Navigate into the wind

機械工程實務 **2024**

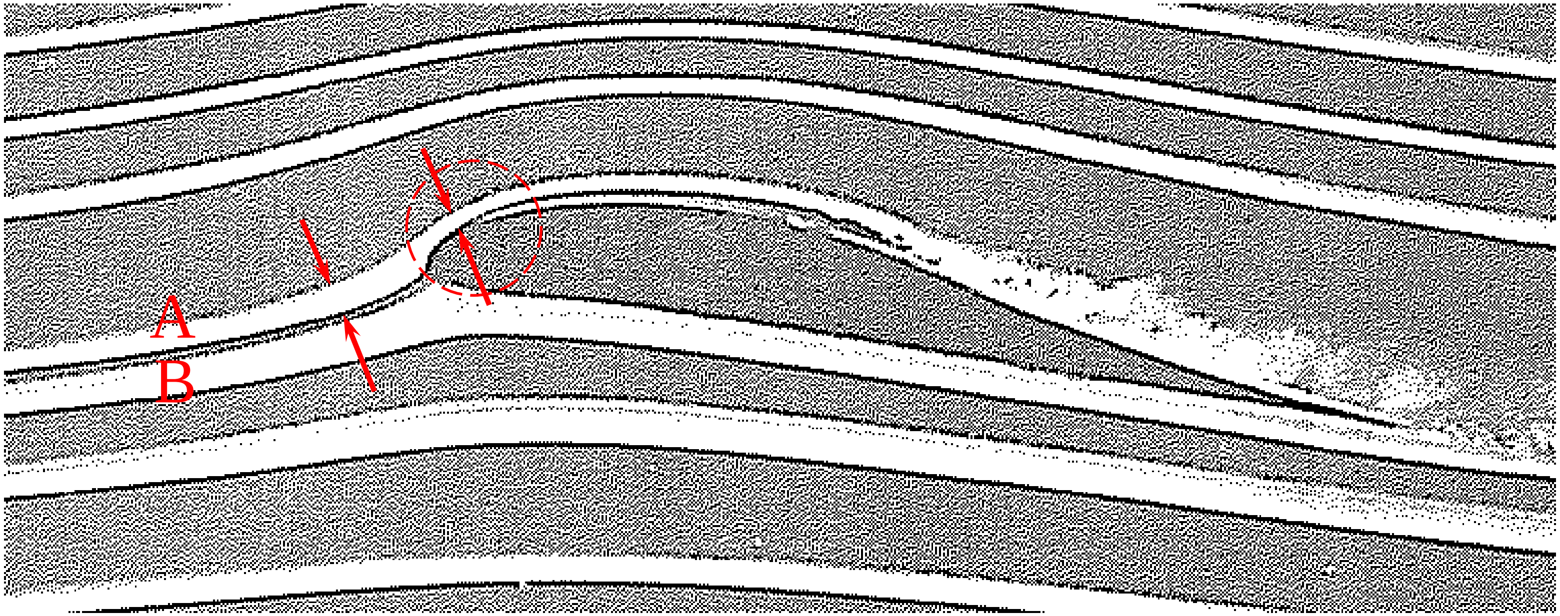
Fu-Ling Yang

Flow body interaction problem: lift vs. drag

1. Lift by deformed streamlines (due to pressure variation)
   - Two comparable streamtubes A & B impinges onto an airfoil
   - Streamtube A is squashed to a smaller cross-sectional area by the curvature of the top-half airfoil; such surface-induced deformation is less severe on streamtube B.

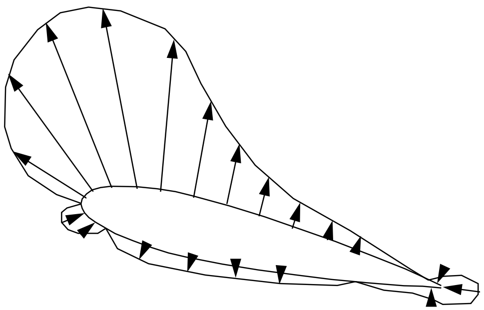
   By mass conservation: ρAV=constant

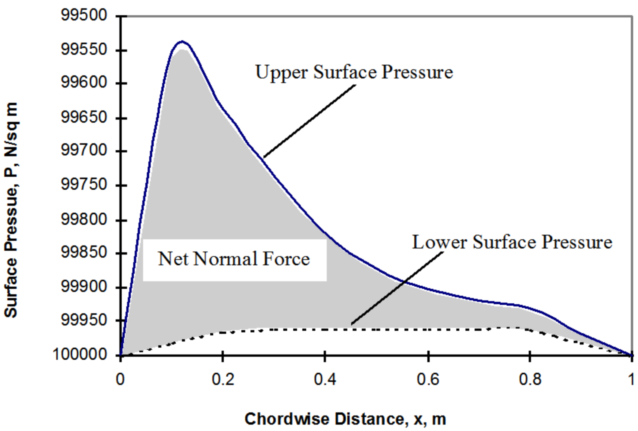
   → Reducing A (cross-sectional area) enhances V (mean velocity)



2. As V ↑ p↓
   - Incompressible, inviscid: **Bernoulli's Equation**

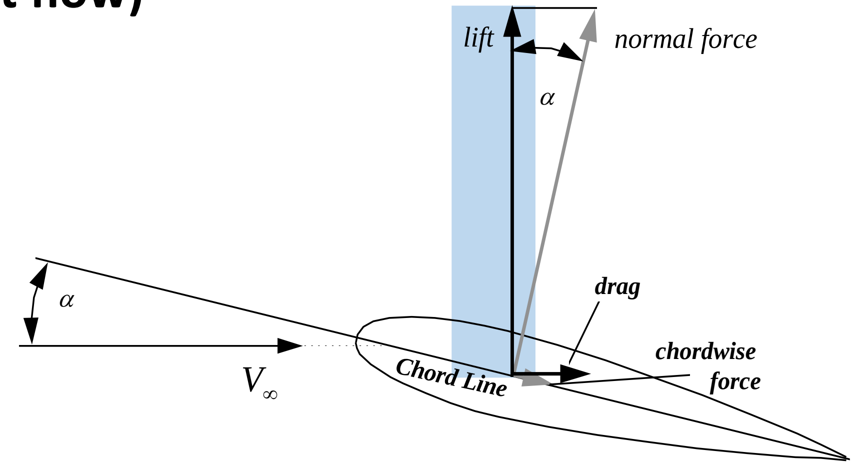
$$p + \frac{1}{2}\rho V^2 = \text{constant} \;\rightarrow\; dp = -\rho V dV$$





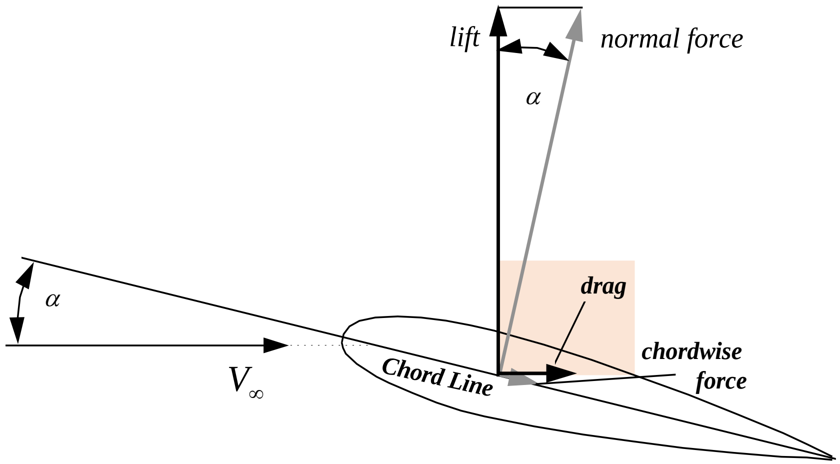
Most of lift is produced in the first 20-30% of airfoil

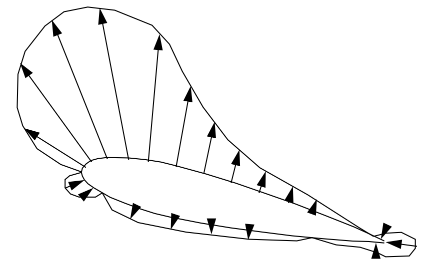
3. Lower pressure over the upper surface plus higher pressure over the bottom surface gives a net upward force→ **Lift (perpendicular to the incident flow)**



Resultant aerodynamic force acts at the Center of Pressure (CP)

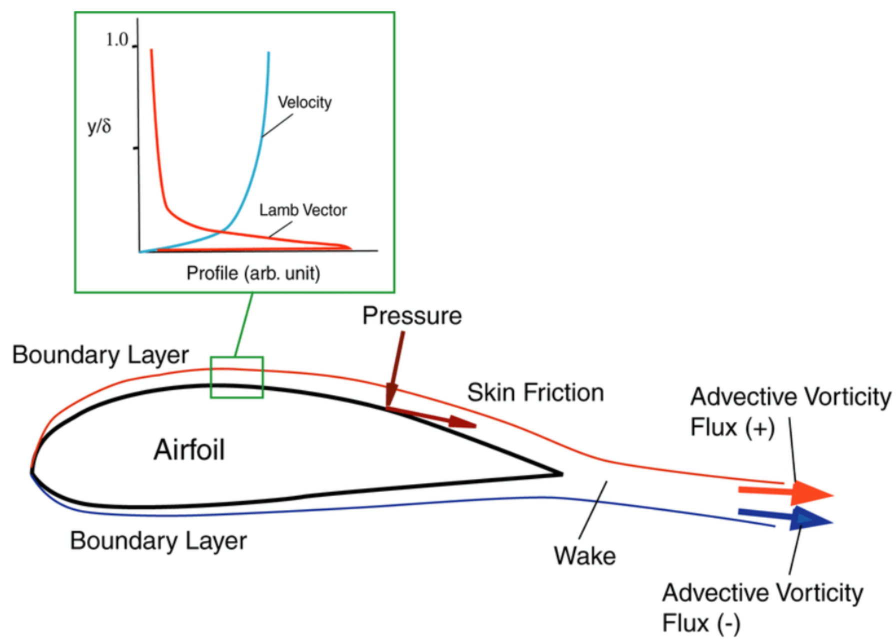
Drag: form drag + skin drag





Form drag (Pressure drag): due to fore-and-apt asymmetry of surface pressure (again, due to curved streamline, predicted via potential flow theory)

The no-slip boundary condition, however, suggests a thin boundary layer next to the solid surface. Flow velocity grows from zero (no-slip) to free stream within this thin layer. Strong shearing $\frac{\partial u}{\partial y}$ develops to induce tangential stress, $\tau = \mu \frac{\partial u}{\partial y}$. Surface integration of this tangential stress component gives the Skin drag (Friction drag).



