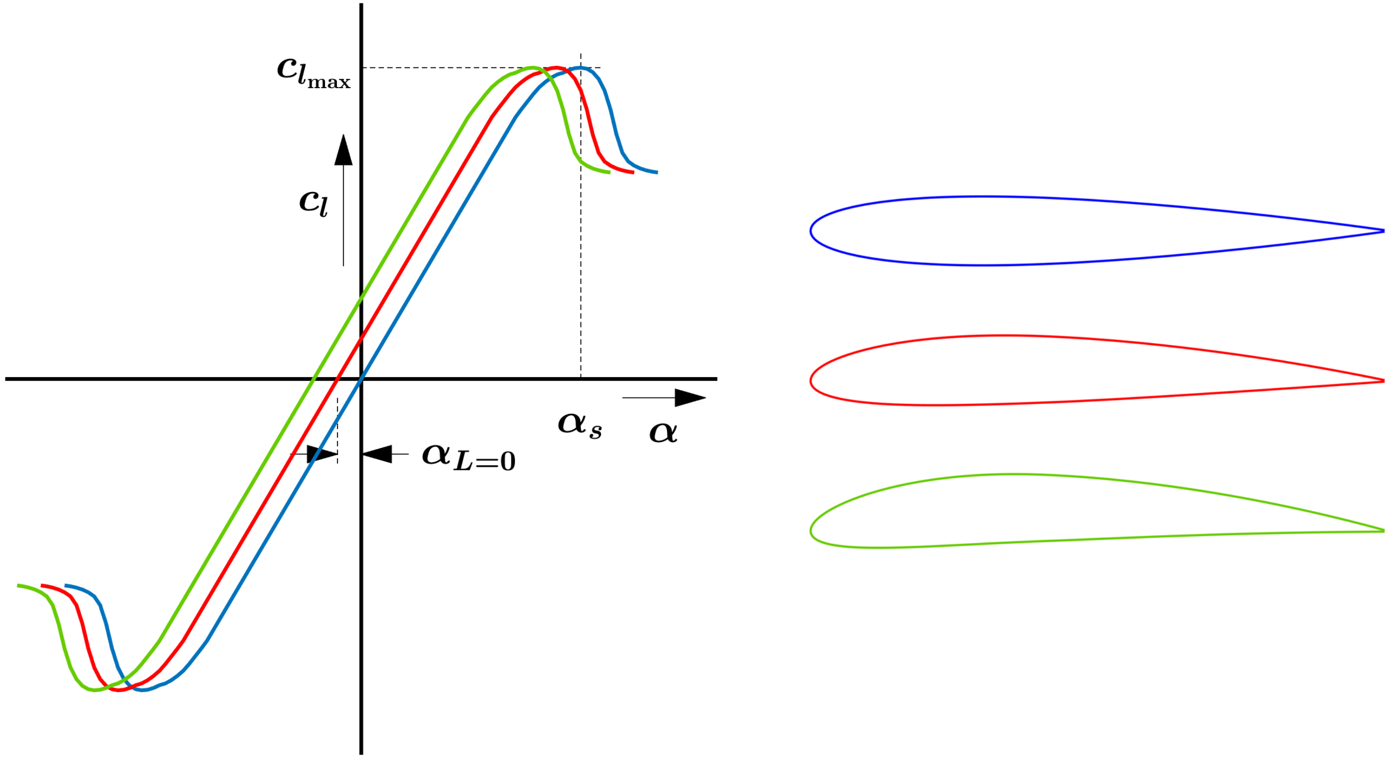
Aerodynamic Characteristics

Aniruddha Sinha



Aerodynamic characteristics of airfoils & wings

Aerodynamic characteristics refer to variation of A/D coefficients:

- Lift, drag and pitching moment coefficients (for airfoils and wings)
- Other 3 coefficients (relevant for wings/aircraft) are of secondary importance

These force/moment coefficients depend on

- Shape of airfoil
- Angle of attack
- Reynolds number (in freestream)
- Mach number (in freestream)
- Aspect ratio (for wings)

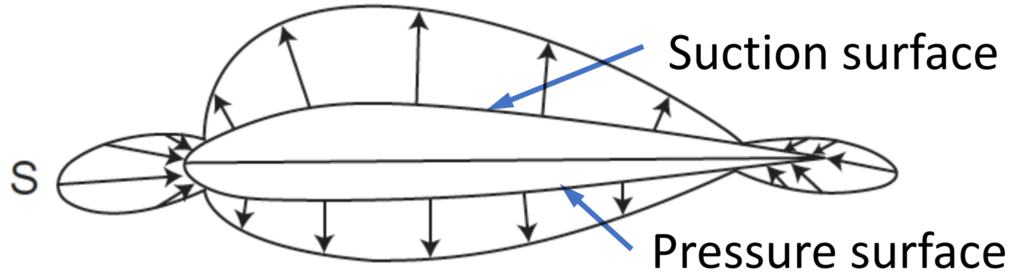
Flow over airfoils

Babinsky, Cambridge University (https://www.youtube.com/watch?v=6UlsArvbTeo)

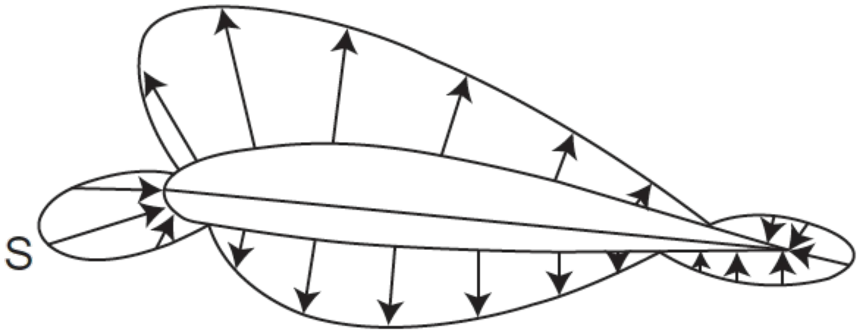
Lift Characteristics of Airfoils

Aerodynamic Characteristics

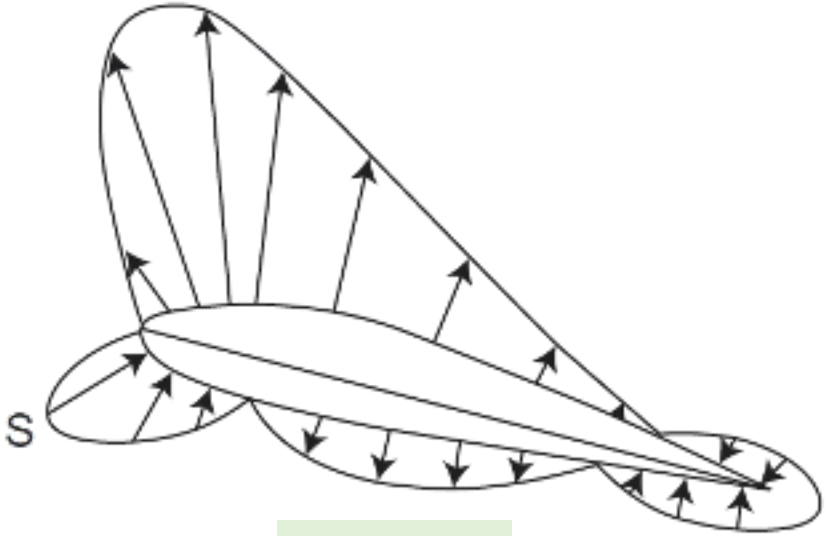
Pressure distribution on an airfoil



$\alpha = 0°$



$\alpha = 6°$



$\alpha = 15°$

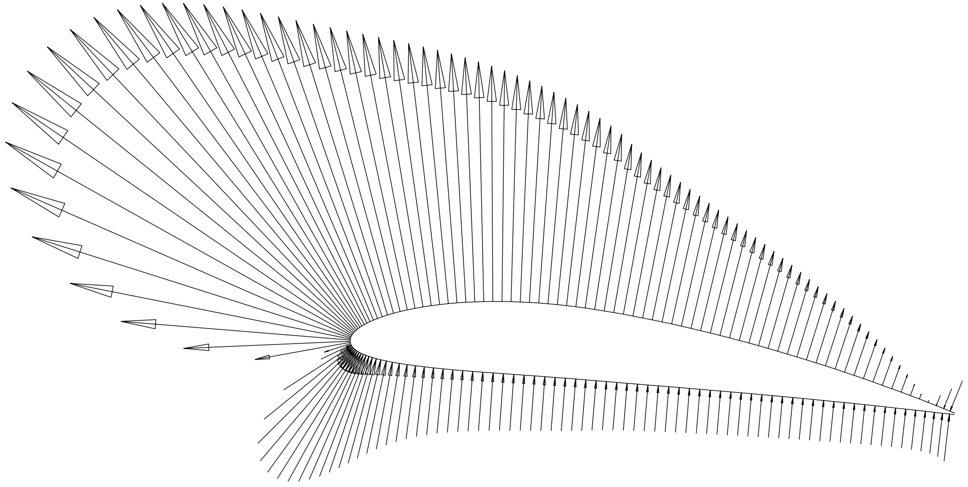
Pressure coefficient, $C_p = \frac{p - p_\infty}{q_\infty}$

- Length of arrows proportional to C_p
- S denotes C_p at stagnation point (where $C_p = 1$)
- Outward arrows indicate suction
- Inward arrows indicate pressure

