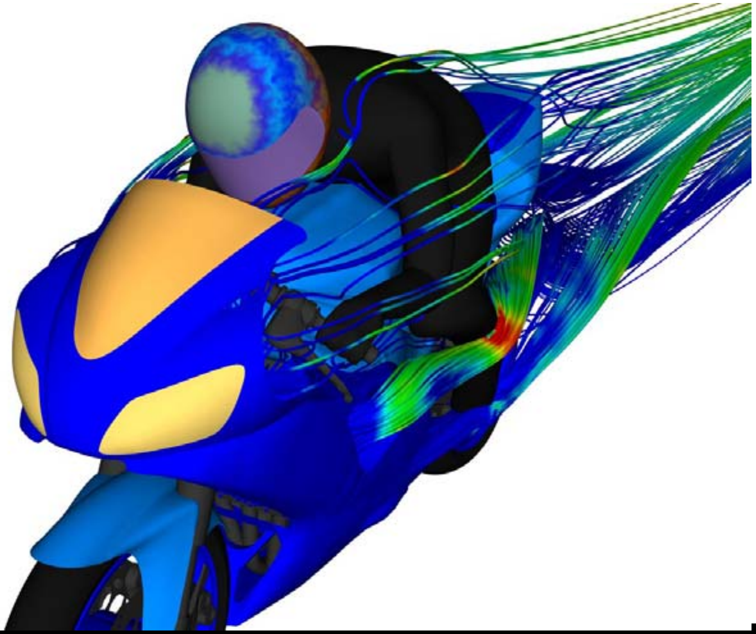
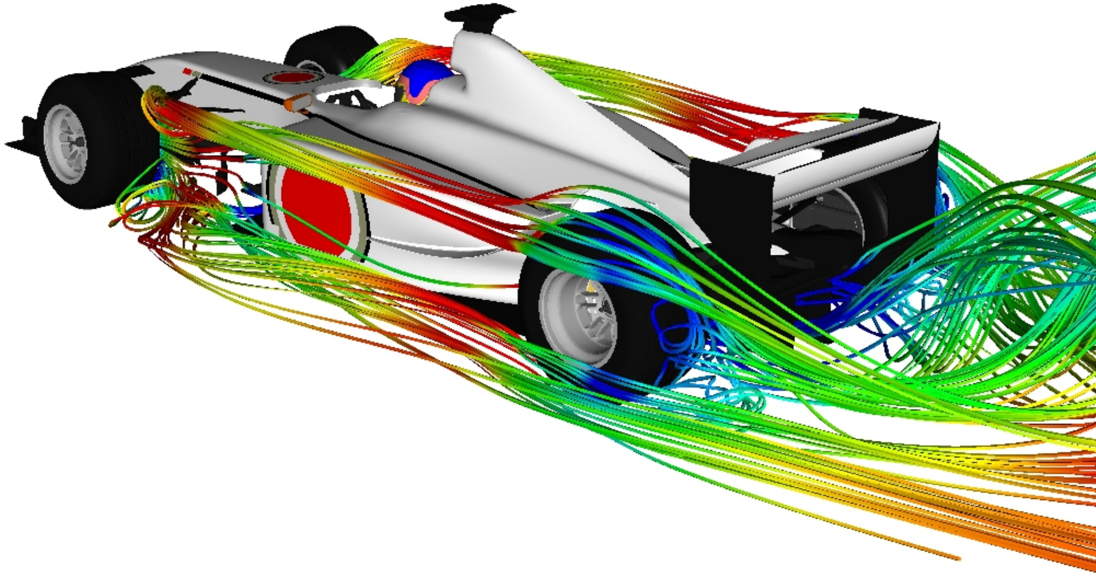
Chapter 11:
Flow over bodies. Lift and drag

Objectives

- Have an intuitive understanding of the various physical phenomena such as drag, friction and pressure drag, drag reduction, and lift.
- Calculate the drag force associated with flow over common geometries.
- Understand the effects of flow regime on the drag coefficients associated with flow over cylinders and spheres
- Understand the fundamentals of flow over airfoils, and calculate the drag and lift forces acting on airfoils.