Aerodynamic coefficients

Lift coefficient

$$\mathrm{C_L} \equiv \frac{\mathrm{L}}{\frac{1}{2}\,\rho U^2\,A}$$

Total Drag coefficient = Pressure drag coefficient + friction drag coefficient

$$\mathrm{C_D} \equiv \frac{F_p + F_f}{\frac{1}{2}\rho U^2 A} = C_p + C_f$$

Considering the role of streamline curvature, $\mathrm{C_D}$ and C_L depend on

Angle of attack α

Reynolds number Re

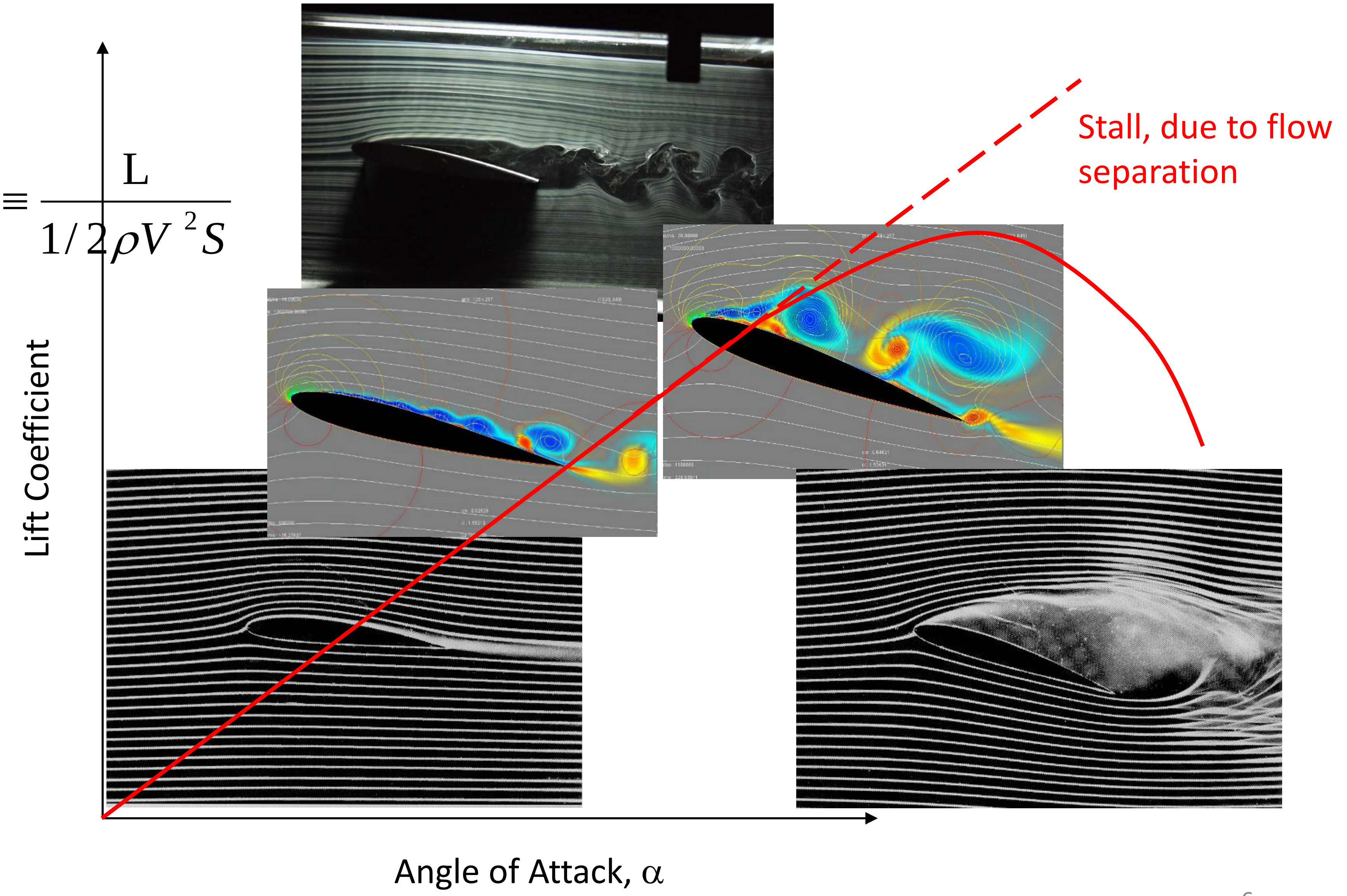
Geometry (chord length c, airfoil camber, …etc)

Aspect ratio (3D effect)