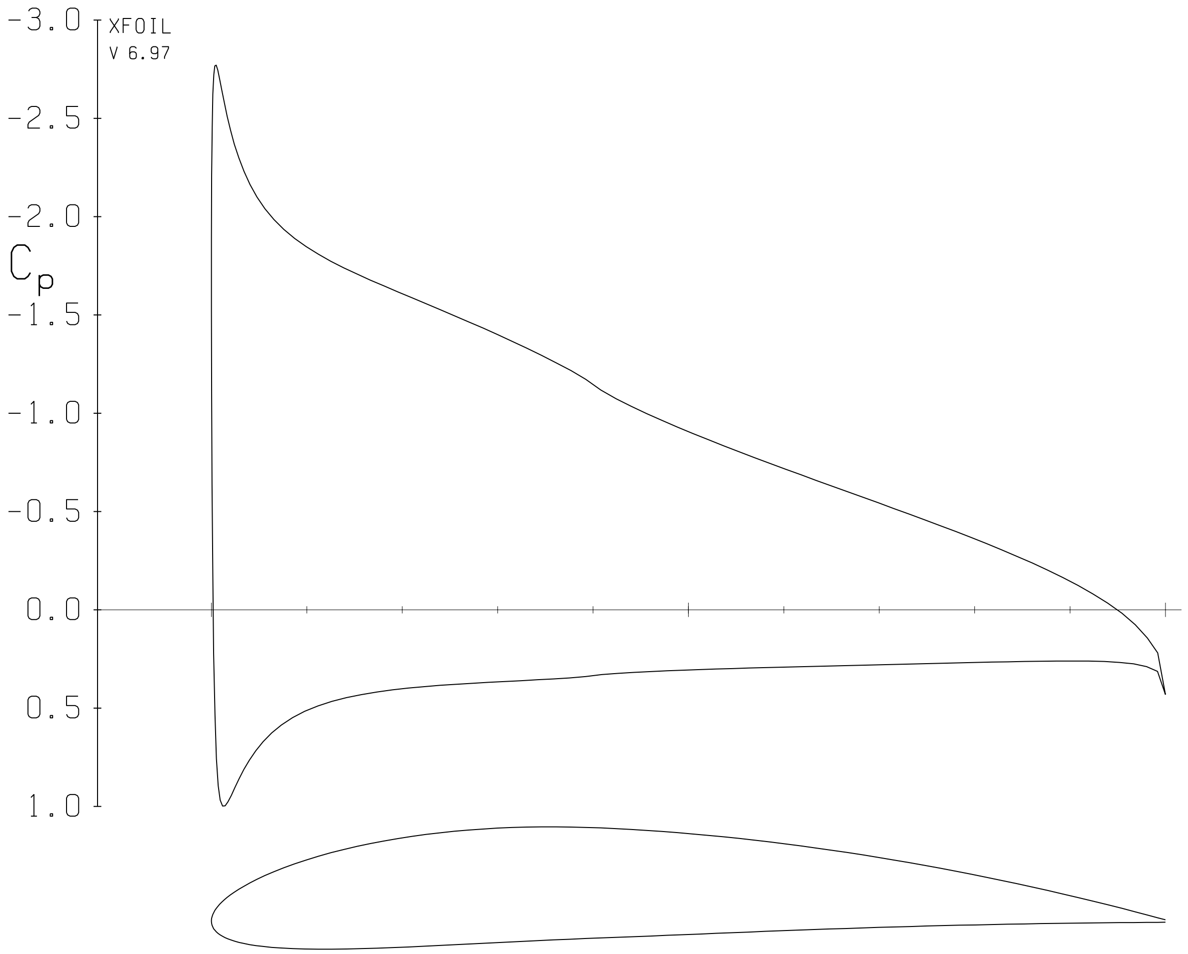
Houghton et al., Aerodynamics for Engineering Students, 2013

Conventional C_p plot

NACA 4412 at 11° AoA



Pressure vector plot



C_p vs. x (chord location) plot

Drela, XFoil

Lift coefficient of symmetric airfoils

Consider a symmetric airfoil in a high-Re flow

c_l increases linearly with α over a large range

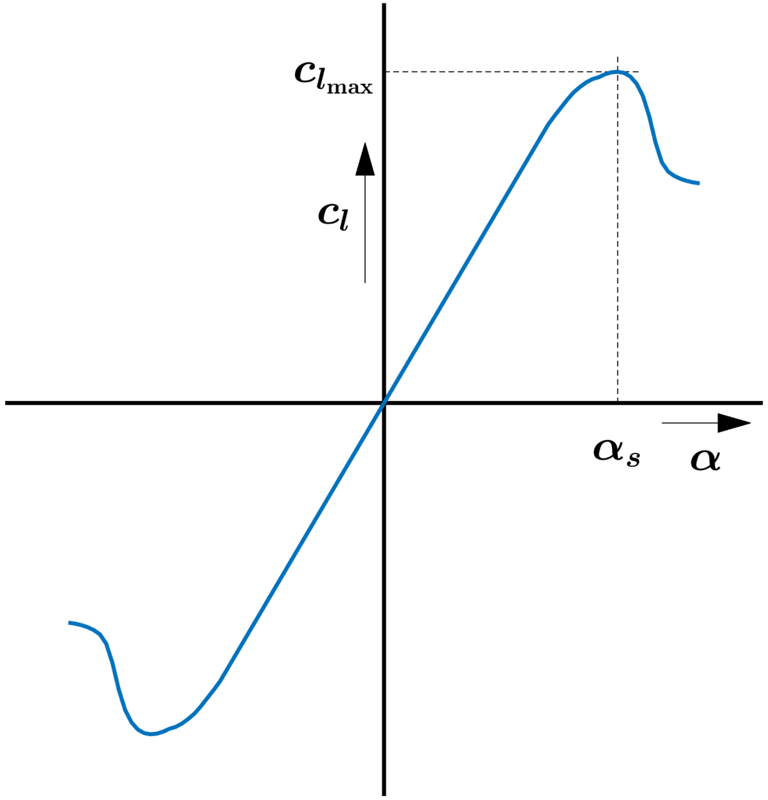
- The slope of this linear regime is called lift slope
- Linearity is imperfect at lower Re

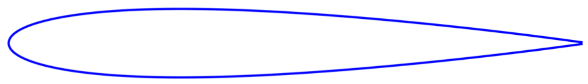
This is followed by a nonlinear regime

- Max ($c_{l_{\max}}$) is reached at α_s, called stall angle
- Stalling is due to (viscous) flow separation

Linear regime corresponds to attached flow

Lift curve of symmetric airfoil is odd function of α





Symmetric airfoil

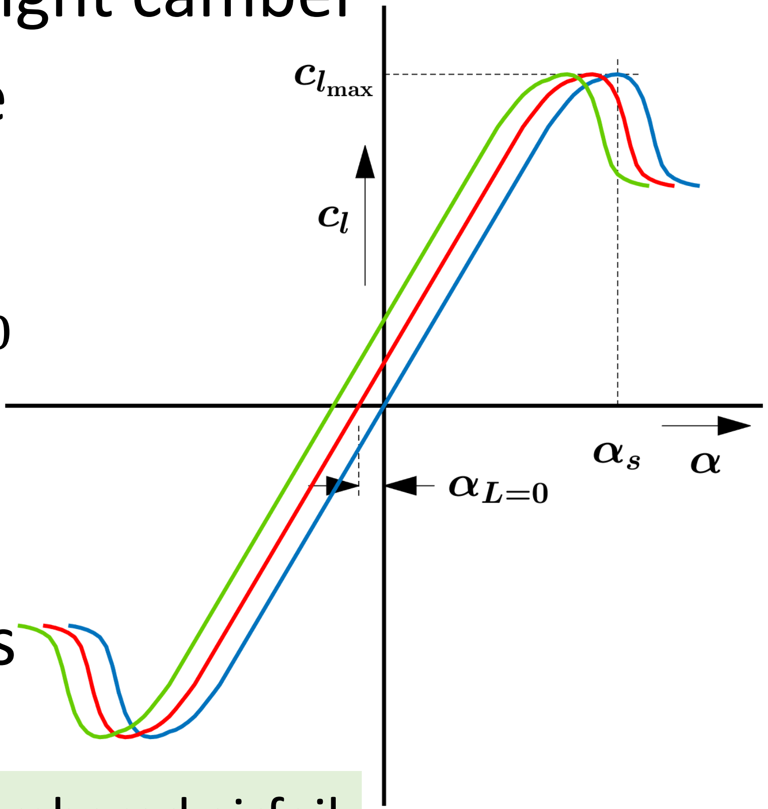
Houghton et al., Aerodynamics for Engineering Students, 2013

Lift coefficient of cambered airfoils

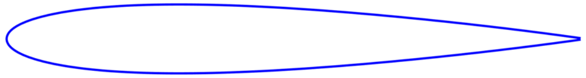
Consider an airfoil with same thickness but with slight camber

- Shape of curve remains same, including lift slope
- For a given α, (positive) camber increases c_l
- Positive camber yields negative “0-lift AoA”, $\alpha_{L=0}$
- $c_{l_{\max}}$ remains almost same, but α_s decreases
- Stalling behaviour may not be as symmetric

Increasing the camber further amplifies the effects



Symmetric airfoil



Slightly cambered airfoil

More cambered airfoil

Houghton et al., Aerodynamics for Engineering Students, 2013

Reynolds number (in)dependence of lift coeff.

c_l is essentially independent of Re, as long as it is sufficiently high, and flow is attached

- General flight regime indeed has high Re
- Viscous effects irrelevant in attached flow