Motivation

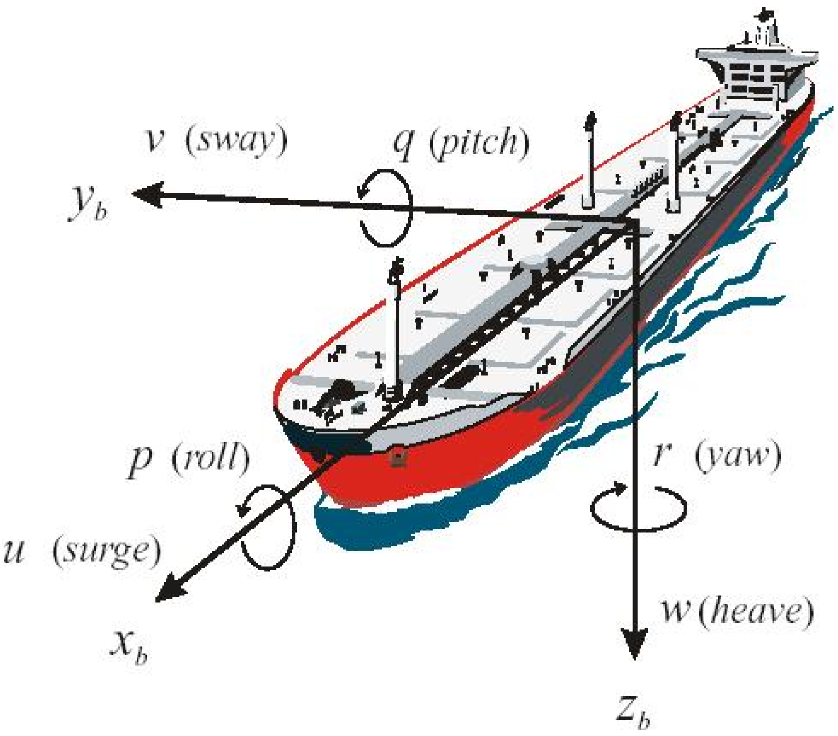




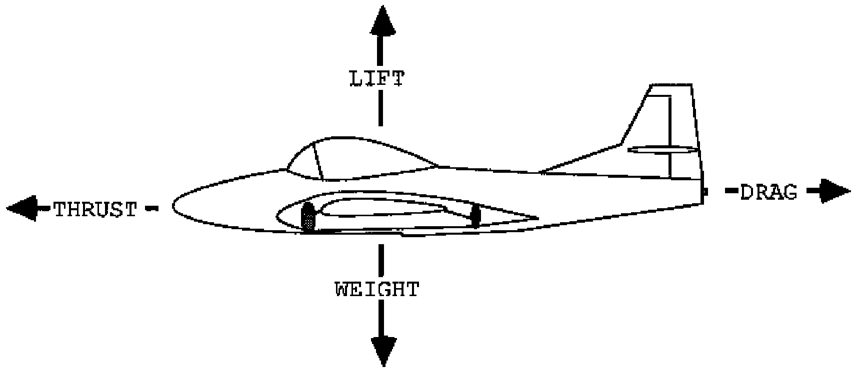
External Flow

- Bodies and vehicles in motion, or with flow over them, experience fluid-dynamic forces and moments.
- Examples include: aircraft, automobiles, buildings, ships, submarines, turbomachines.
- These problems are often classified as ***External Flows.***
- Fuel economy, speed, acceleration, maneuverability, stability, and control are directly related to the aerodynamic/hydrodynamic forces and moments.
- General 6DOF motion of vehicles is described by 6 equations for the linear (surge, sway, heave) and angular (roll, pitch, yaw) momentum.

Fluid Dynamic Forces and Moments

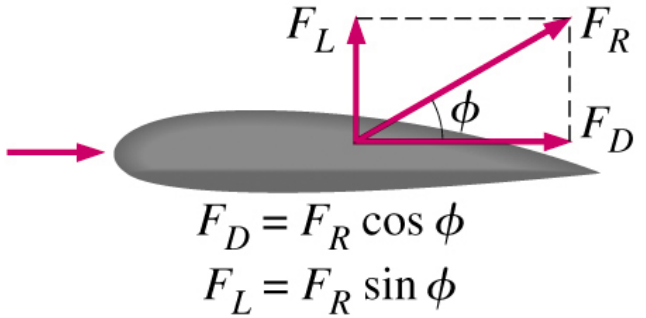


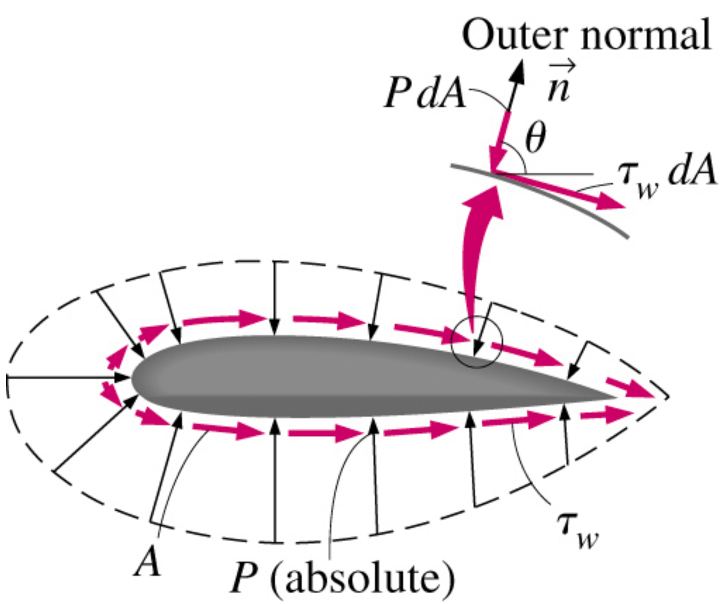
Ships in waves present one of the most difficult 6DOF problems.