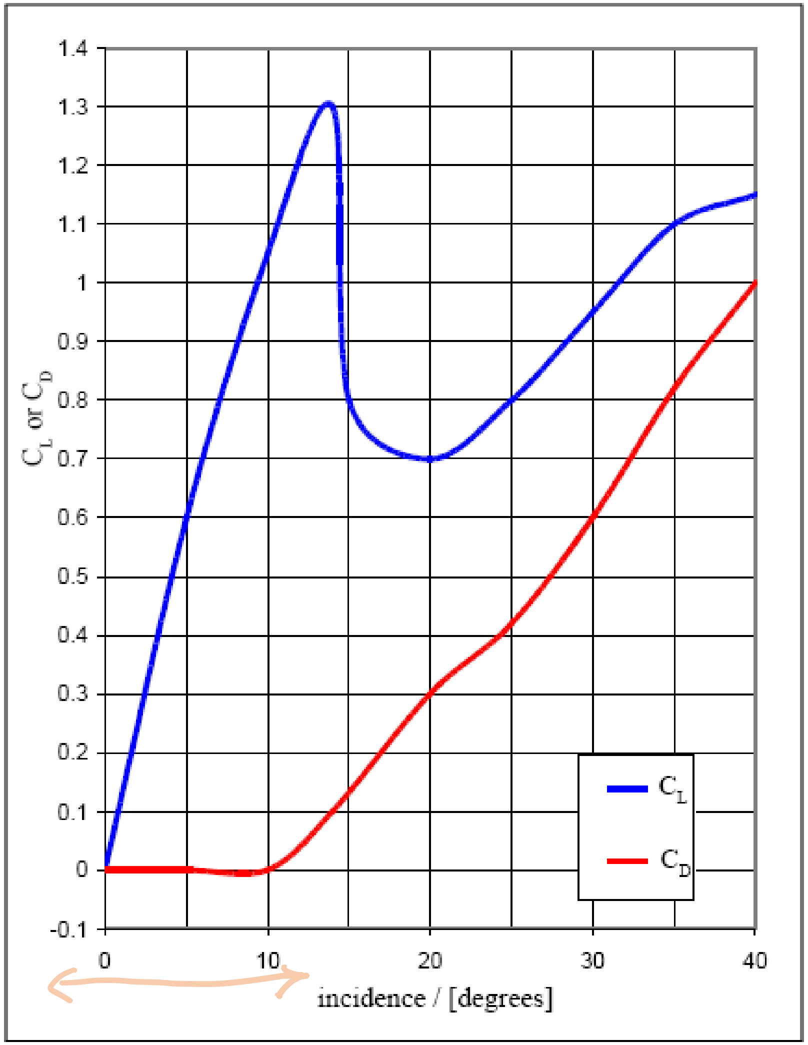
Ground effect

Lift coefficient

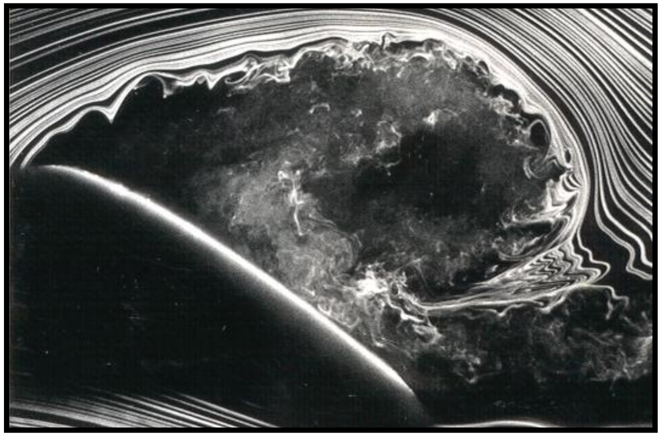
$$C_L \equiv \frac{L}{1/2\rho V^2 S}$$

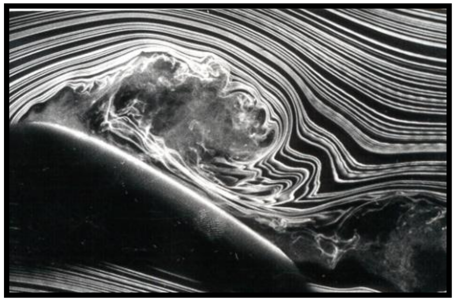


Lift and Total Drag Coefficients for a NACA 0012 Aerofoil



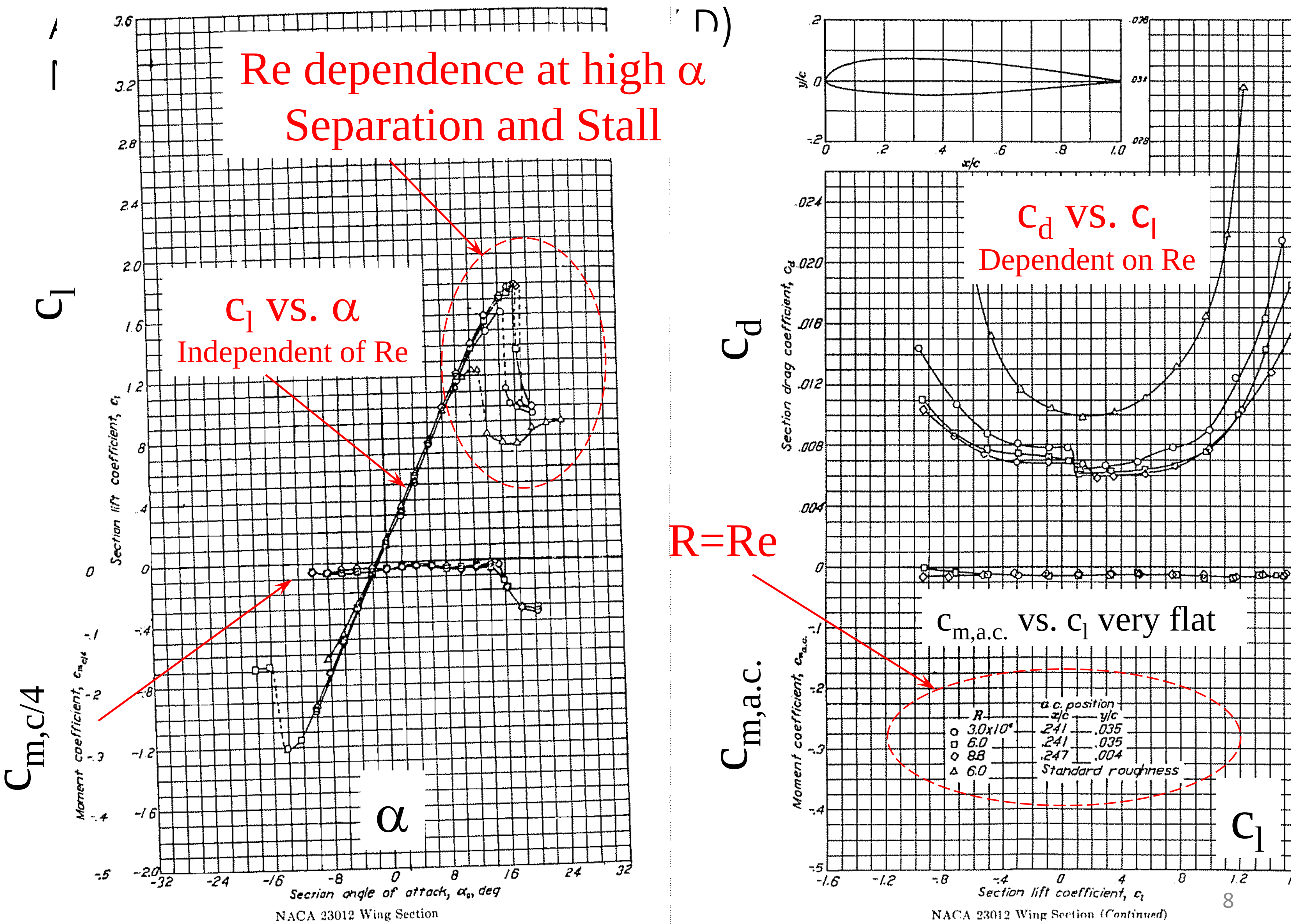
Stall around 14deg.:
abrupt drop of lift/rise of drag



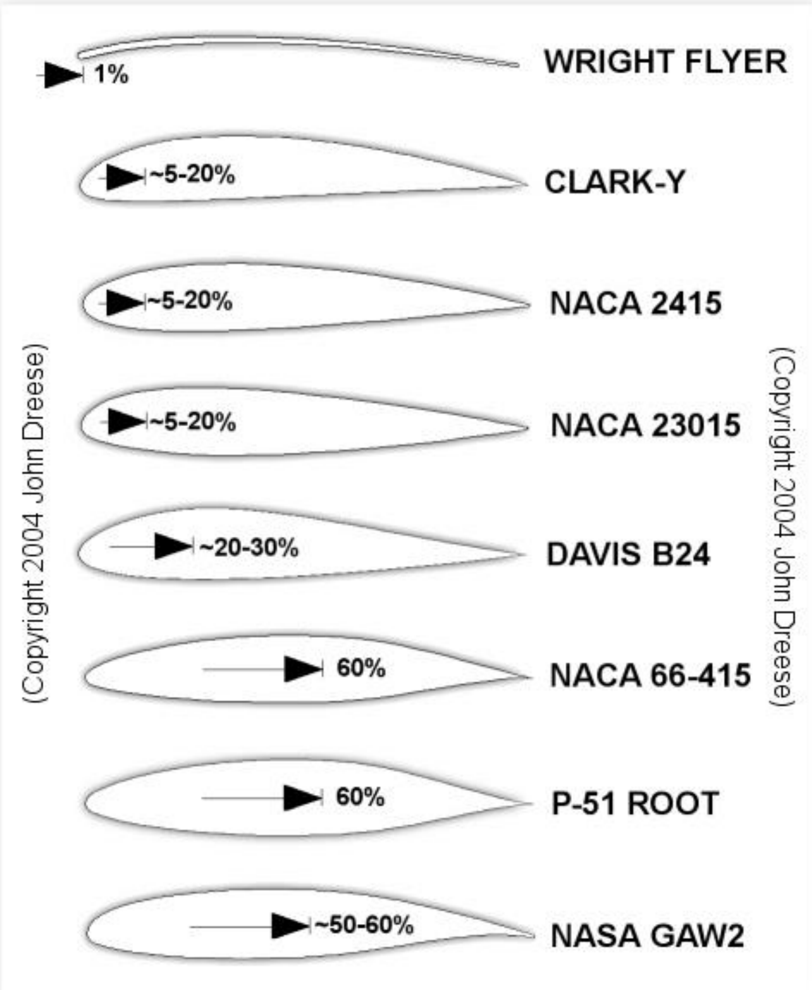


Low incidence:
large lift/small drag

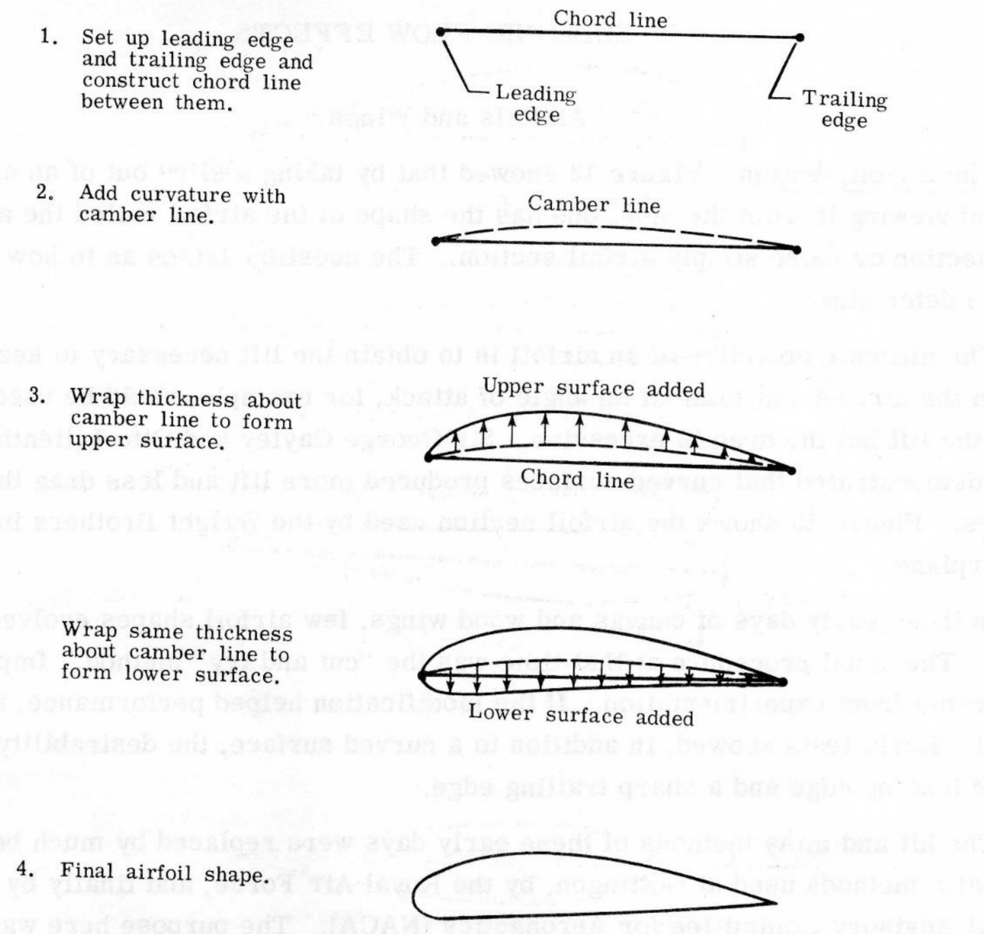
NACA airfoil performance charts can also be easily found online



Airfoil



Geometric Construction of an Airfoil

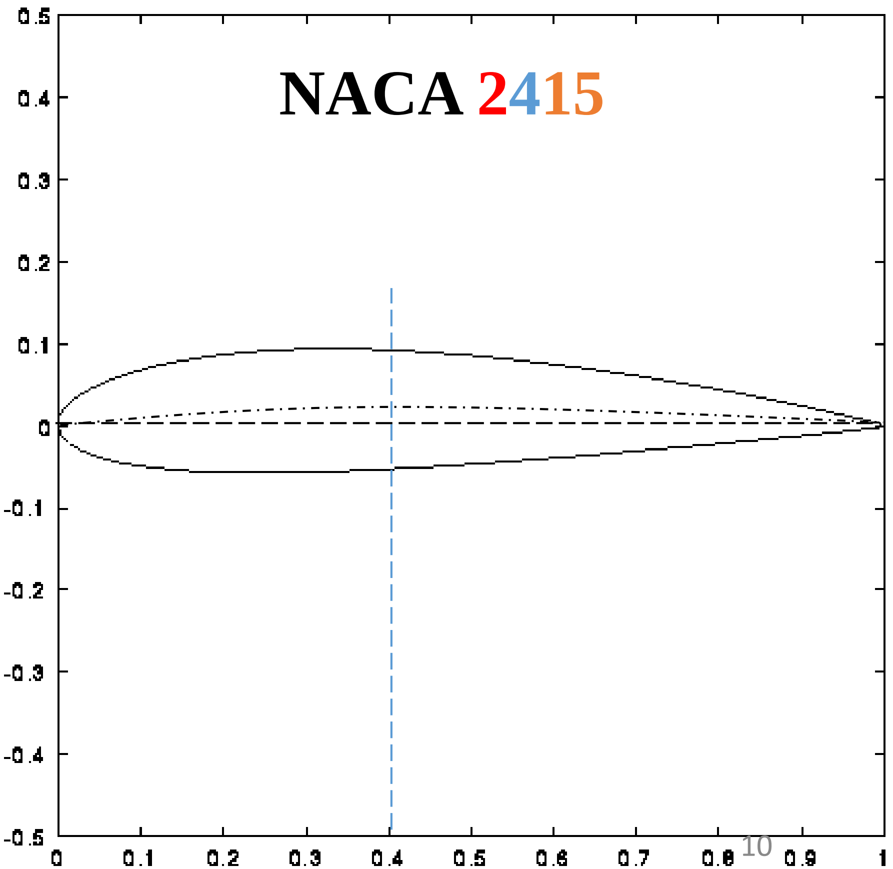


NACA 4-digits series

- **First digit** specifies maximum camber in percentage of chord
- **Second digit** indicates position of maximum camber in tenths of chord
- **Last two digits** provide maximum thickness of airfoil in percentage of chord