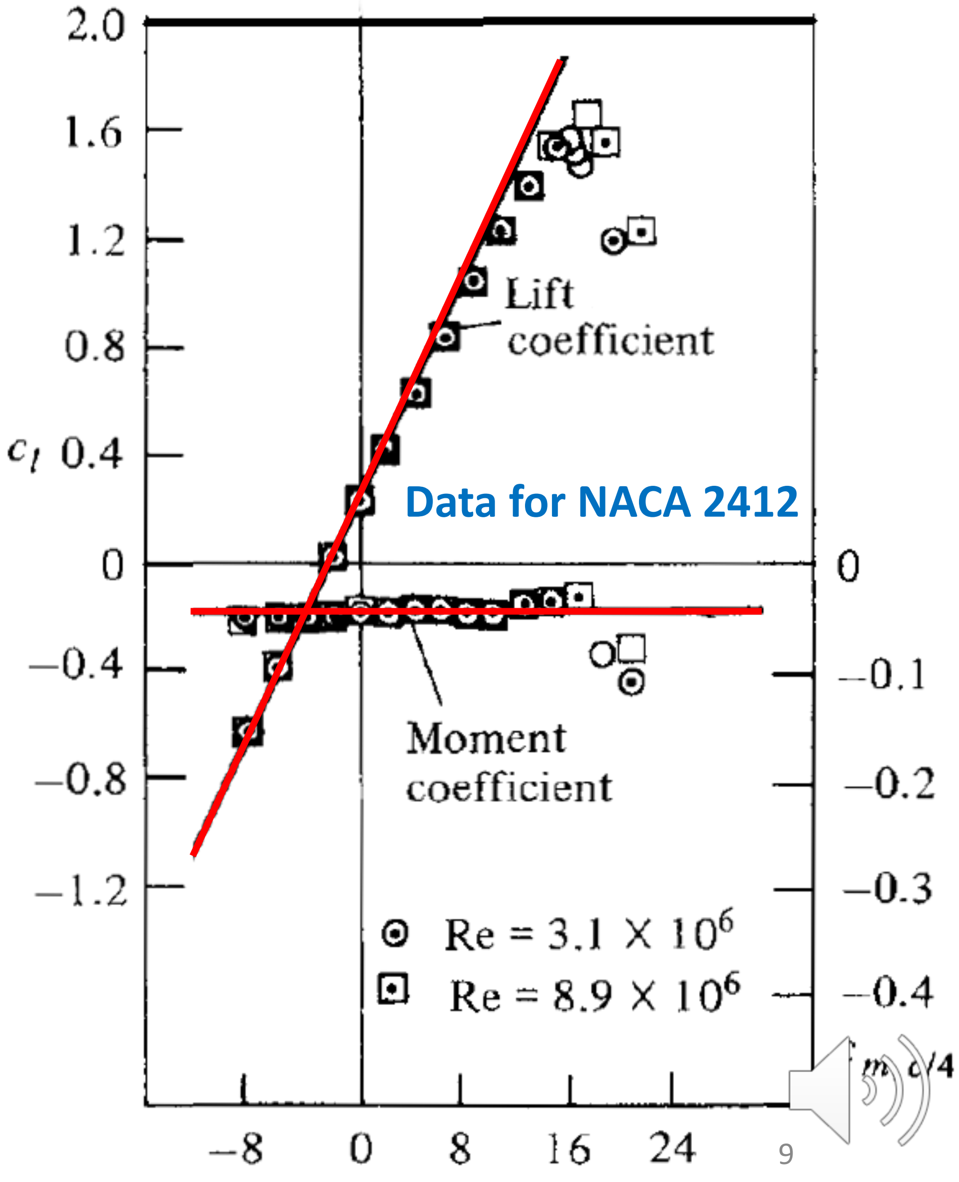
Separation (& stalling) are viscous effects

- $c_{l_{\max}}$ increases with Re
- Boundary layer energy increases with Re

Use inviscid theory to predict lift & moment for attached flow on airfoils (and wings)

- The straight lines result from this theory

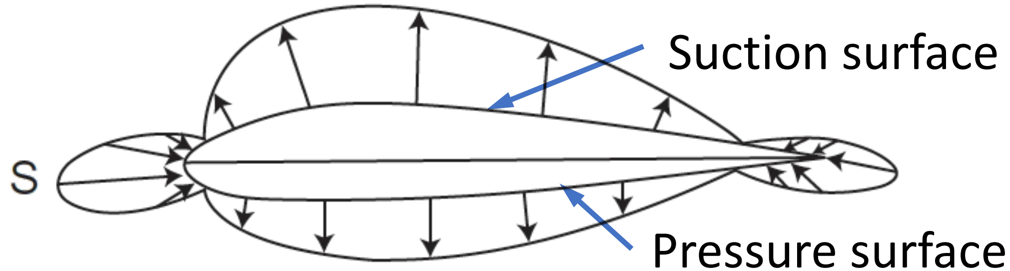
Abbott and Doenhoff, Theory of Wing Sections, 1959



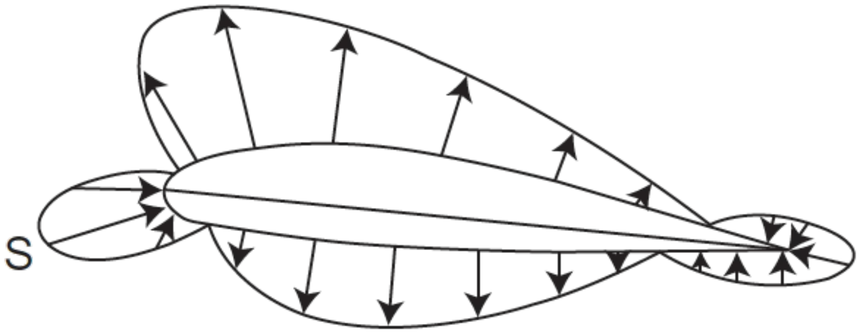
Airfoil stall and maximum lift

Aerodynamics Characteristics

Pressure distribution on an airfoil: revisited



$\alpha = 0°$



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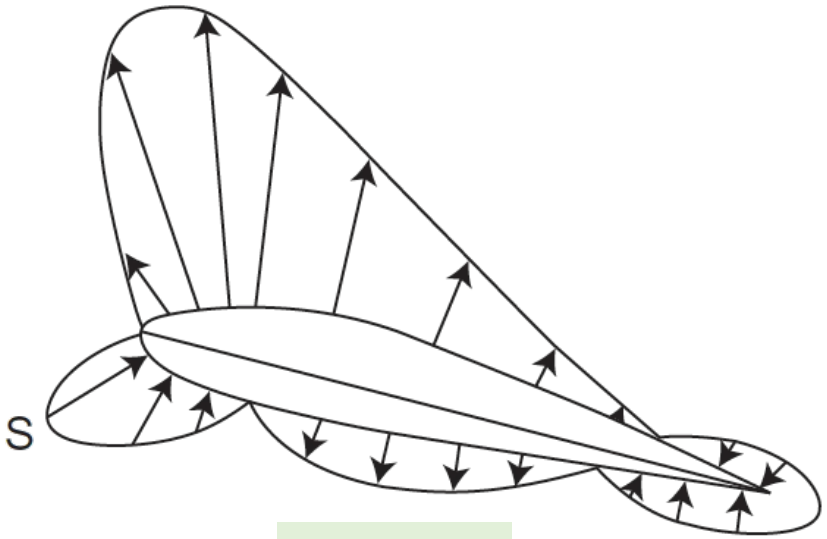

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- Length of arrows proportional to C_p
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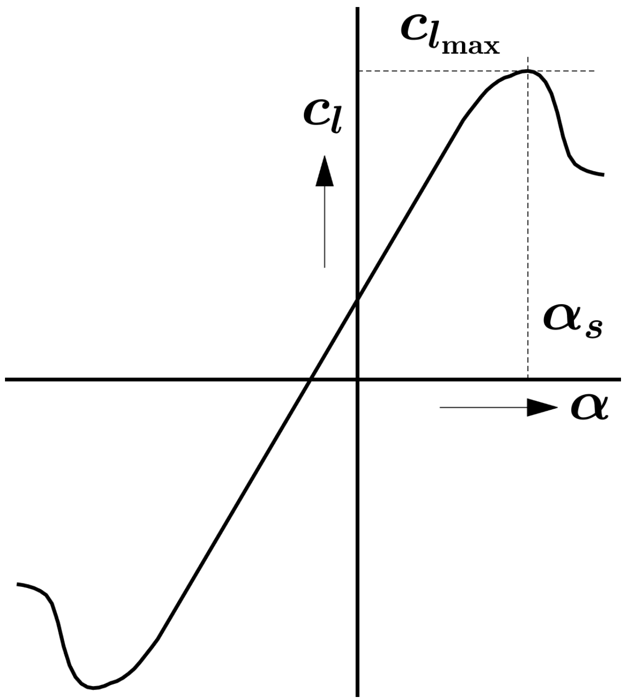
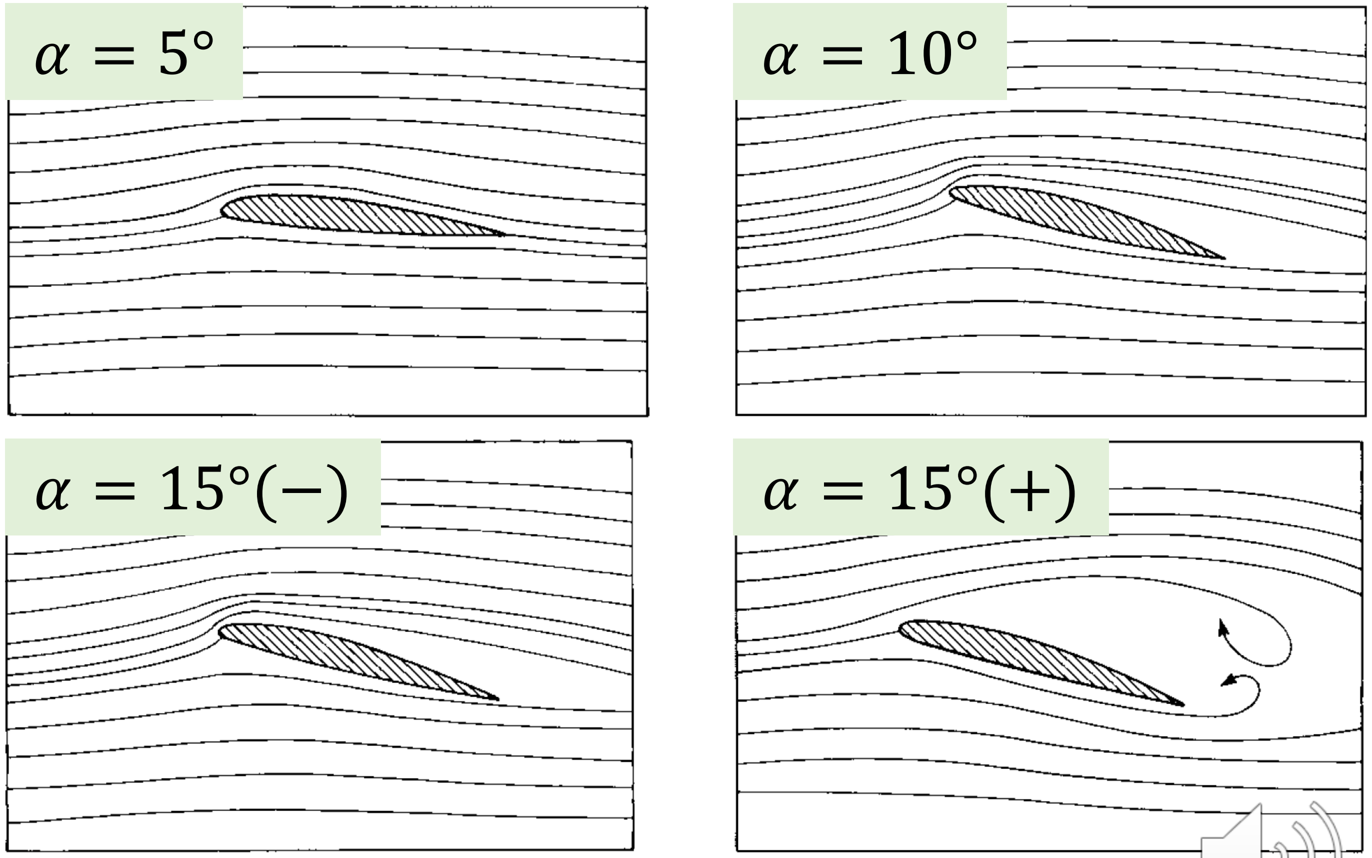
- Inward arrows indicate pressure