Airplane in level steady flight: drag = thrust and lift = weight.

Drag and Lift





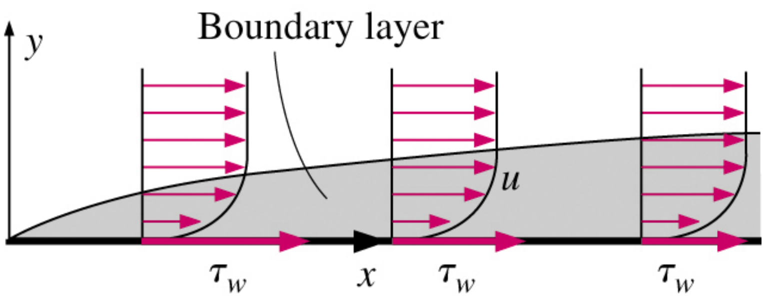
- Fluid dynamic forces are due to pressure and viscous forces acting on the body surface.
- Drag: component parallel to flow direction.
- Lift: component normal to flow direction.

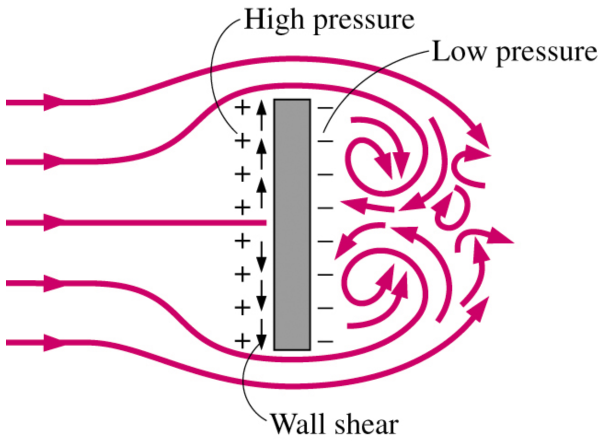
Drag and Lift

- Lift and drag forces can be found by integrating pressure and wall-shear stress.

$$F_D = \int_A dF_D = \int_A (-P cos\theta + \tau_w sin\theta)\ dA$$

$$F_L = \int_A dF_L = -\int_A (P sin\theta + \tau_w cos\theta)\ dA$$





Drag and Lift

- In addition to geometry, lift F_L and drag F_D forces are a function of density ρ and velocity V.
- Dimensional analysis gives 2 dimensionless parameters: lift and drag coefficients.

$$C_D = \frac{F_D}{\frac{1}{2}\rho V^2 A} \qquad C_L = \frac{F_L}{\frac{1}{2}\rho V^2 A}$$

- Area A can be frontal area (drag applications), planform area (wing aerodynamics), or wetted-surface area (ship hydrodynamics).