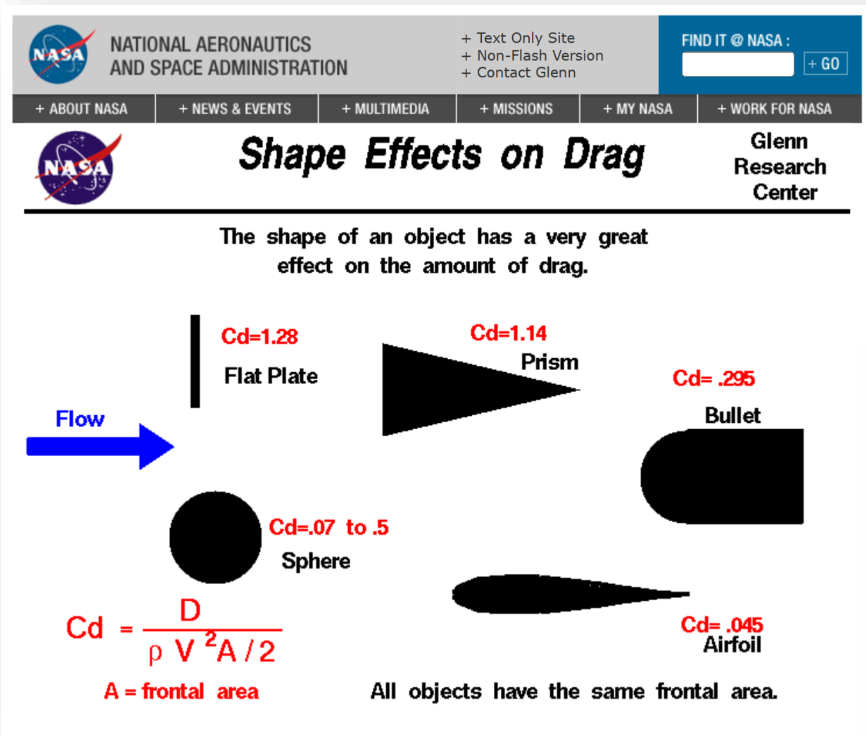
Example: **NACA 2415**

- Airfoil has maximum thickness of **15** of chord (0.15c)
- Camber of **2%** (0.02c) located **40%** back from airfoil leading edge (0.4c)

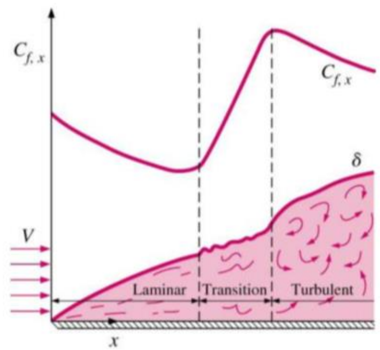


Streamlined vs. blunt body

When $C_D > C_L$: blunt body; $C_D < C_L$: streamlined object



Flat Plate Drag



- Local friction c $C_{f,x} = \frac{0.664}{Re_x^{1/2}}$
  - Laminar: $C_{f,x} = \frac{0.059}{Re_x^{1/5}}$
  - Turbulent:
- Avera $C_f = \frac{1}{L}\int_0^L C_{f,x}\,dx$
  $C_f = \frac{1.33}{Re_L^{1/2}}$
  - Laminar: $C_f = \frac{0.074}{Re_L^{1/5}}$
  - Turbulent:

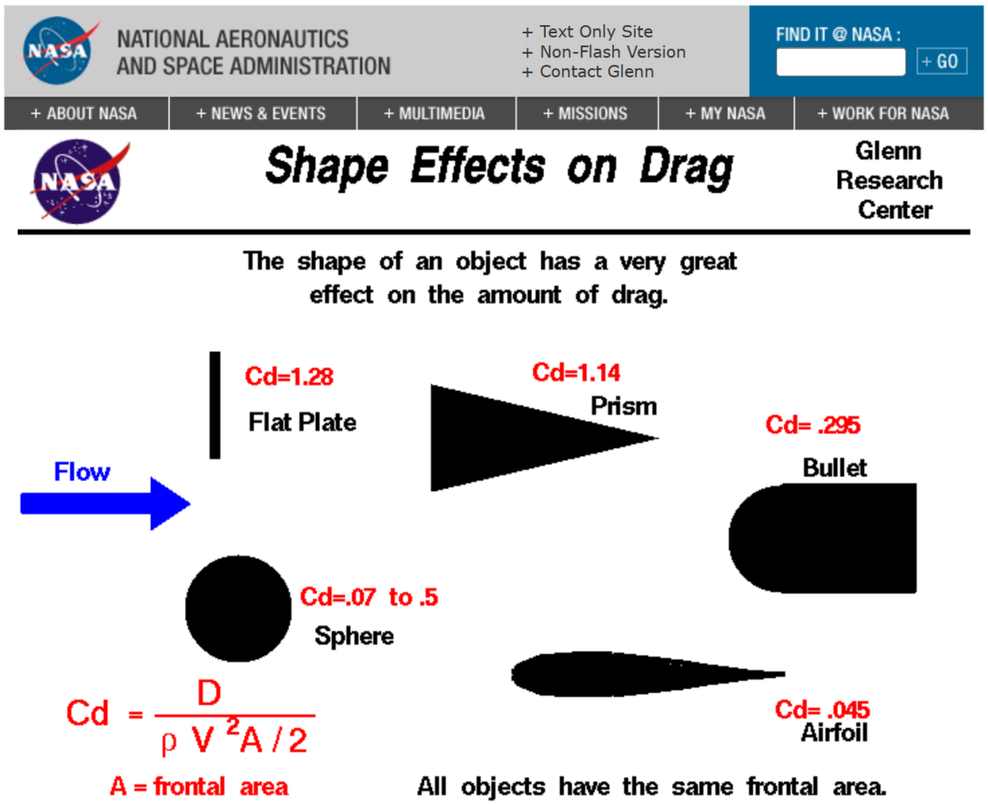
For some cases, plate is long enough for turbulent flow, but not long enough to neglect laminar portion

$$C_f = \frac{1}{L}\left(\int_0^{x_{cr}} C_{f,x,lam}\,dx + \int_{x_{cr}}^{L} C_{f,x,turb}\,dx\right) \qquad C_f = \frac{0.075}{Re_L^{1/5}} - \frac{1742}{Re_L}$$

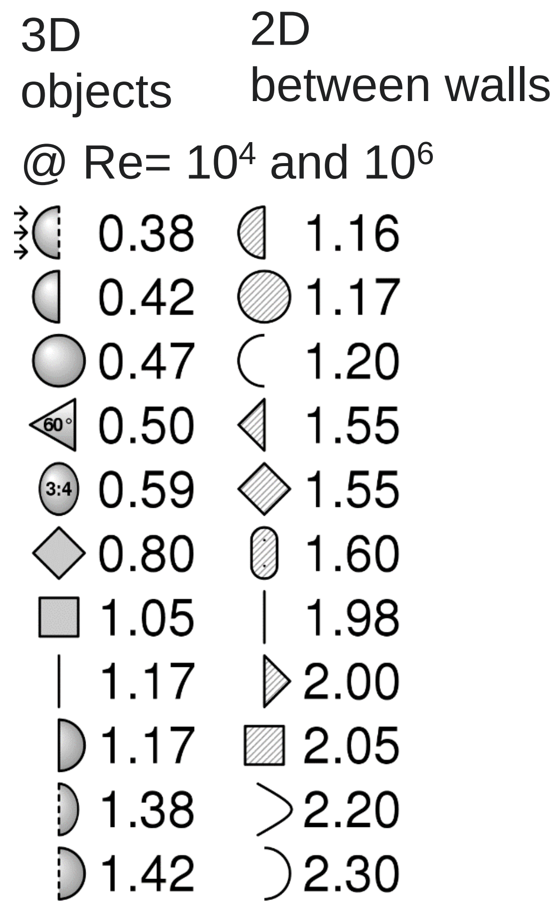
$C_D \sim C_f$ friction drag dominated

Negligible C_L, C_p

Non-airfoil?



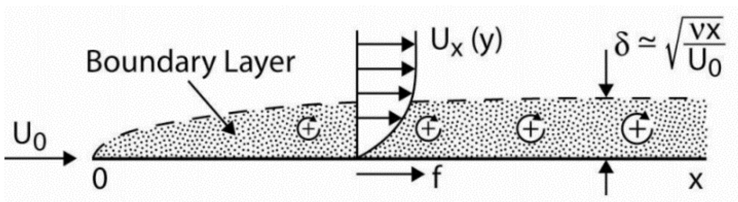
Shape Effects on Drag (archive.org)