Houghton et al., Aerodynamics for Engineering Students, 2013

Leading edge stall (e.g. NACA 4412 @ Re=2.1e5)

- Separation initiated at LE; rapid decrease of lift in post-stall
- Occurs for thin airfoils (typically < 16% thick)

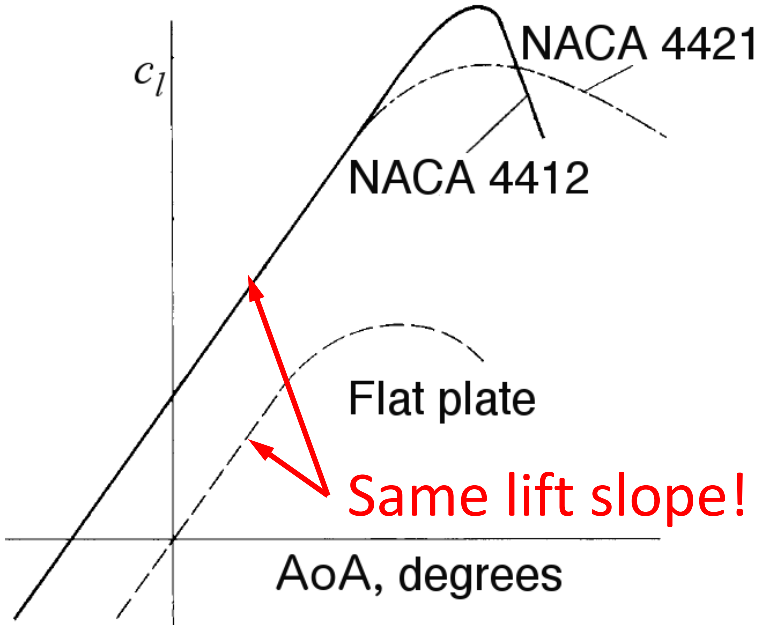


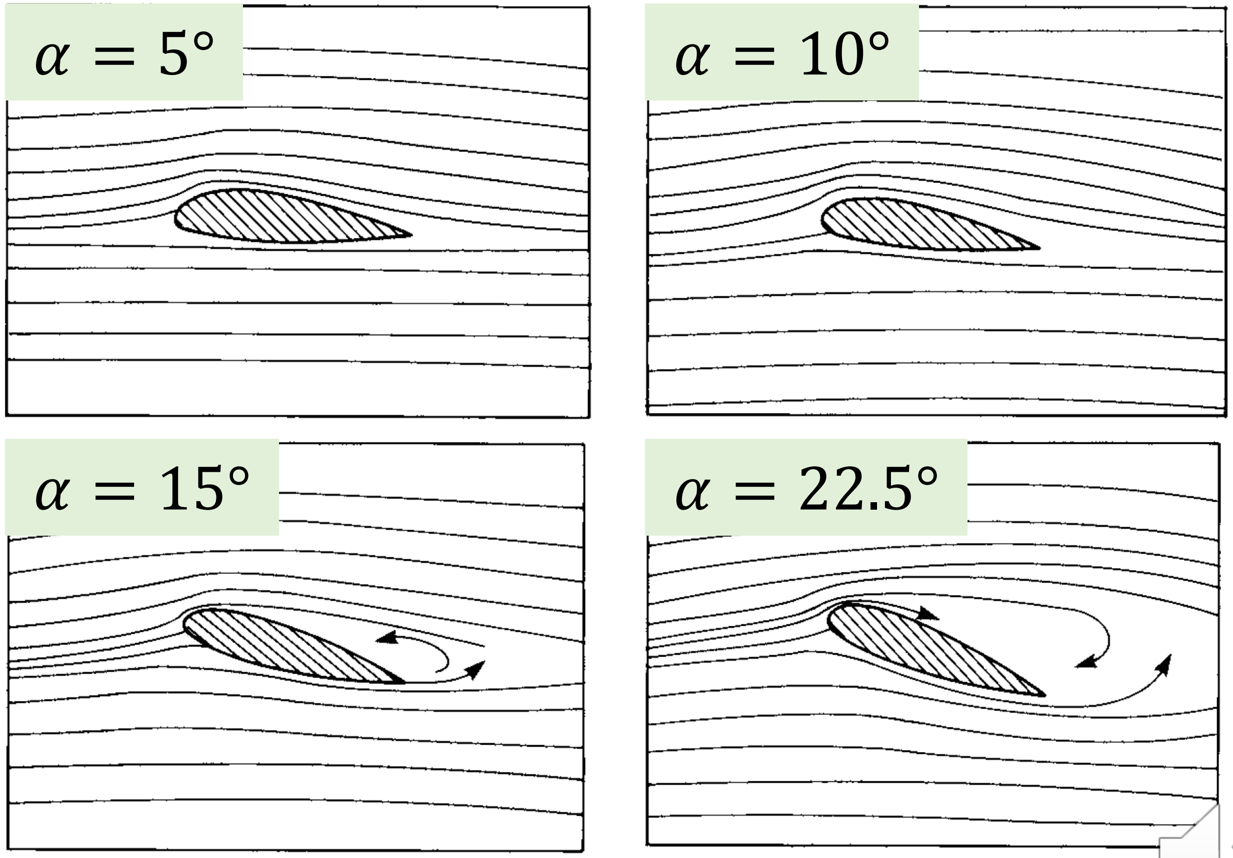


Anderson, Fundamentals of Aerodynamics, 2011

Trailing edge stall (e.g. NACA 4421 @ Re=2.1e5)

- Occurs for thicker airfoils
- Separation initiated at TE; gradual decrease of lift in post-stall





- Thickness doesn't affect lift if flow is attached

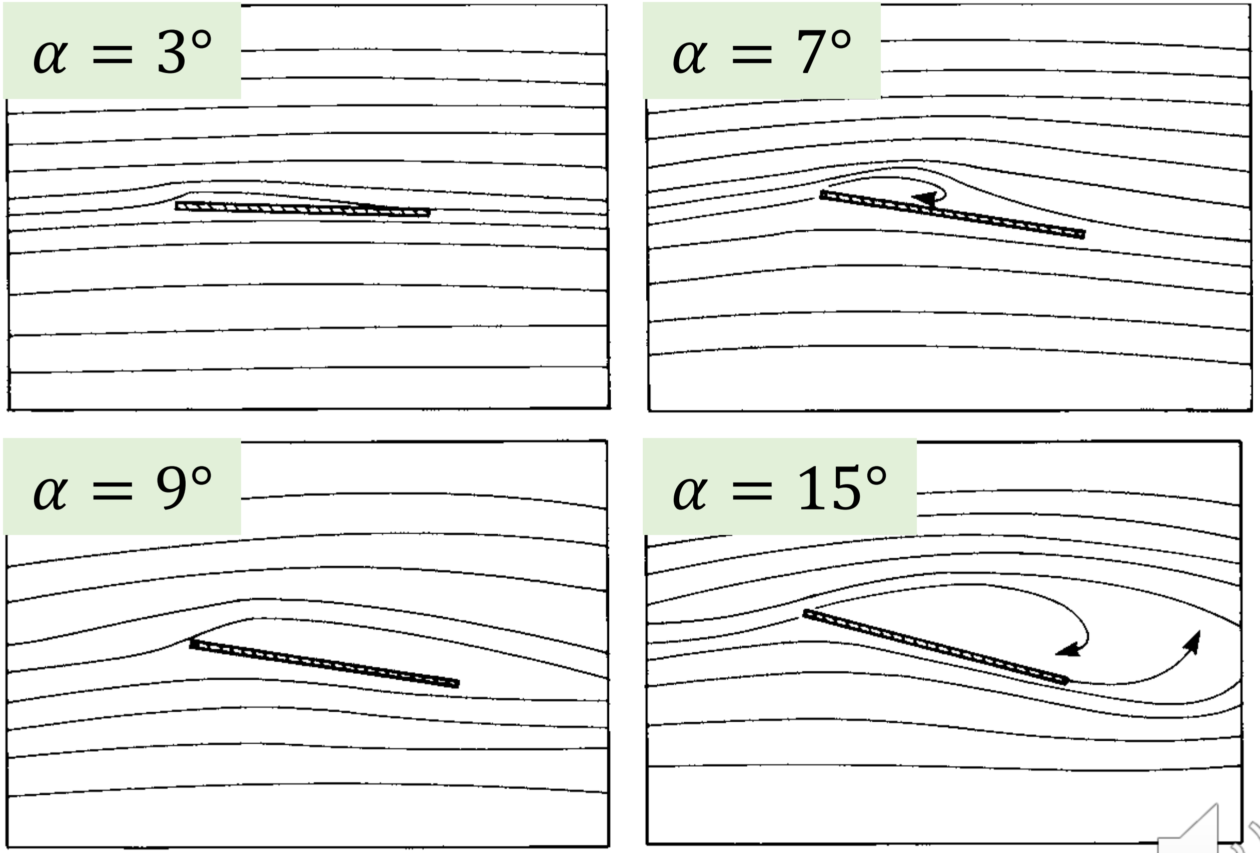
Anderson, Fundamentals of Aerodynamics, 2011

Thin airfoil stall (e.g. flat plate)

Flow separation occurs on suction surface even at $\alpha = 3°$, but the flow reattaches to form a separation bubble

- Separation region increases with α, until it covers entire suction surface
- Further increase of α leads to massive separation and stall

Recall: Lift slope is same as in cambered airfoil!



