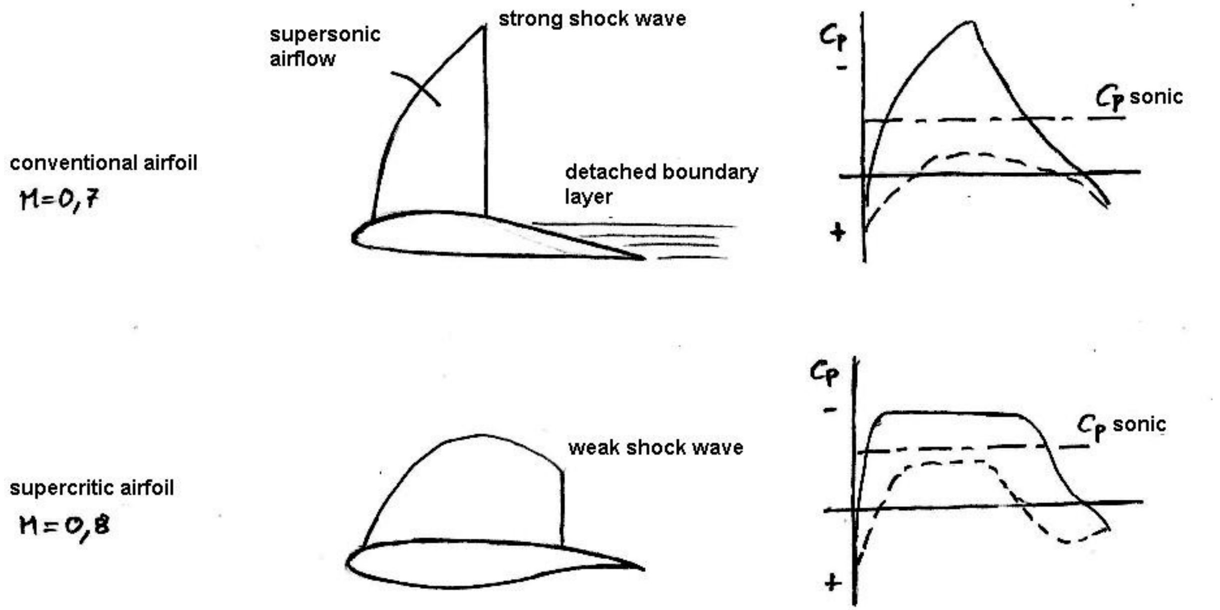
- Preventing Laminar Separation

- Avoid using airfoils below their critical Reynolds number
  - Above, laminar separation unlikely
  - Below, laminar separation very likely
  - Typically around 100 - 200k
- Cause transition to turbulent before the separation bubble forms
  - Turbulators (vortex generators)
  - Sharp leading edges
- Energize boundary layer
  - Suck out stagnant layer
  - Energize by blowing air into it



- Supercritic Airfoils

- Designed primarily to delay the onset of wave drag in the transonic speed range
- Flattened upper surface