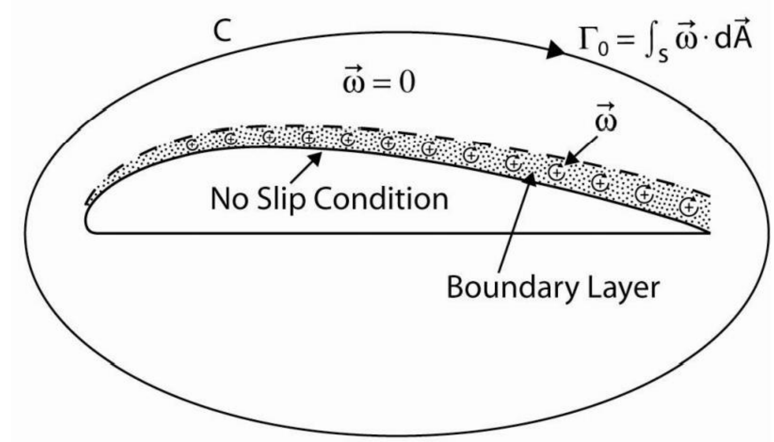


Hoerner fluid dynamic drag coefficients - Drag coefficient - Wikipedia

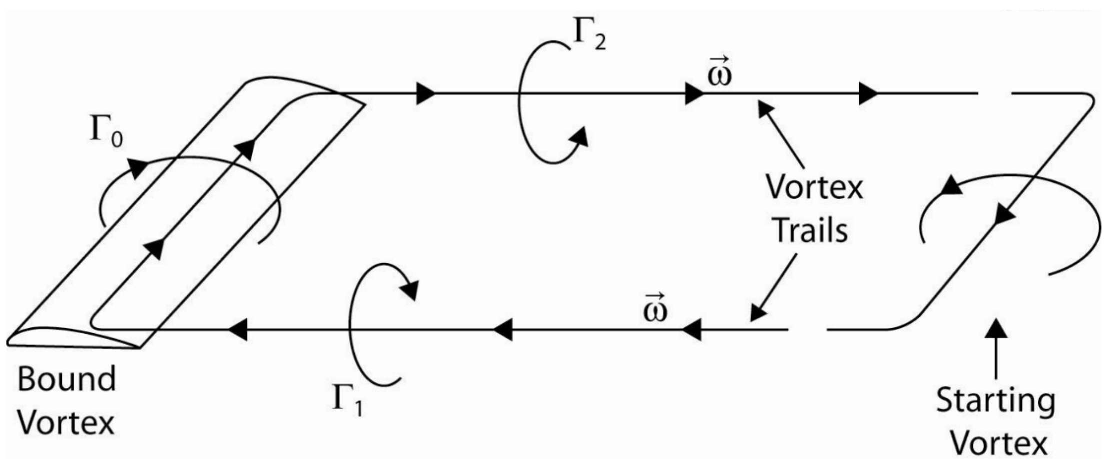
Effect of finite span

Strong shearing in the boundary layer → vortex sheet develops above the solid surface



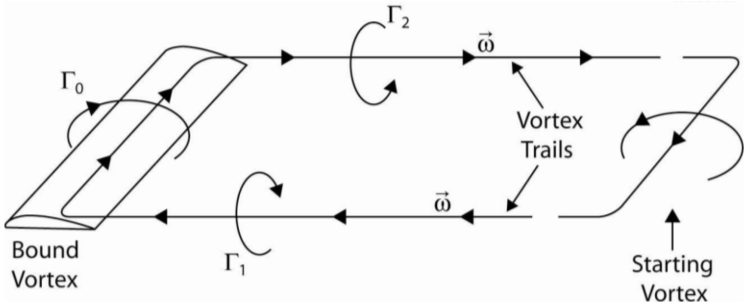


With finite span, 3D vorticity loop developed in space to conserve total vorticity.

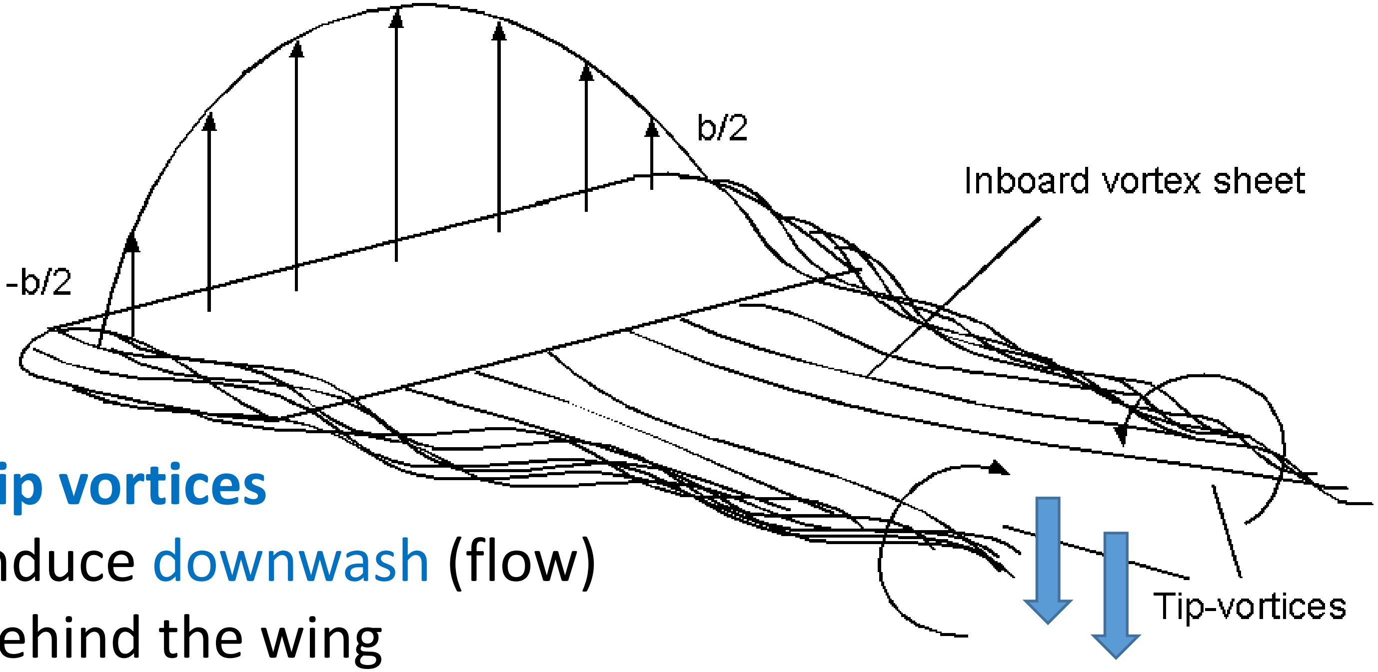


Note: $\Gamma_1 = \Gamma_2 = \Gamma_0$, vortex trails cannot be avoided.

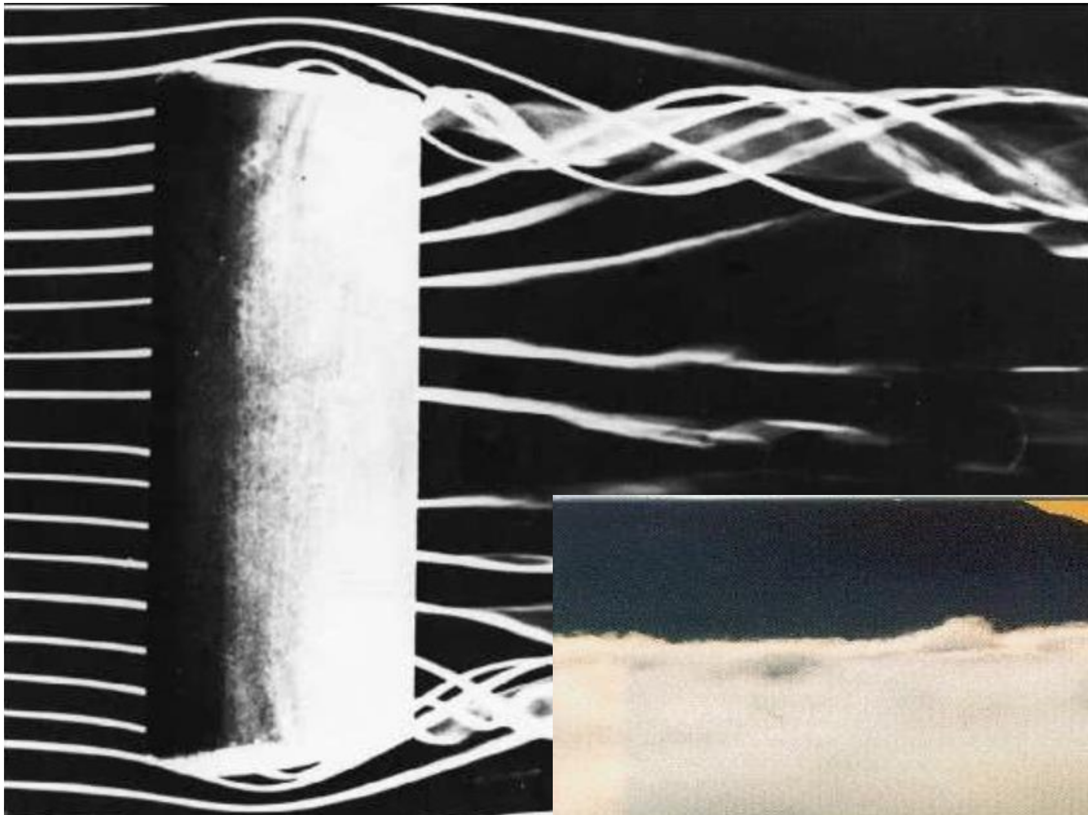
Tip vortex & downwash



Bound vortex (distributed circulation over the wing)→ **Lift**

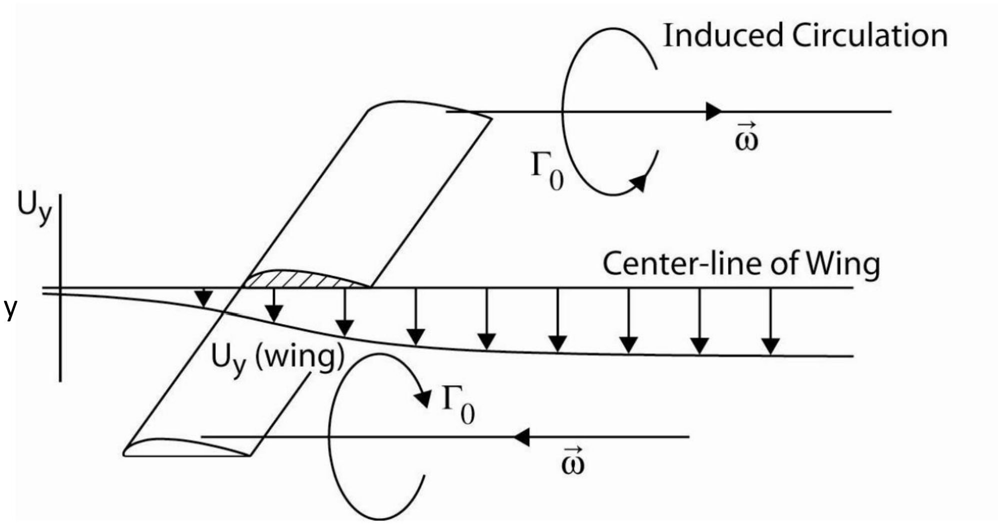


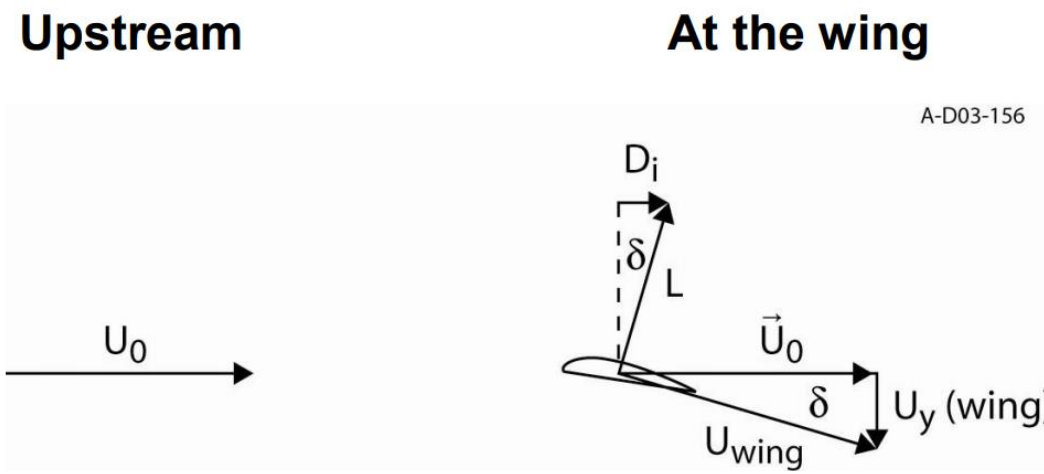
Tip vortices
induce downwash (flow)
behind the wing