Anderson, Fundamentals of Aerodynamics, 2011

Maximum lift coefficient $c_{l_{\max}}$ vs. thickness

In attached flow, c_l is a very weak function of thickness

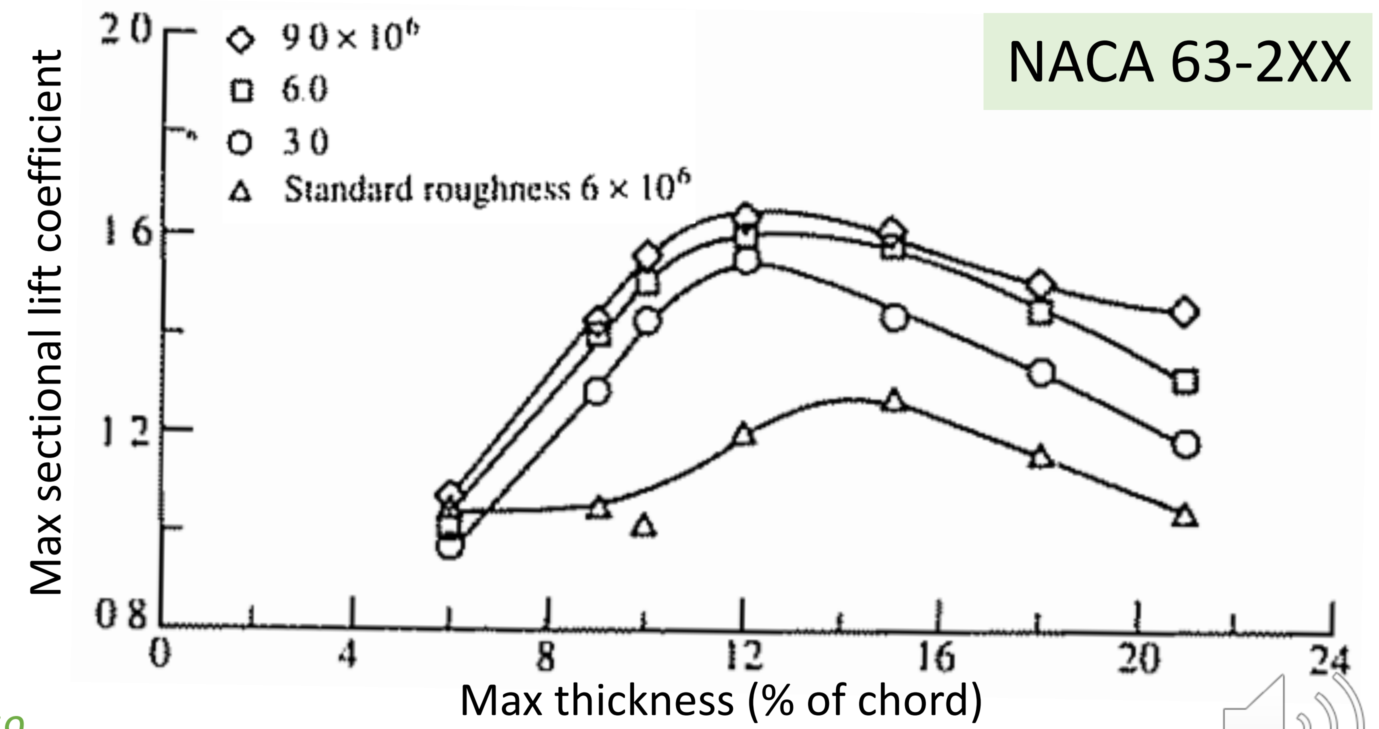
- Thin plate is sufficient for lift (impractical structure!)

NACA 63-212

However, thickness affects stalling characteristics

- Optimum thickness needed for high $c_{l_{\max}}$

We have already seen that Re affects max $c_{l_{\max}}$ too

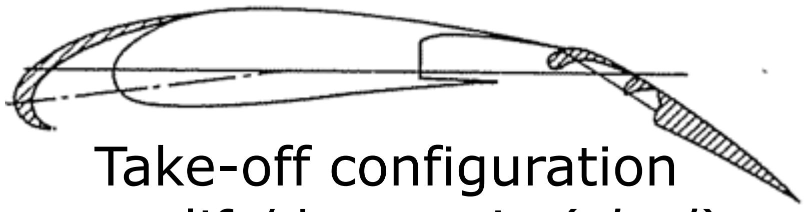


Abbott and Doenhoff, Theory of Wing Sections, 1959

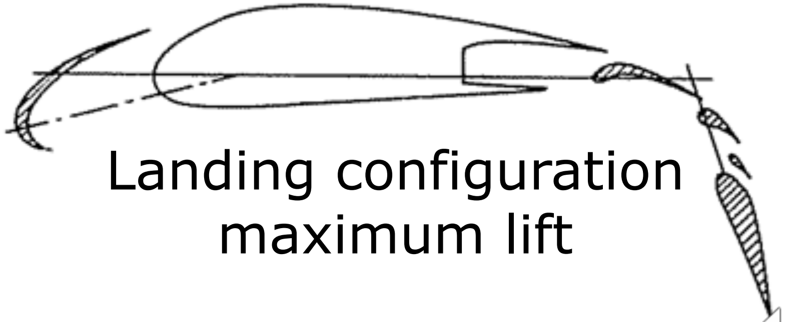
Flaps and high-lift devices

- Some portions of wing have reconfigurable airfoils made of several separate sections
- Sections change their relative position to change their aerodynamic characteristics or act as aerodynamic controls
- Effective chord and/or camber is changed

Cruise configuration
minimum drag



Take-off configuration
max lift/drag ratio (L'/D')

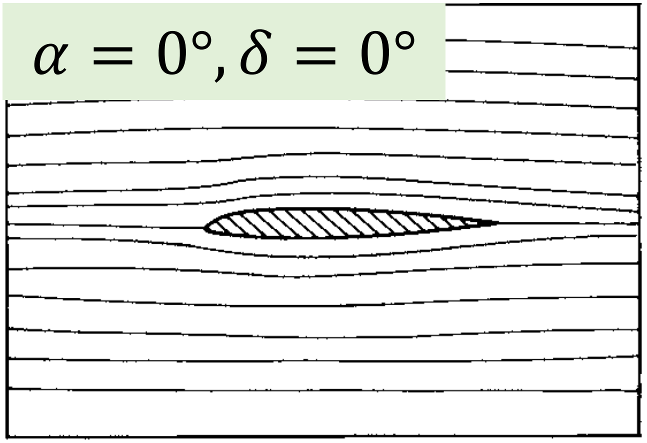


Landing configuration
maximum lift

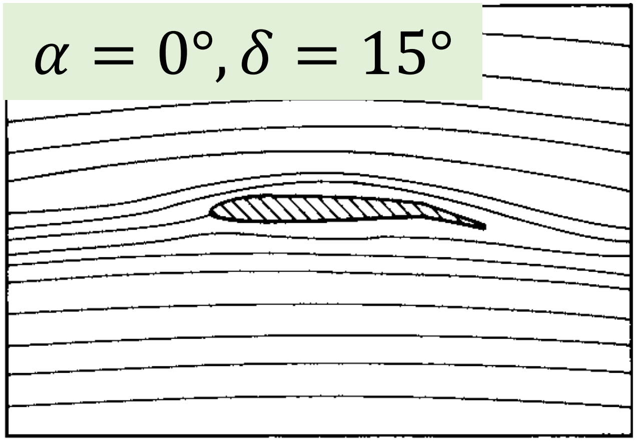
Anderson, Fundamentals of Aerodynamics, 2011

Effect of flaps

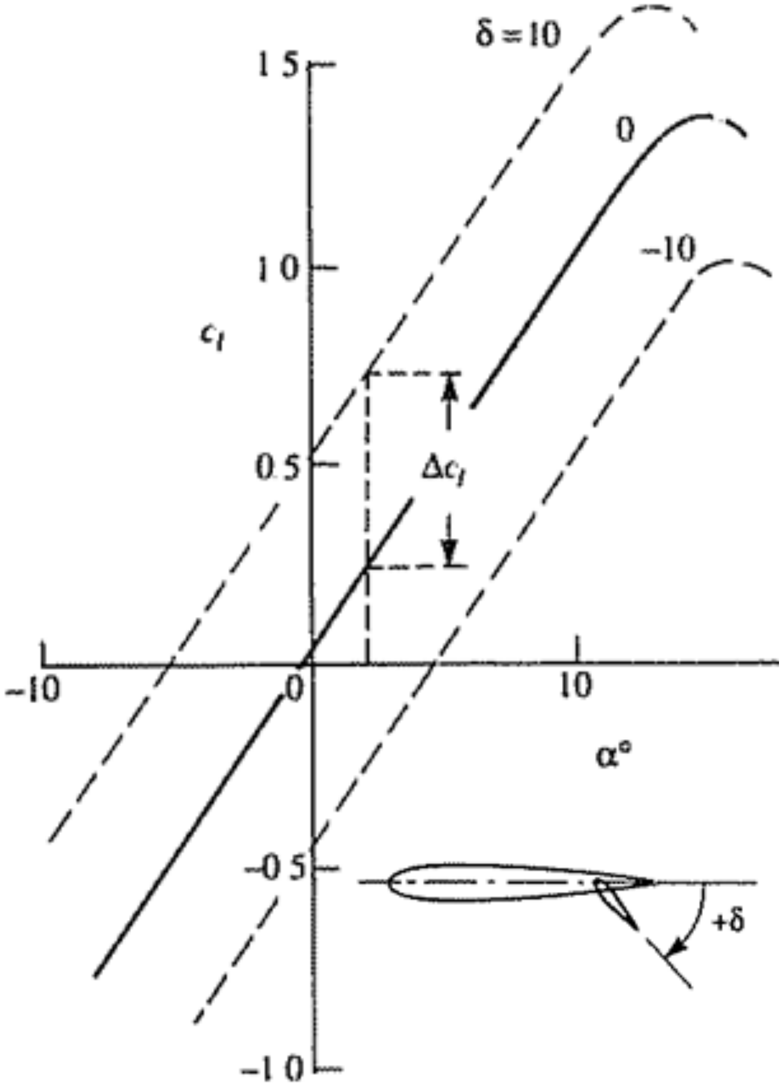
- Flaps increase lift for same angle of attack
- This can be considered as the effective increase in camber of airfoil
- However, unlike increasing camber, flaps also increase $c_{l_{\max}}$