Example: Automobile Drag

Scion XB

$C_D = 1.0,\ A = 25\ ft^2,\ C_D A = 25 ft^2$

Porsche 911

$C_D = 0.28,\ A = 10\ ft^2,\ C_D A = 2.8 ft^2$

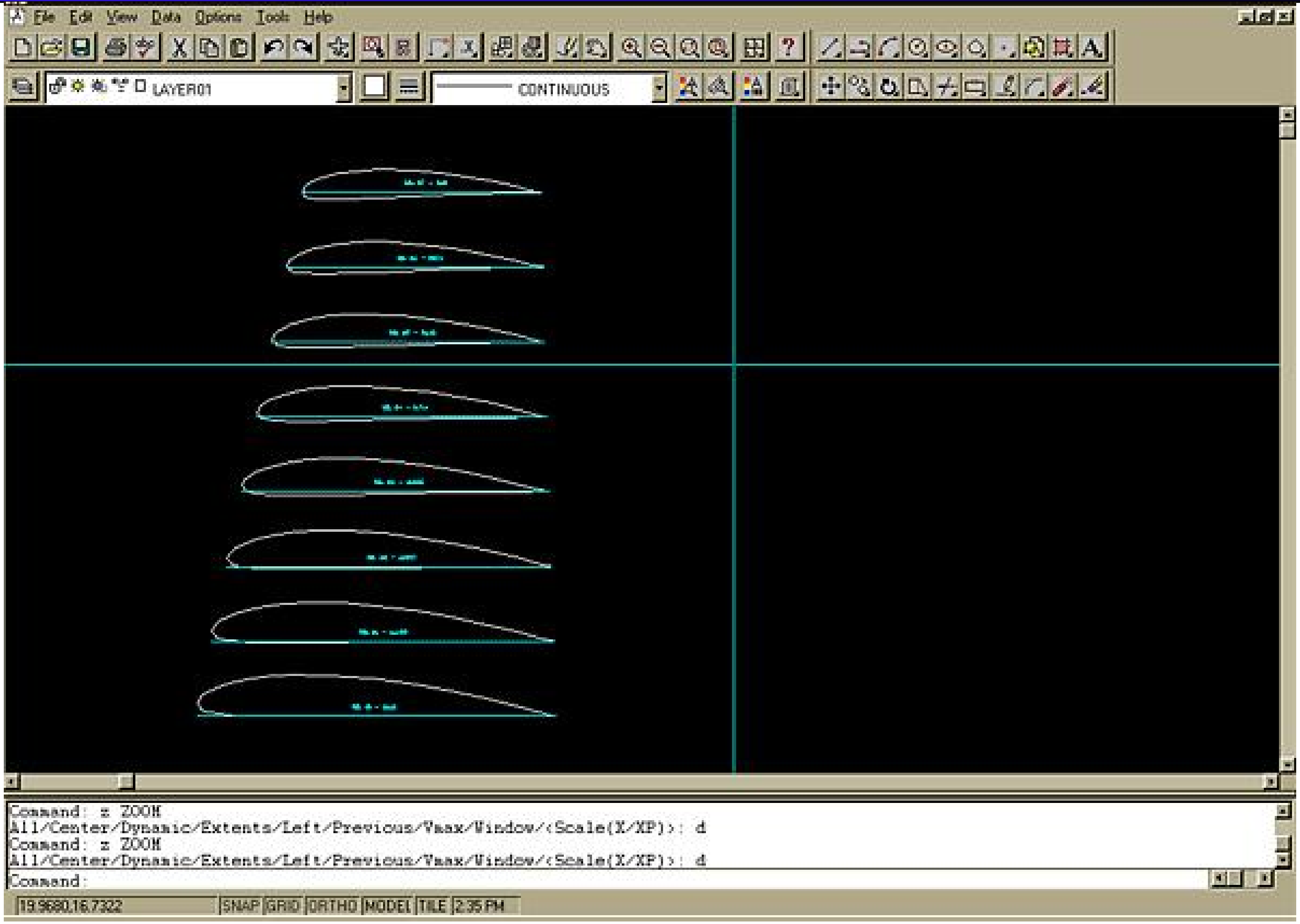
- Drag force $F_D = 1/2 \rho V^2 (C_D A)$ will be ~ 10 times larger for Scion XB
- Source is large C_D and large projected area
- Power consumption $P = F_D V = 1/2 \rho V^3 (C_D A)$ for both scales with V^3!

Drag and Lift

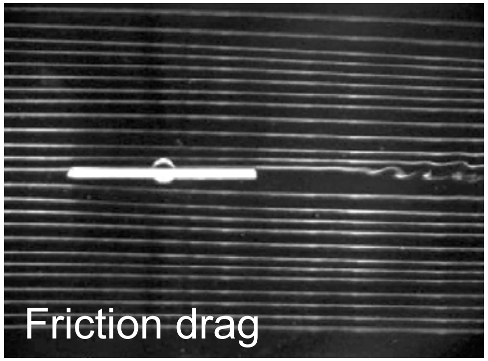
- For applications such as tapered wings, C_L and C_D may be a function of span location. For these applications, a local $C_{L,x}$ and $C_{D,x}$ are introduced and the total lift and drag is determined by integration over the span L

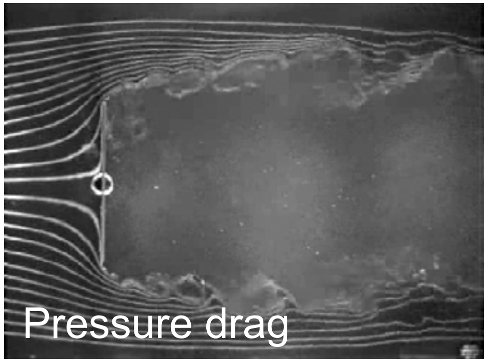
$$C_L = \frac{1}{L}\int_0^L C_{L,x}\, dx \qquad C_D = \frac{1}{L}\int_0^L C_{D,x}\, dx$$