Modified drag

Downwash velocity U_y

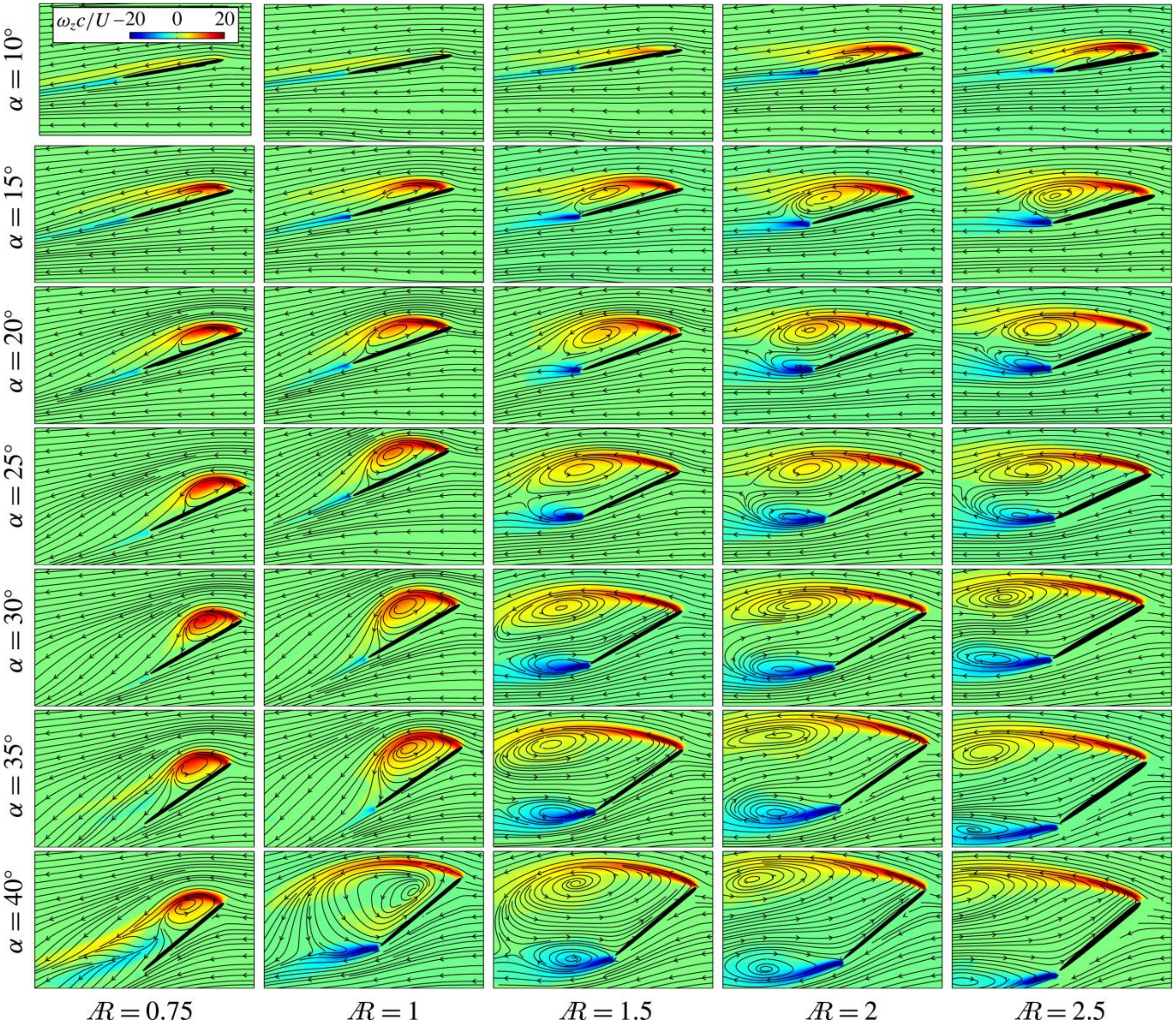




U_y tilts the total velocity vector at the wing surface
Effective lift at the midplane changes from from L to $Lcos\delta$ at midplane, (⊥ incoming U_0); likewise, local drag is modified (//- U_0)

Modified flow structure

On the mechanism of high-incidence lift generation for steadily translating low-aspect-ratio wings | Journal of Fluid Mechanics | Cambridge Core



Re=8E5, @ Midplane

Modified aerodynamic coefficients

[On the mechanism of high-incidence lift generation for steadily translating low-aspect-ratio wings | Journal of Fluid Mechanics | Cambridge Core]

Re=8E5

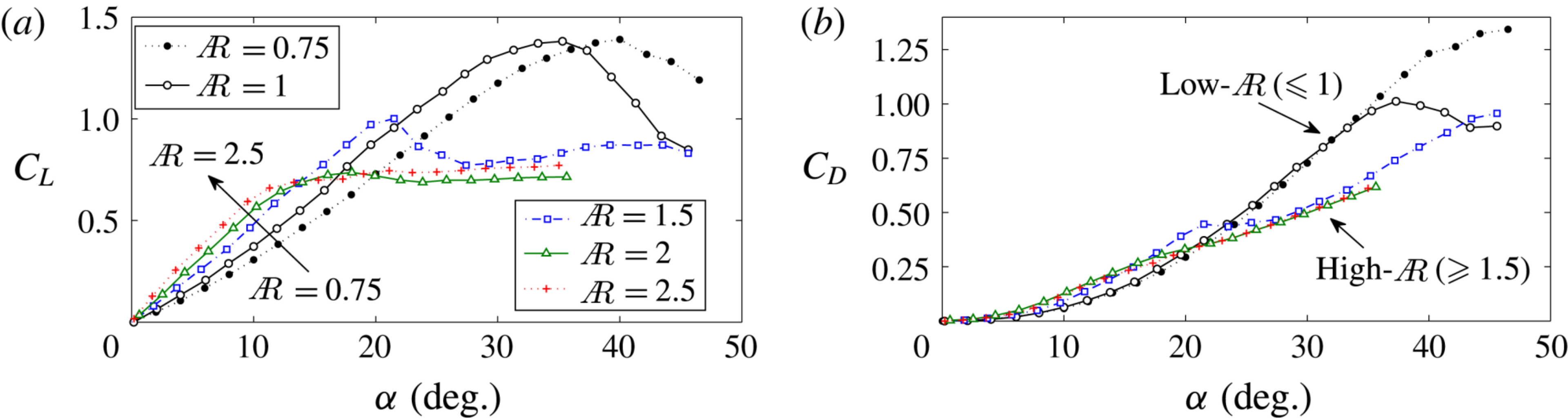
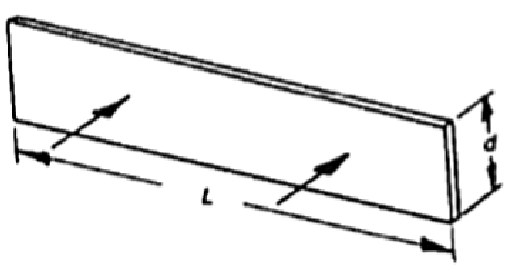
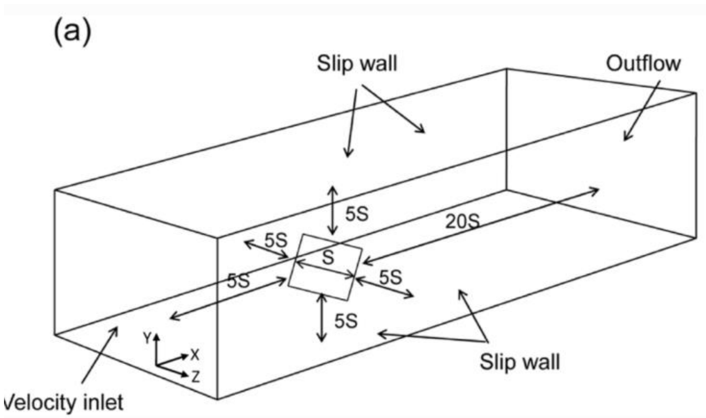
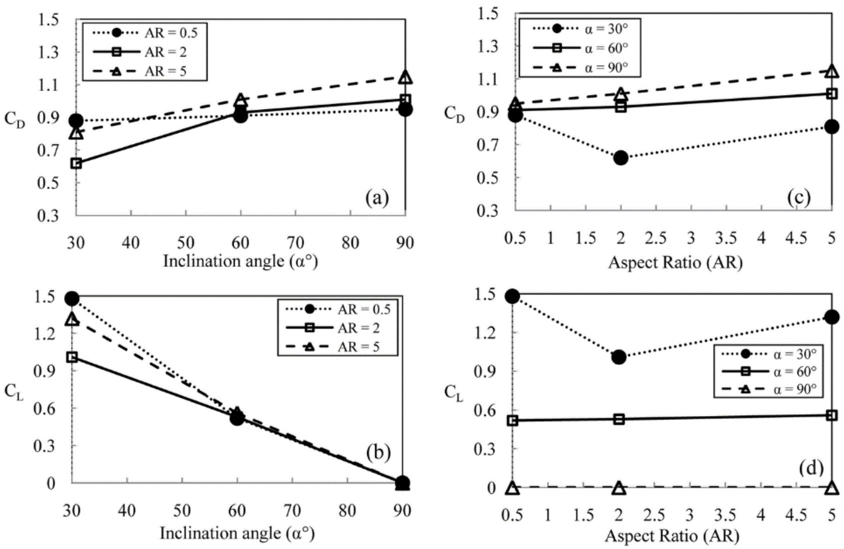