$\alpha = 0°, \delta = 0°$



$\alpha = 0°, \delta = 15°$



Anderson, Fundamentals of Aerodynamics, 2011

Drag Characteristics of Airfoils

Aerodynamic Characteristics

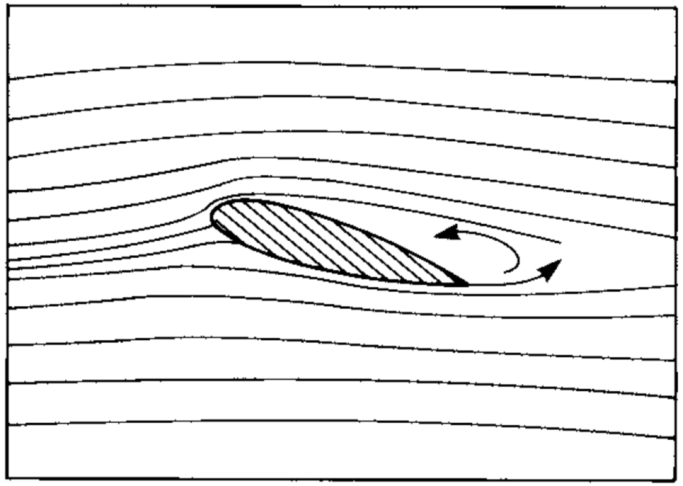
Airfoil drag characteristics

For airfoil sections in low speed flow, origin of drag are

a) Skin friction

b) Pressure drag due to flow separation (also called 'form drag')

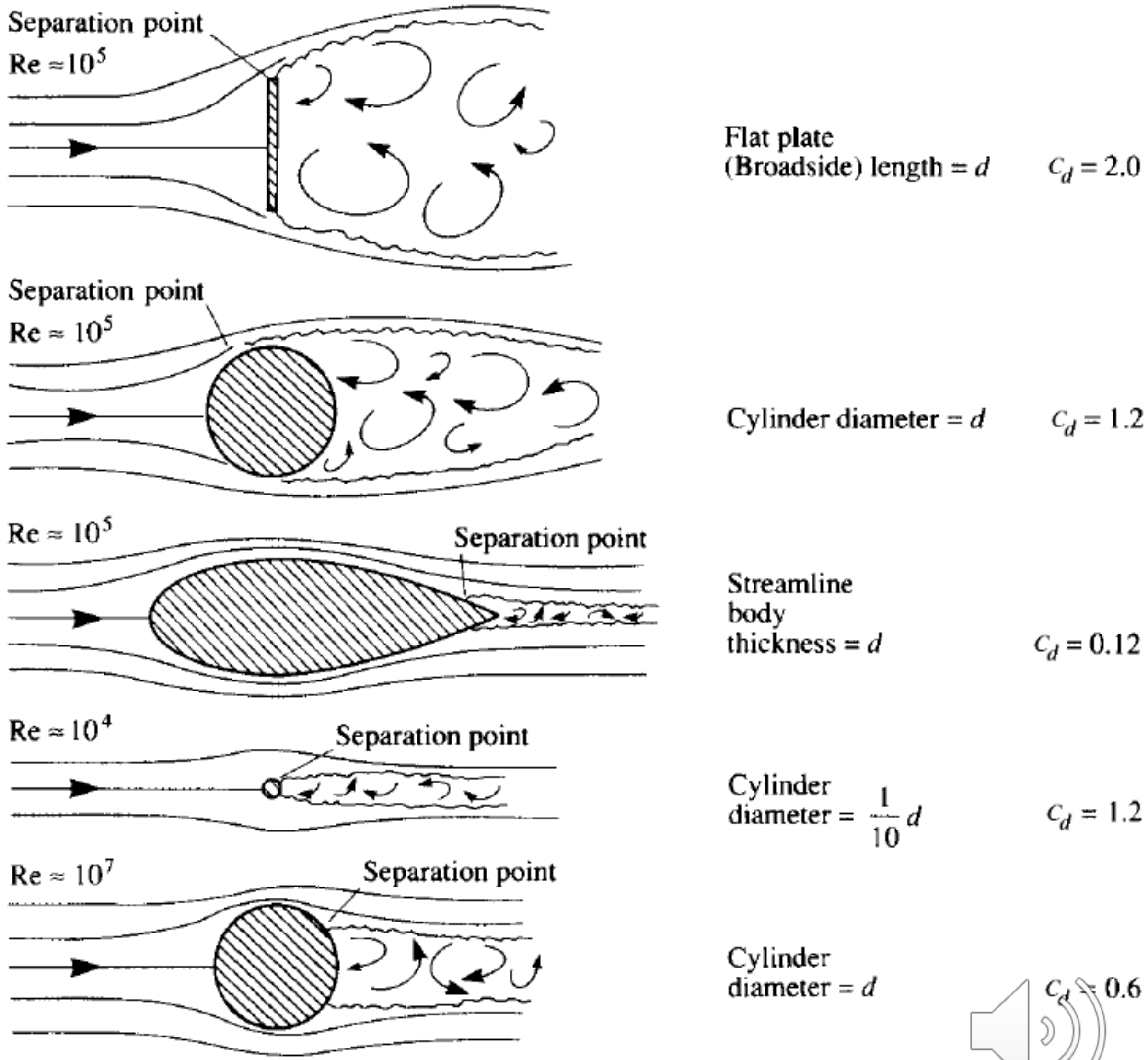
- Together they constitute 'profile drag'



Anderson, Fundamentals of Aerodynamics, 2011

Typical drag coefficients on immersed bodies

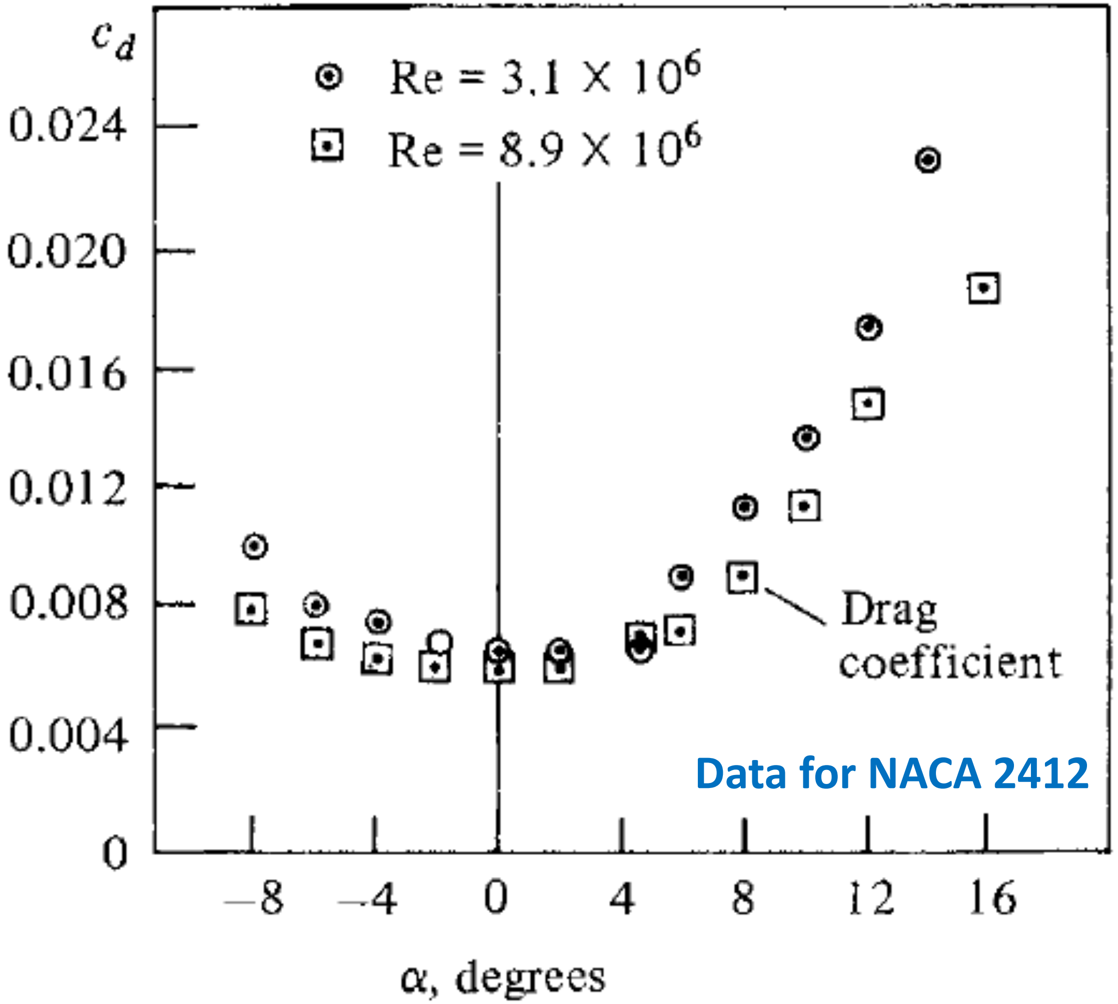
- We previously looked at relative drag forces on some typical bodies
- Now we study the more relevant drag coefficients in the same cases
- N.B.: cases 2 & 4 of cylinder flows have same c_d, though their Re are separated by 1 order of magnitude
- Although drag force increases at the much higher Re, c_d decreases
- Streamlined airfoil has least c_d



Airfoil drag characteristics

c_d is a strong function of *Re*

- Both sources of profile drag depend on Re
- Also depends strongly on α

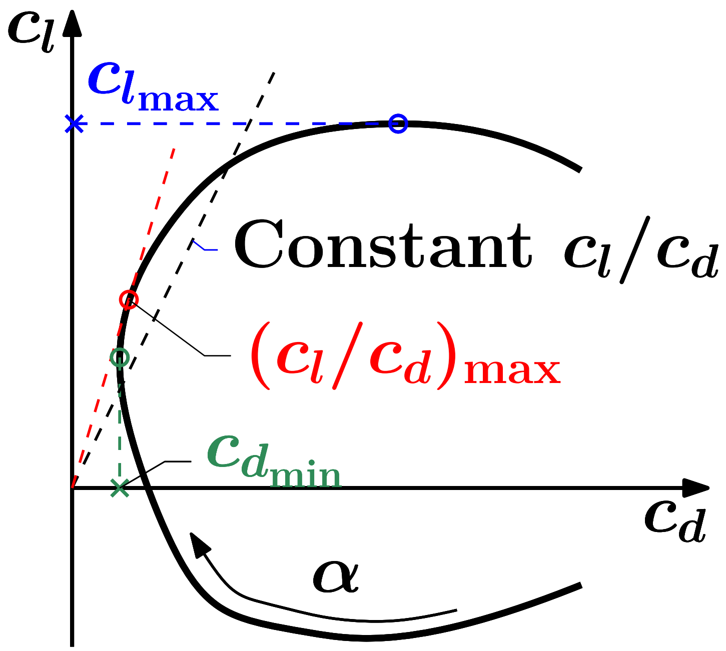


Abbott and Doenhoff, Theory of Wing Sections, 1959

Drag polar

It is a plot of $c_l(\alpha)$ vs. $c_d(\alpha)$, or vice versa

- More useful than c_l vs. α and c_d vs. α for evaluating performance
- How much drag penalty has to be paid for a given amount of lift (to offset some weight)?
- It directly gives the important $c_{l_{\max}}$ & $c_{d_{\min}}$
- To obtain a specific c_l/c_d (efficiency), we find the two operating points by drawing the line with this slope passing through the origin
- In the tangential limit, we find the maximum achievable efficiency, $(c_l/c_d)_{\max}$, from airfoil