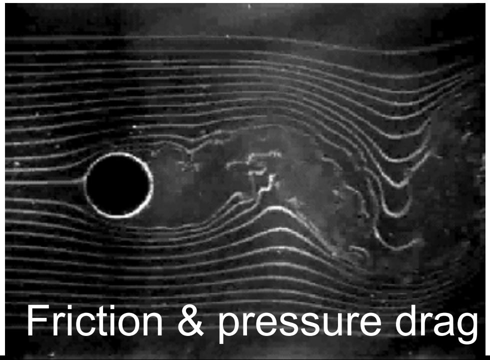
"Lofting" a Tapered Wing



Friction and Pressure Drag

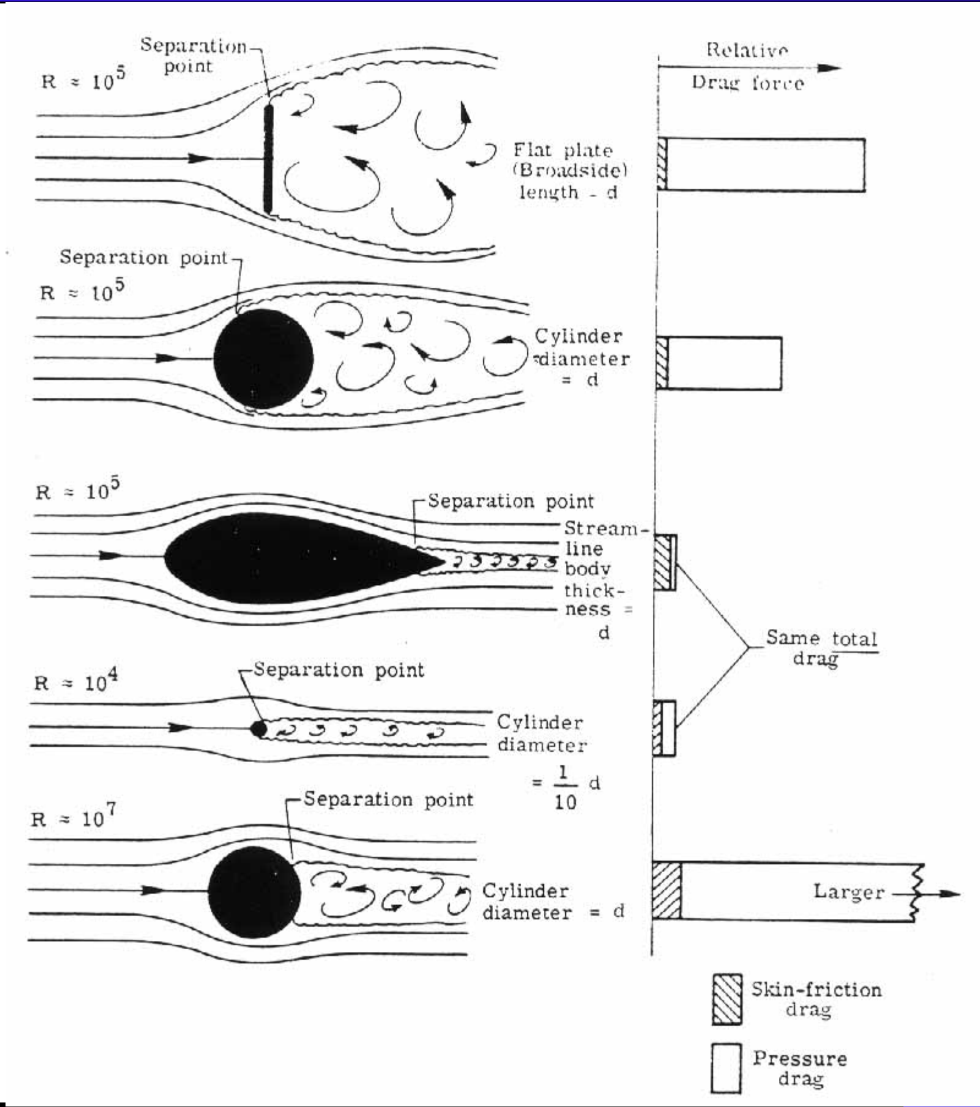






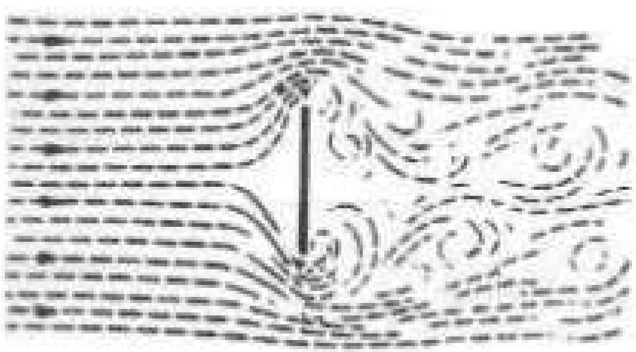
- Fluid dynamic forces are comprised of pressure and friction effects.
- Often useful to decompose,
  - $F_D = F_{D,friction} + F_{D,pressure}$
  - $C_D = C_{D,friction} + C_{D,pressure}$
- This forms the basis of ship model testing where it is assumed that
  - $C_{D,pressure} = f(Fr)$
  - $C_{D,friction} = f(Re)$