Illustration	Description	L / d	C_d	R_e / 10^4	Frontal Area
	Rectangular Flat Plate	1	1.15	60	L d
		2	1.16		
		5	1.20		
		10	1.22		
		30	1.62		
		∞	1.98		

(AR)

[Rectangular Flat Plate Drag Drag Coefficient Equation and Calculator (engineersedge.com)]





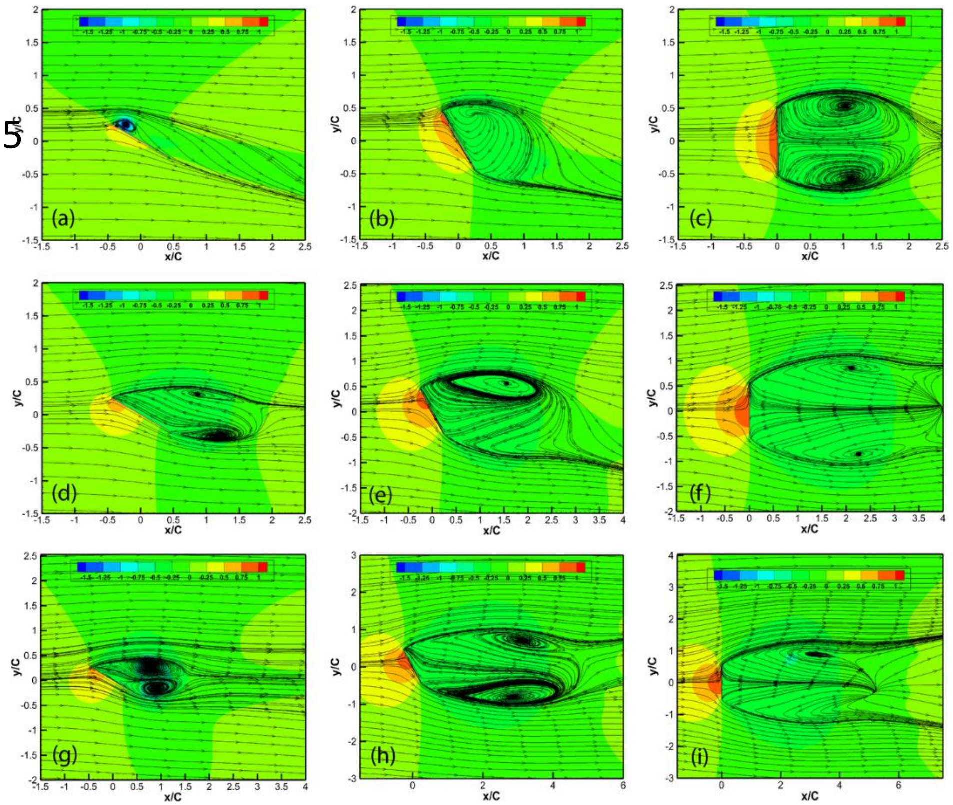
Re=0.75-1.5E5

Pressure coefficient contours

AR =0.5

2

5



α = 30°　　60°　　90°

[Effects of aspect ratio and inclination angle on aerodynamic loads of a flat plate | Advances in Aerodynamics | Full Text (springeropen.com)]

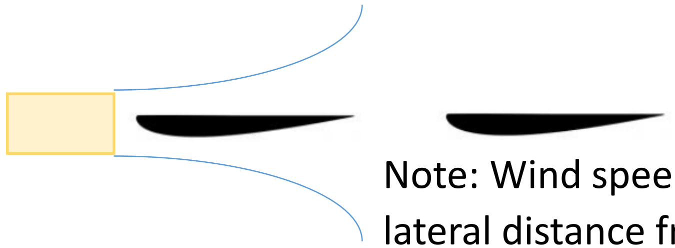
Pre-design thinking

Flow structure (streamlines) modifies pressure distribution that couples with the BL evolution; hence the p-induced lift, p-induced form drag, and shearing-induced friction drag all change with the local flow structure.

Look up a table within the range of possible Re is where to start to have a quick estimation of the lift/drag.

$$Re = \frac{\rho U C}{\mu} \rightarrow C_{D,L}(Re, \alpha)$$

$$D, L = C_{D,L} \times \frac{1}{2} \rho U^2 A$$

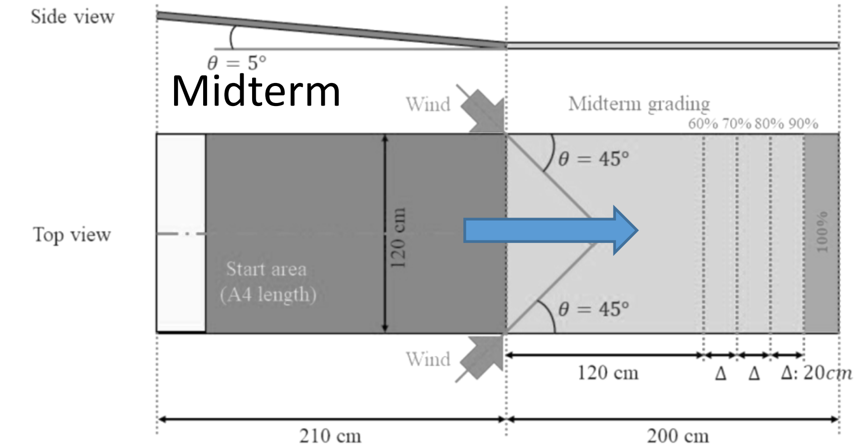


Note: Wind speed U drops with lateral distance from the blower.

Decide on a geometry

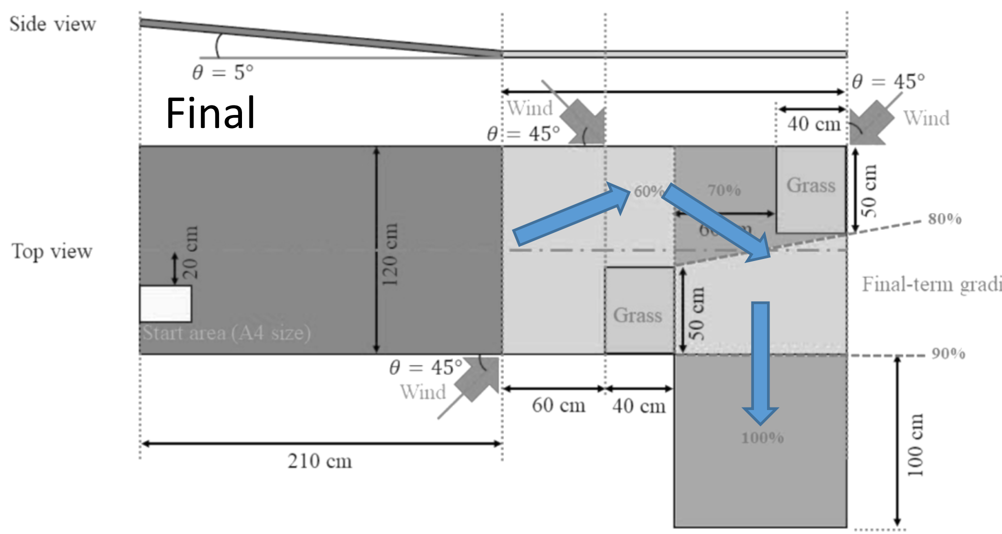
But! What is your design objective?

What is the function of your hydrodynamic force (let it be lift or drag)?



Downstream propulsion?

A. What do you need to overcome?



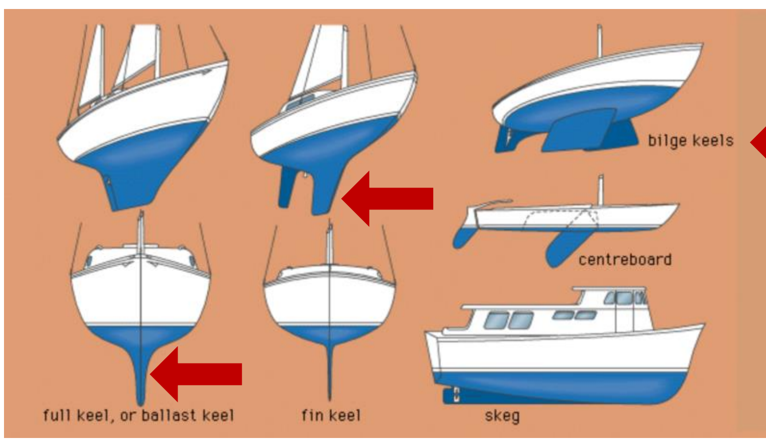
B. What do you need to navigate?

C. Grip to enhance maneuverability (when weight is limited)?

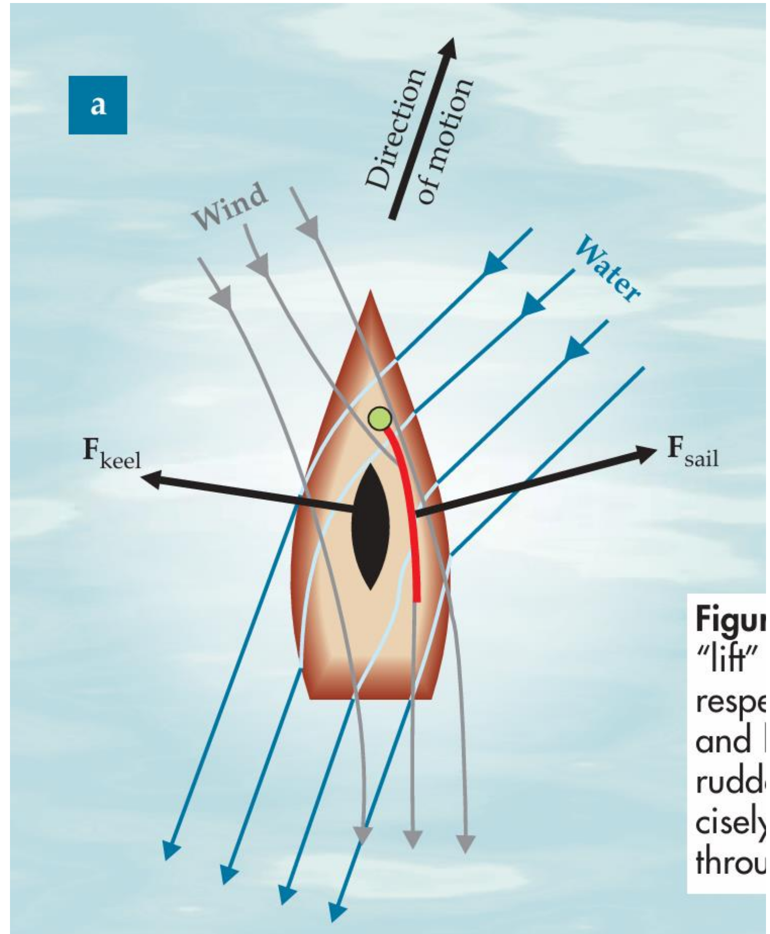
Navigation into the wind

Physics_of_sailing.pdf (nasa.gov)

Sail



Keel



Keel force is equivalent to the wheel friction force that can act off-line of the hydrodynamic force extracted from the ambient flow.