Compressibility (Mach) Effects

Aerodynamic Characteristics

Mach number dependence of lift coefficient

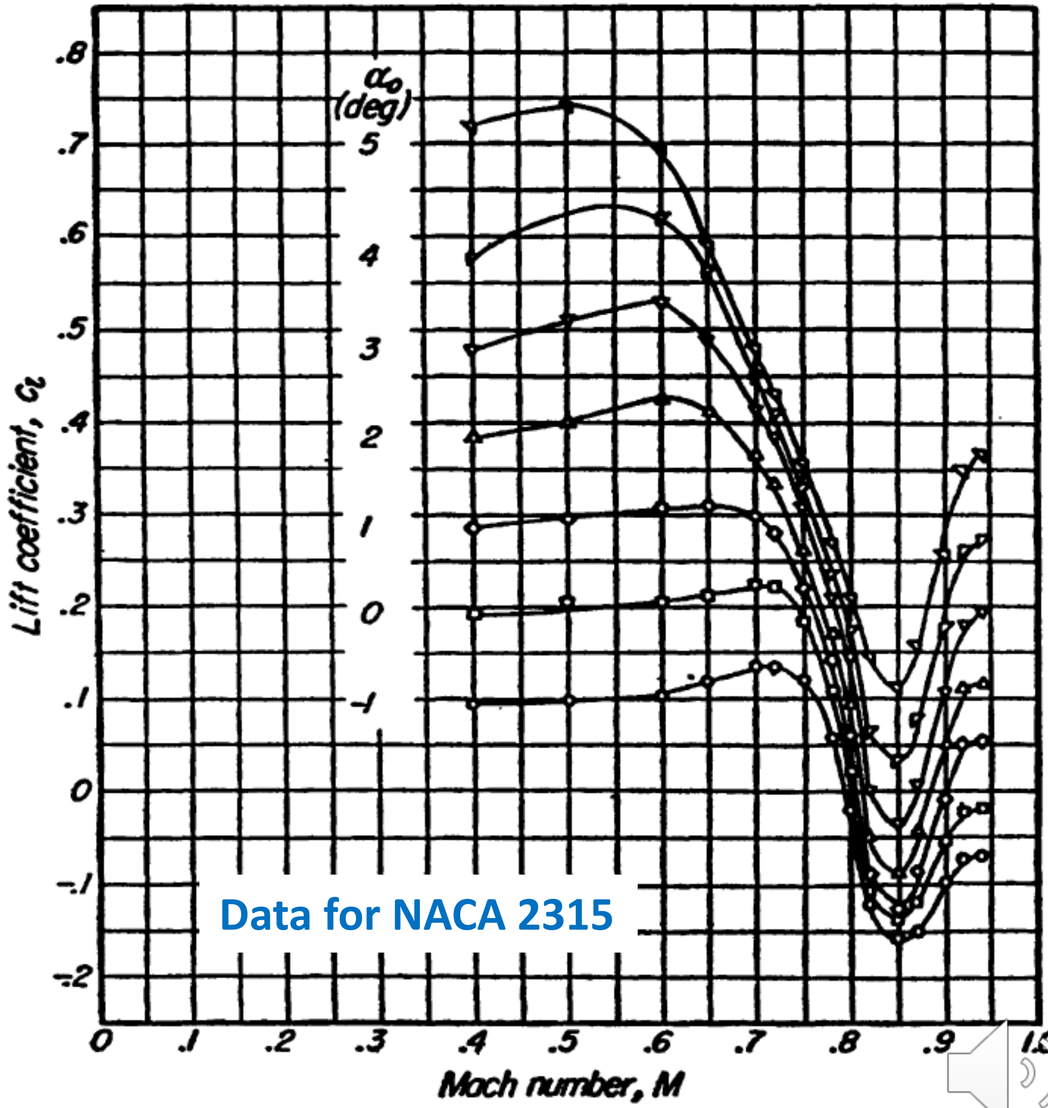
At low Mach numbers, c_l is essentially independent of Mach number

- Hence *incompressible aerodynamics*

At higher Mach nos., c_l first increases slightly, before decreasing drastically

- Higher the AoA, lower the M at which Mach no. dependence sets in

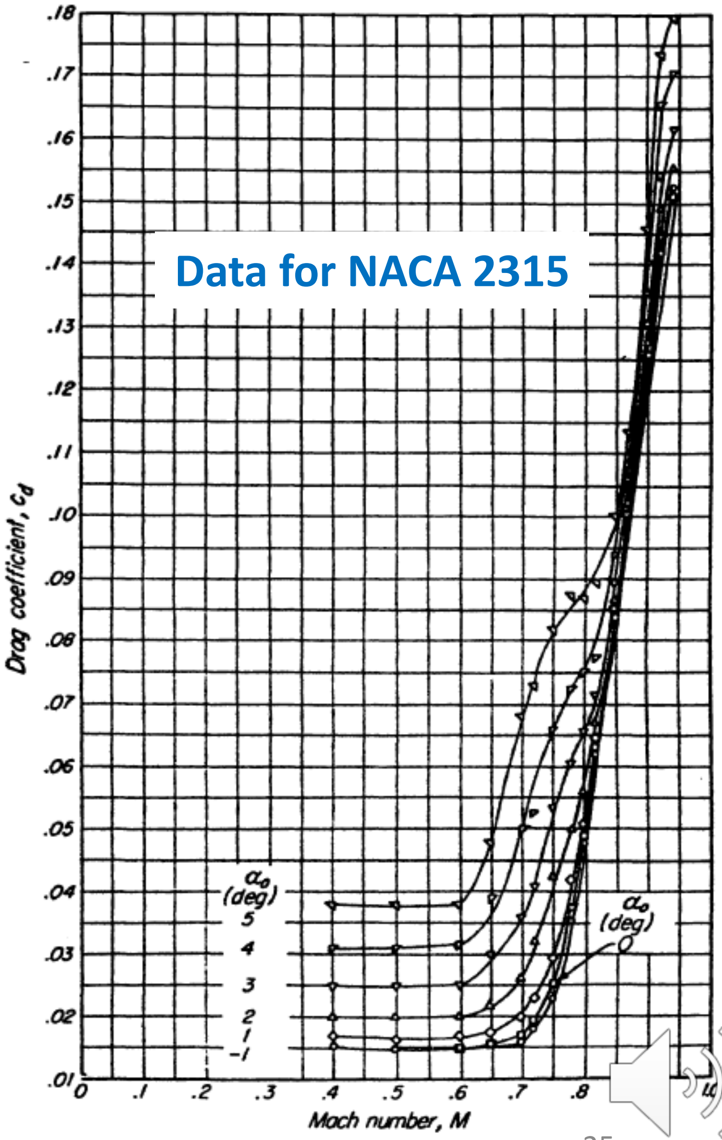
Airfoil designs for subsonic, transonic and supersonic flight differ greatly from each other



Abbott and Doenhoff, Theory of Wing Sections, 1959

Mach number dependence of drag coefficient

- At low Mach numbers, c_d (like c_l) is essentially independent of Mach number
- Approaching sonic speed, c_d increases greatly
- This is called "drag divergence"
- Mach no. dependence of c_d (like c_l) sets in at lower Mach nos. for higher AoA's
- Airfoils have to be specifically designed for crossing the so-called "sound barrier"
- Propulsion also must be much more powerful to overcome the high drag



Abbott and Doenhoff, Theory of Wing Sections, 1959

Wave drag

This is an additional drag mechanism in transonic/supersonic flows

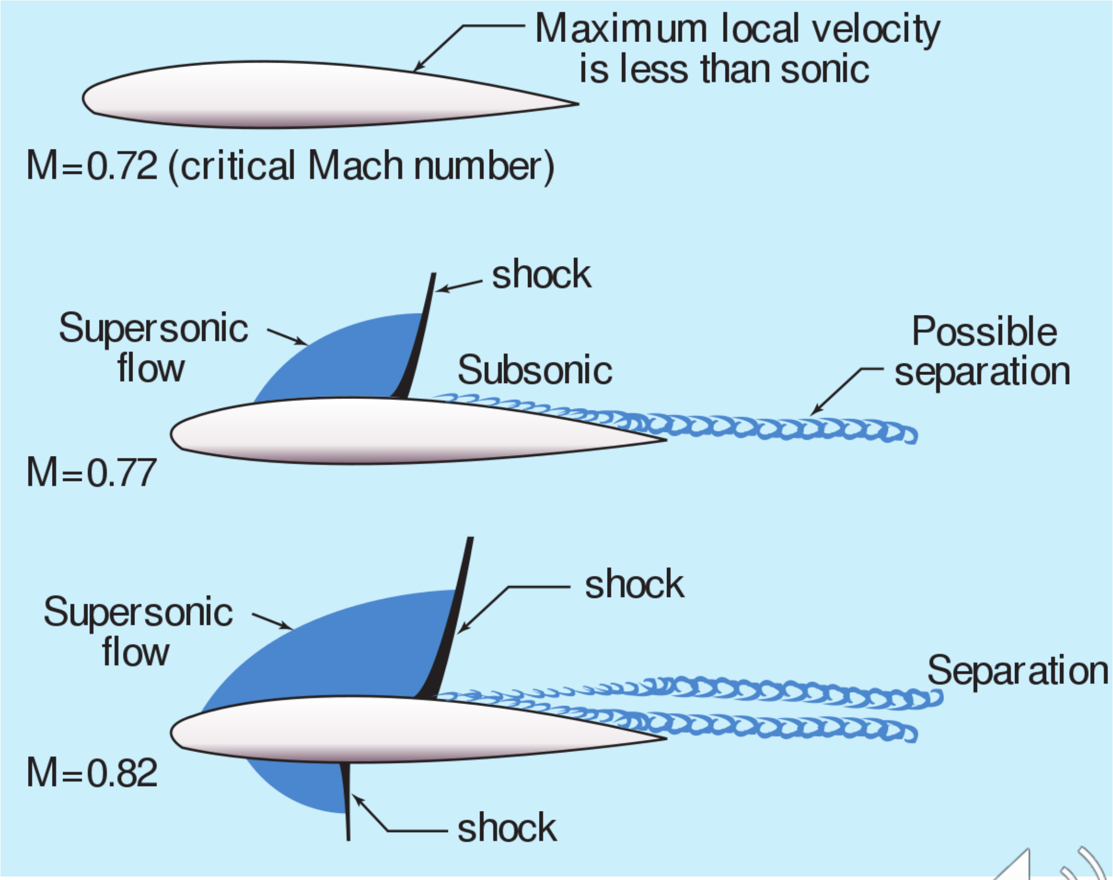
These flows have local shock waves that cause increase of entropy

Drastic increase of pressure behind shock waves leads to suction loss

- The suction loss can be estimated with *inviscid* theory!