Streamlining

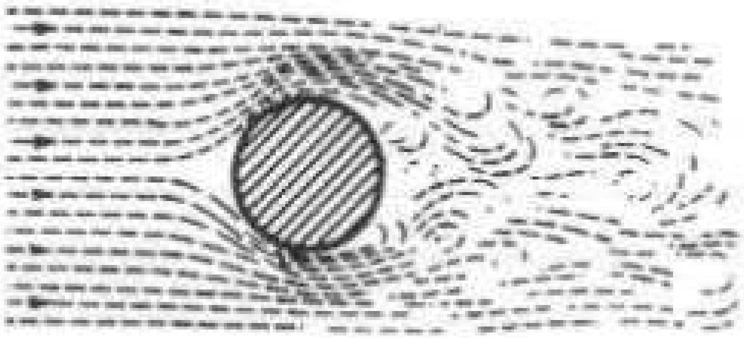


- Streamlining reduces drag by reducing $F_{D,pressure}$, at the cost of increasing wetted surface area and $F_{D,friction}$.
- Goal is to eliminate flow separation and minimize total drag F_D
- Also improves structural acoustics since separation and vortex shedding can excite structural modes.

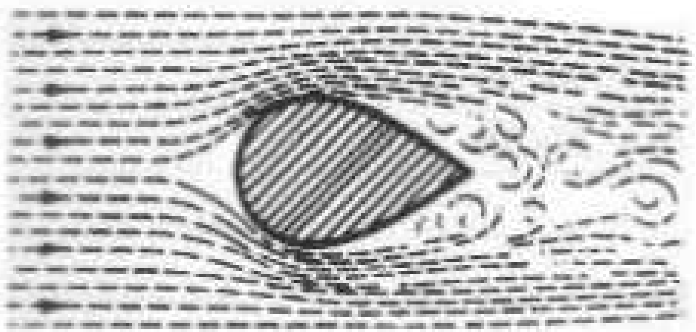
Streamlining



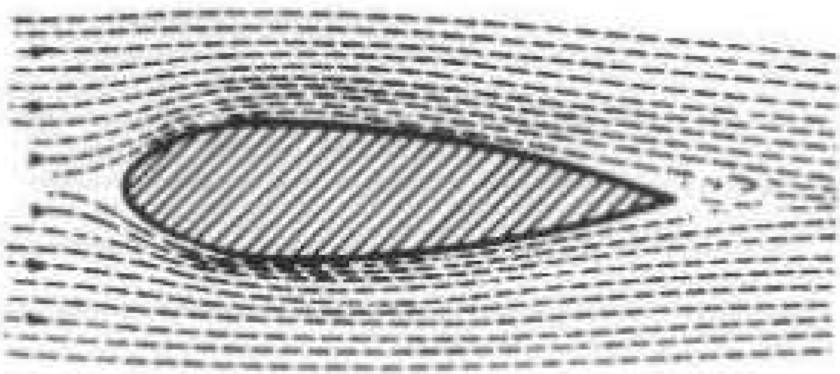
Resistance, 100%



Resistance, 50%



Resistance, 15%



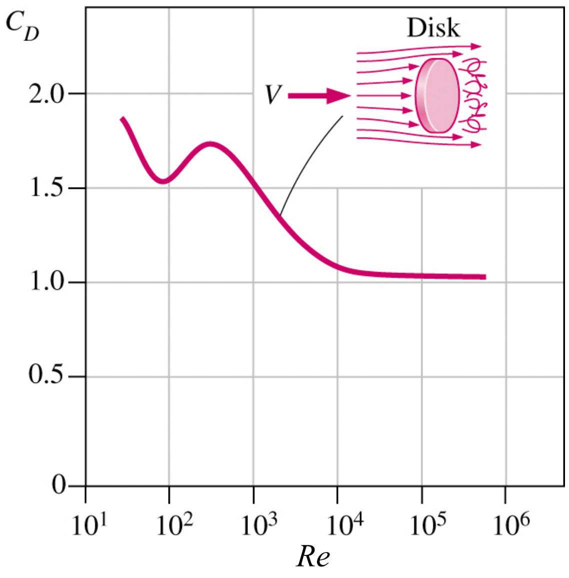
Resistance, 5%

Streamlining via Active Flow Control

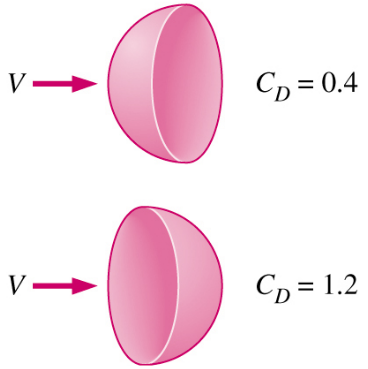
Rounded corners plus pneumatic control (blowing air from slots) reduces drag and improves fuel efficiency for heavy trucks

(Dr. Robert Englar, Georgia Tech Research Institute).