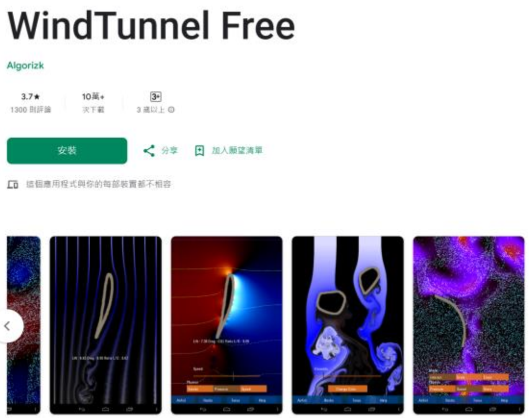
Identify your system first

- Gravity force
- Basal friction force
- Hydrodynamic force

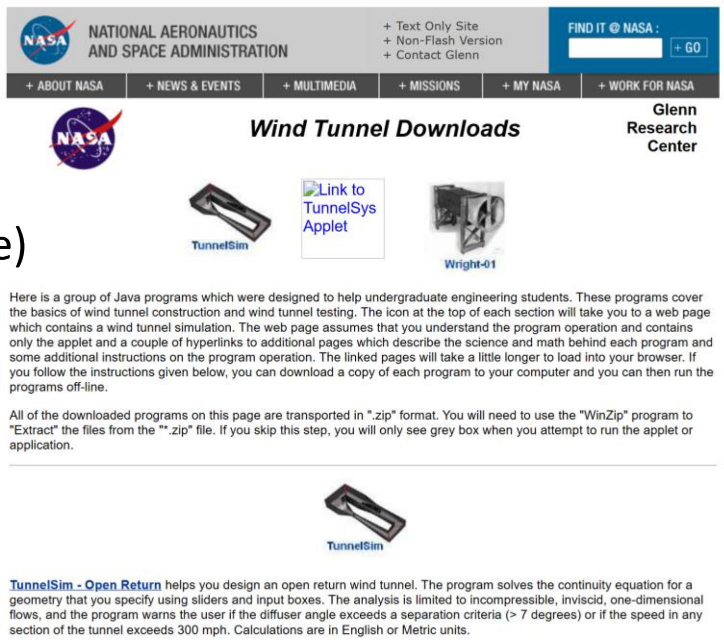
Decide on a geometry (C, A) and installation (α, distance from blower--U) relative to the ambient wind to determine whether lift or drag is exploited. Then go back to your charts to settle the design parameters for the first roung.

Some online resources

2D flow visualization



3D flow simulator (data base)


NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

+ Text Only Site
+ Non-Flash Version
+ Contact Glenn

FIND IT @ NASA : + GO

+ ABOUT NASA | + NEWS & EVENTS | + MULTIMEDIA | + MISSIONS | + MY NASA | + WORK FOR NASA

Wind Tunnel Downloads

Glenn Research Center

TunnelSim | Link to TunnelSys Applet | Wright-01

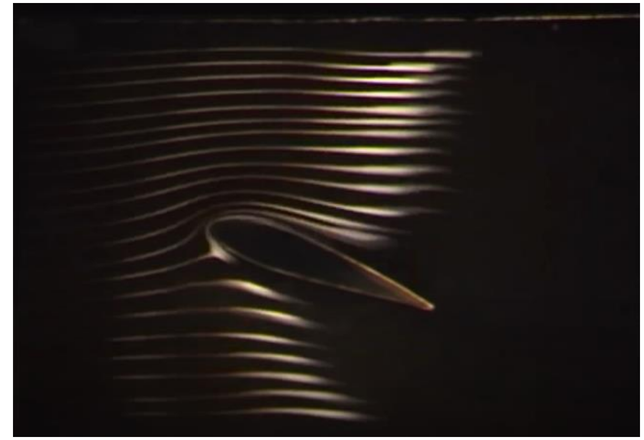
Here is a group of Java programs which were designed to help undergraduate engineering students. These programs cover the basics of wind tunnel construction and wind tunnel testing. The icon at the top of each section will take you to a web page which contains a wind tunnel simulation. The web page assumes that you understand the program operation and contains only the applet and a couple of hyperlinks to additional pages which describe the science and math behind each program and some additional instructions on the program operation. The linked pages will take a little longer to load into your browser. If you follow the instructions given below, you can download a copy of each program to your computer and you can then run the programs off-line.

All of the downloaded programs on this page are transported in ".zip" format. You will need to use the "WinZip" program to "Extract" the files from the "*.zip" file. If you skip this step, you will only see grey box when you attempt to run the applet or application.

TunnelSim

TunnelSim - Open Return helps you design an open return wind tunnel. The program solves the continuity equation for a geometry that you specify using sliders and input boxes. The analysis is limited to incompressible, inviscid, one-dimensional flows, and the program warns the user if the diffuser angle exceeds a separation criteria (> 7 degrees) or if the speed in any section of the tunnel exceeds 300 mph. Calculations are in English or Metric units.

Wind Tunnel Downloads (nasa.gov)



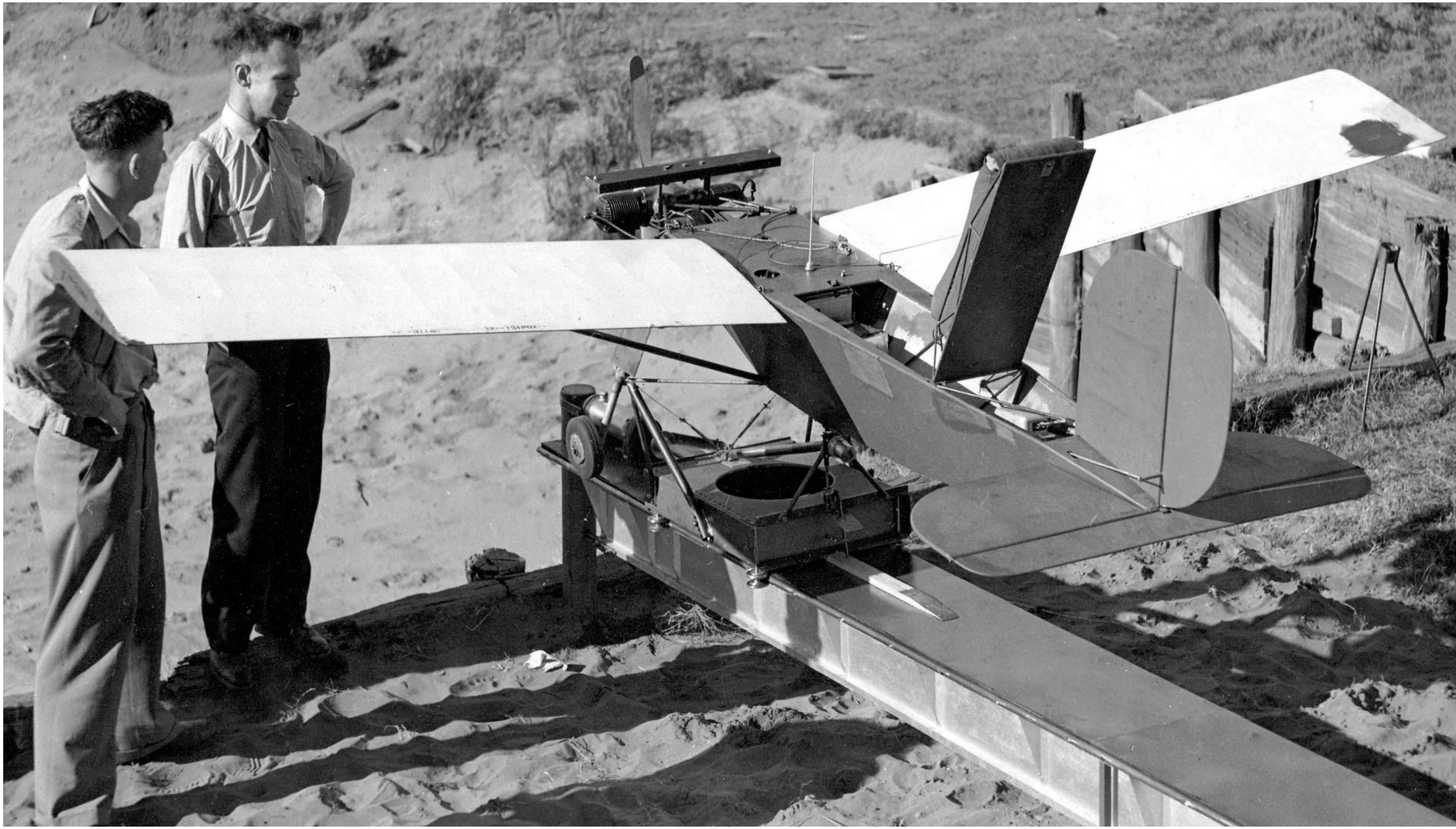
Airfoil data, pre-analysis software (potential flow based)

UIUC:
UIUC Airfoil Data Site (illinois.edu)

MIT: XFOIL
https://web.mit.edu/drela/Public/web/xfoil/

Javafoil
JavaFoil (mh-aerotools.de)

PDAS (sources of aeronautical software)
Public Domain Aeronautical Software (PDAS)
Sources of Aeronautical Software (pdas.com)



http://s6.aeromech.usyd.edu.au/aerodynamics/index.php/resources/

Observe and learn from the existing designs.
Think, propose, test and debug with logics!