The adverse pressure gradient also causes flow separation (form drag)

- This isn't predicted by inviscid theory



https://en.wikipedia.org/wiki/Transonic

Aerodynamic Characteristics of Wings

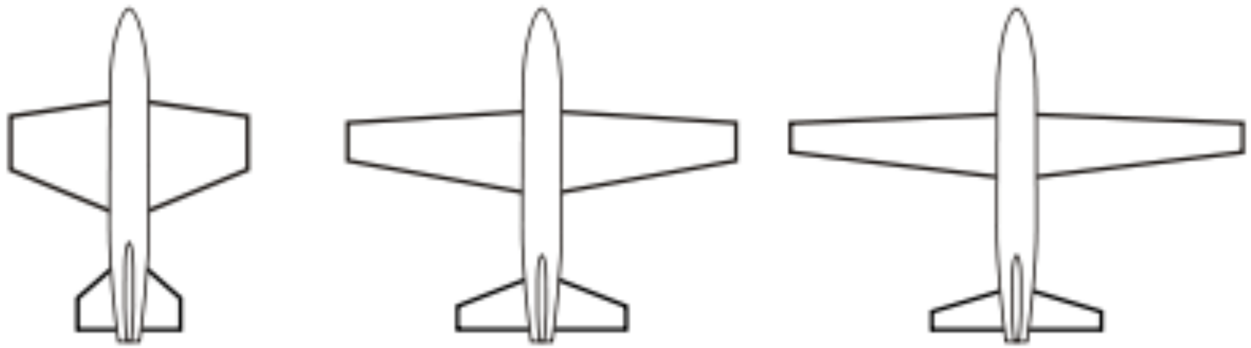
Aerodynamic Characteristics

Vortex system trailing an aircraft

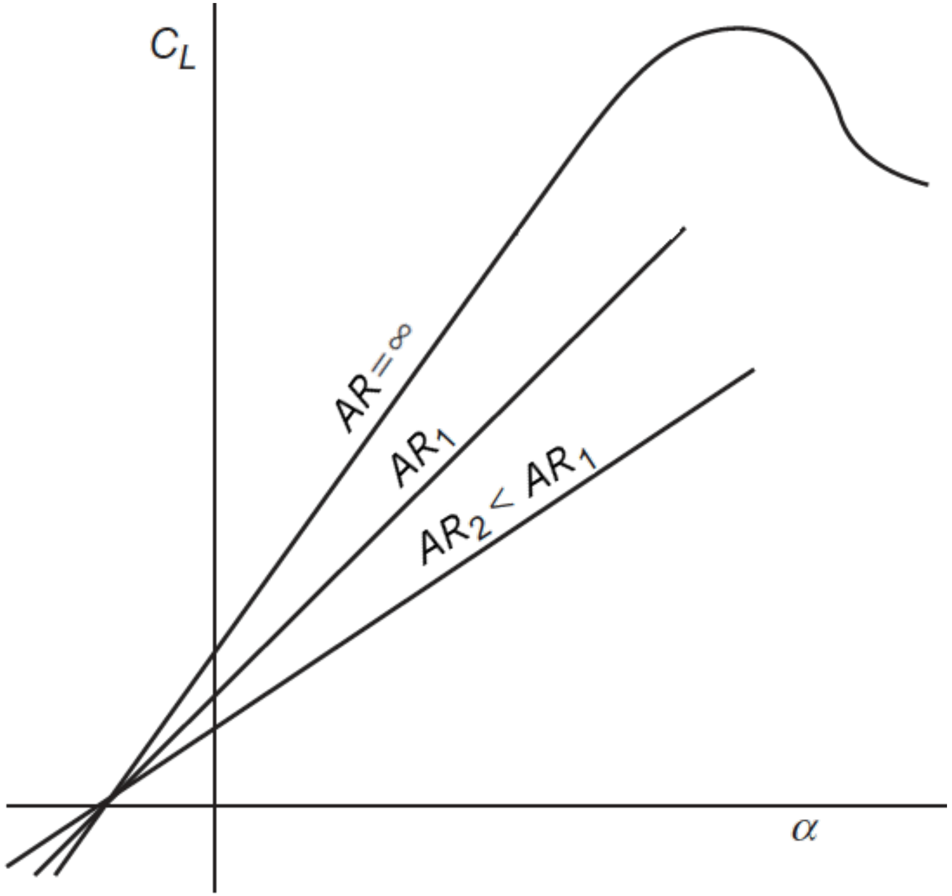
https://www.youtube.com/watch?v=BaRb46vv_bQ

Lift coefficient of wings

- As $\mathrm{AR} \to \infty$, wing tends to airfoil section
- For same AoA, C_L is a strong function of aspect ratio
- Lift slope decreases with decrease of AR
- $\alpha_{L=0}$ remains same



Low aspect ratio Moderate aspect ratio High aspect ratio



Houghton et al., Aerodynamics for Engineering Students, 2013

Drag coefficient of wings – (lift) induced drag

- *Lift-induced drag* (also called induced drag) is a by-product of the lifting mechanism (pressure difference across wing)
- Creates vortices in the vicinity of the wing that don't contribute to lift but take away energy – drag
- Lower the aspect ratio, greater the three-dimensionality of the flow, greater is the induced drag

Drag polar for various aspect ratios

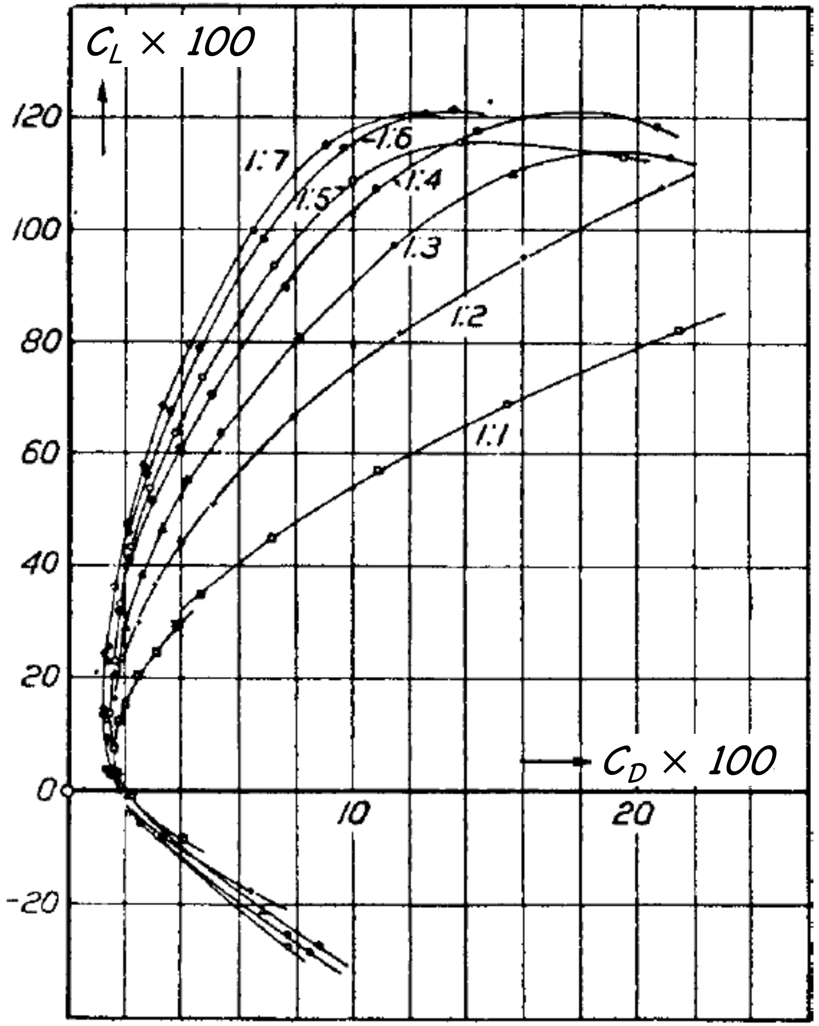
Shown here is Prandtl's classic rectangular wing data for aspect ratios from 1 to 7 (1:1 to 1:7)

- It presents the dramatic dependence of lift & drag on AR

Increasing AR beyond 6 or 7 doesn't appear to affect behaviour

- 3D effects are low for high-AR wings – i.e., essentially 2D airfoil!

Prandtl was able to model these variations from *inviscid theory*!



Prandtl, L., Applications of modern hydrodynamics to aeronautics, NACA Report No. 116, 1921

Conclusion

- Inviscid theory is appropriate for lift and pitching moment prediction
  - This is not only true for airfoils but approximately so for wings too
  - Theoretical predictions rarely use viscous theory
  - Computations may use viscous models, but not always
- Incompressible theory is appropriate for low subsonic speeds
- Wings with high aspect ratio can be modelled as airfoil sections
- Inviscid theory also yields “lift-induced drag” and “wave drag”
- Of course, viscous theory needed for predicting “profile drag”, i.e.
  - Skin friction drag, and
  - Form drag

End of Topic

Aerodynamic Characteristics