C_D of Common Geometries



A hemisphere at two different orientations for Re > 10^4



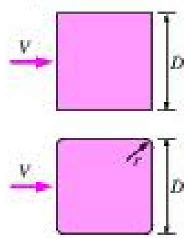
- For many geometries, total drag C_D is constant for $Re > 10^4$
- C_D can be very dependent upon orientation of body.
- As a crude approximation, superposition can be used to add C_D from various components of a system to obtain overall drag. However, there is no mathematical reason (e.g., linear PDE's) for the success of doing this.

C_D of Common Geometries

TABLE 11–1

Drag coefficients C_D of various two-dimensional bodies for Re > 10^4 based on the frontal area $A = bD$, where b is the length in direction normal to the page (for use in the drag force relation $F_D = C_D A \rho V^2/2$ where V is the upstream velocity)

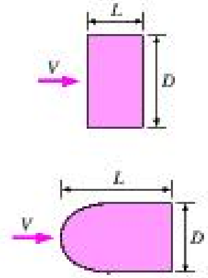
Square rod



Sharp corners: $C_D = 2.2$

Round corners ($r/D = 0.2$): $C_D = 1.2$

Rectangular rod



Sharp corners:

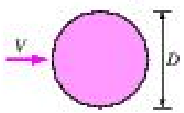
L/D	C_D
0.0*	1.9
0.1	1.9
0.5	2.5
1.0	2.2
2.0	1.7
3.0	1.3

* Corresponds to thin plate

Round front edge:

L/D	C_D
0.5	1.2
1.0	0.9
2.0	0.7
4.0	0.7

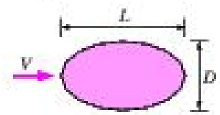
Circular rod (cylinder)



Laminar: $C_D = 1.2$

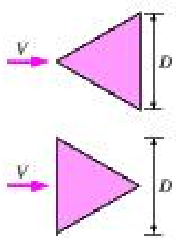
Turbulent: $C_D = 0.3$

Elliptical rod



	C_D	
L/D	Laminar	Turbulent
2	0.60	0.20
4	0.35	0.15
8	0.25	0.10

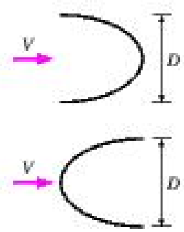
Equilateral triangular rod



$C_D = 1.5$

$C_D = 2.0$

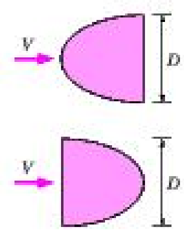
Semicircular shell



$C_D = 2.3$

$C_D = 1.2$

Semicircular rod



$C_D = 1.2$

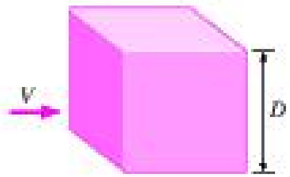
$C_D = 1.7$

C_D of Common Geometries

TABLE 11–2

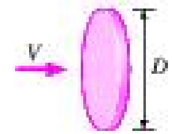
Representative drag coefficients C_D for various three-dimensional bodies for Re > 10^4 based on the frontal area (for use in the drag force relation $F_D = C_D A \rho V^2/2$ where V is the upstream velocity)

Cube, $A = D^2$



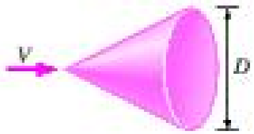
$C_D = 1.05$

Thin circular disk, $A = \pi D^2/4$



$C_D = 1.1$

Cone (for $\theta = 30°$), $A = \pi D^2/4$

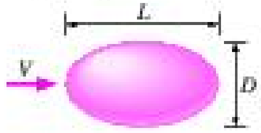


$C_D = 0.5$

Sphere, $A = \pi D^2/4$

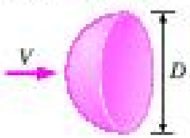
Laminar: $C_D = 0.5$
Turbulent: $C_D = 0.2$