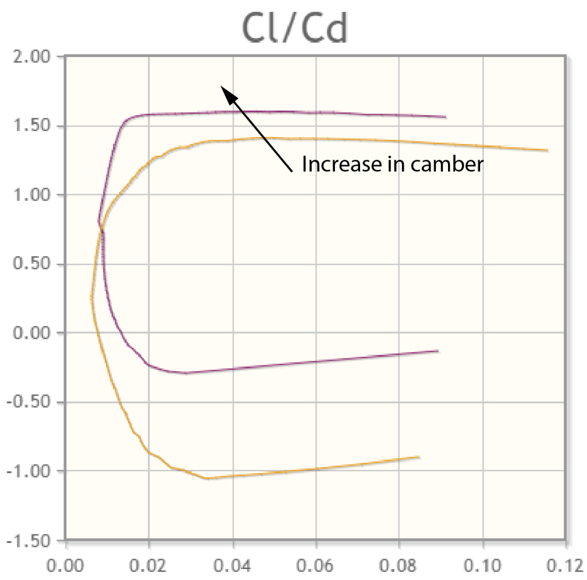


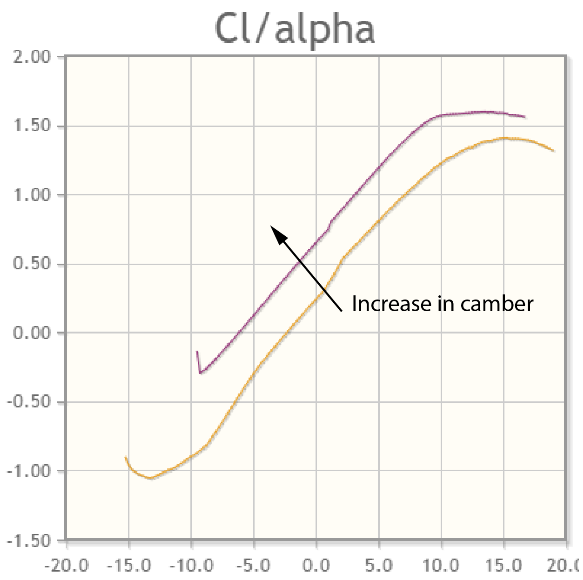
- NACA Airfoils

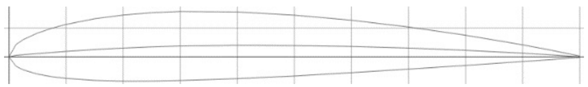
- Defined mathematically
  - ***4-Series (4 digits)***
    - 1 – camber percentage
    - 2 – maximum camber position (1 corresponds to 10 %)
    - 3, 4 – relative thickness (thickness as a percentage of the chord)
  - ***5-Series (5 digits)***
    - 1 – c_l of maximum efficiency (1 corresponds to 0.15)
    - 2, 3 – maximum camber position (10 corresponds to 5 %)
    - 4, 5 – relative thickness
  - ***6-Series (6 digits) – laminar airfoils***
    - 1 – series
    - 2 – minimum pressure position (1 corresponds to 10 %)
    - 3 – half width of the laminar bucket (1 corresponds to 0.1)
    - 4 – c_l in the center of the laminar bucket (1 corresponds to 0.1)
    - 5, 6 – relative thickness

Airfoil Drag Polars and Lift Curves

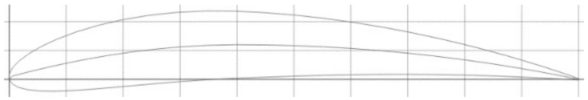
- Effect of camber







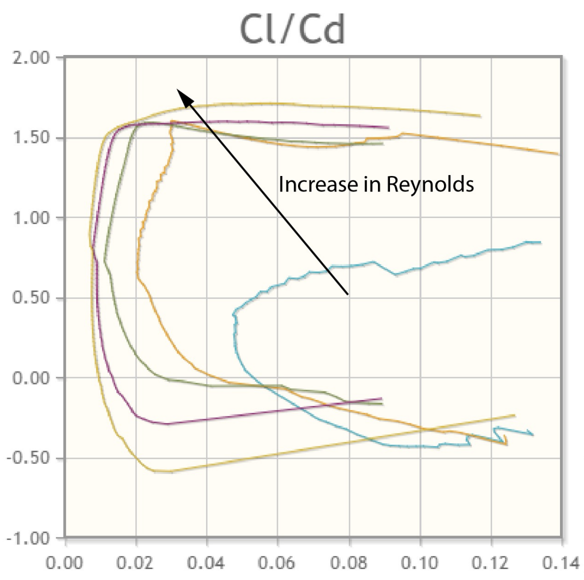
NACA 2412

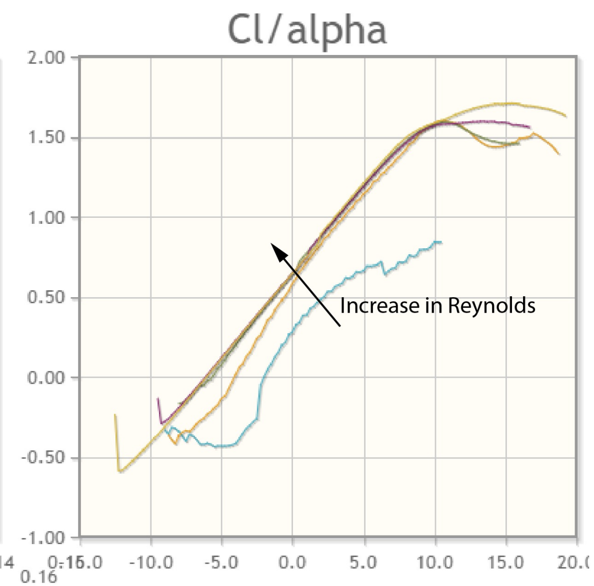


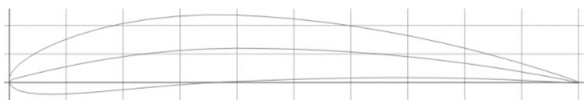
NACA 6412

- As camber increases, ***c_l* vs α curve shifts up** and $c_{l_{max}}$ ***increases***
- ***c_l at $c_{d_{min}}$ increases***

- Effect of Reynolds number







NACA 6412

- As Reynolds number increases, $\mathbf{c_{d_{min}}}$ **decreases**

Airfoil Design and Selection

- Online databases
  - Airfoil Tools
    http://airfoiltools.com/
  - UIUC Airfoil Coordinates Database
    http://m-selig.ae.illinois.edu/ads/coord_database.html

- Design and analysis software
  - JavaFoil
    http://www.mh-aerotools.de/airfoils/javafoil.htm
  - XFOIL
    http://web.mit.edu/drela/Public/web/xfoil/
  - XFLR5
    http://www.xflr5.com/xflr5.htm