Ellipsoid, $A = \pi D^2/4$

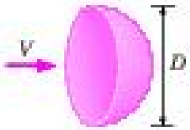


	C_D	
L/D	Laminar	Turbulent
0.75	0.5	0.2
1	0.5	0.2
2	0.3	0.1
4	0.3	0.1
8	0.2	0.1

Hemisphere, $A = \pi D^2/4$

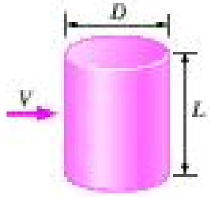


$C_D = 0.4$



$C_D = 1.2$

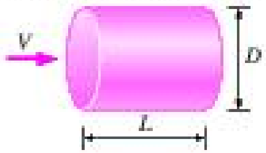
Short cylinder, vertical, $A = LD$



L/D	C_D
1	0.6
2	0.7
5	0.8
10	0.9
40	1.0
∞	1.2

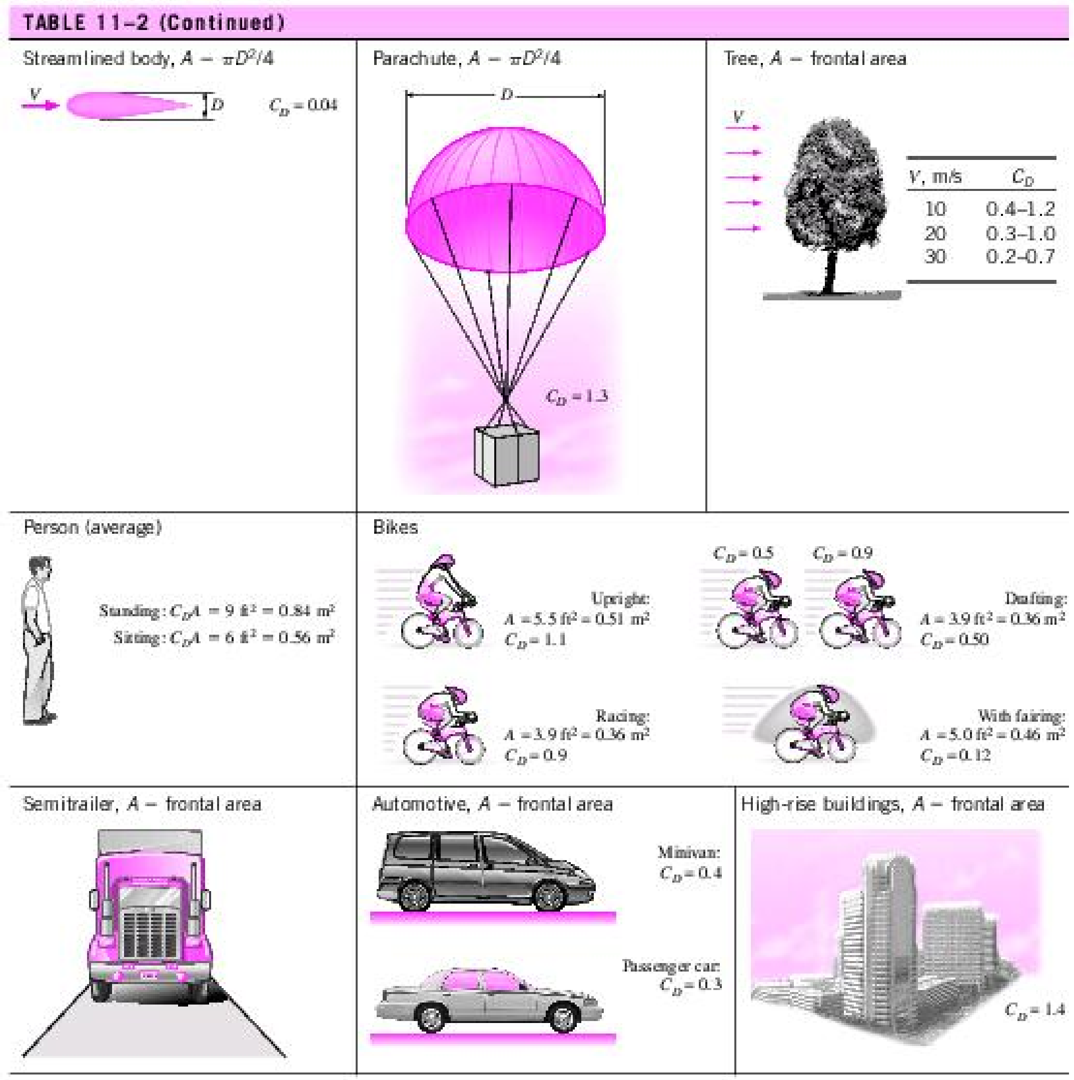
Values are for laminar flow

Short cylinder, horizontal, $A = \pi D^2/4$

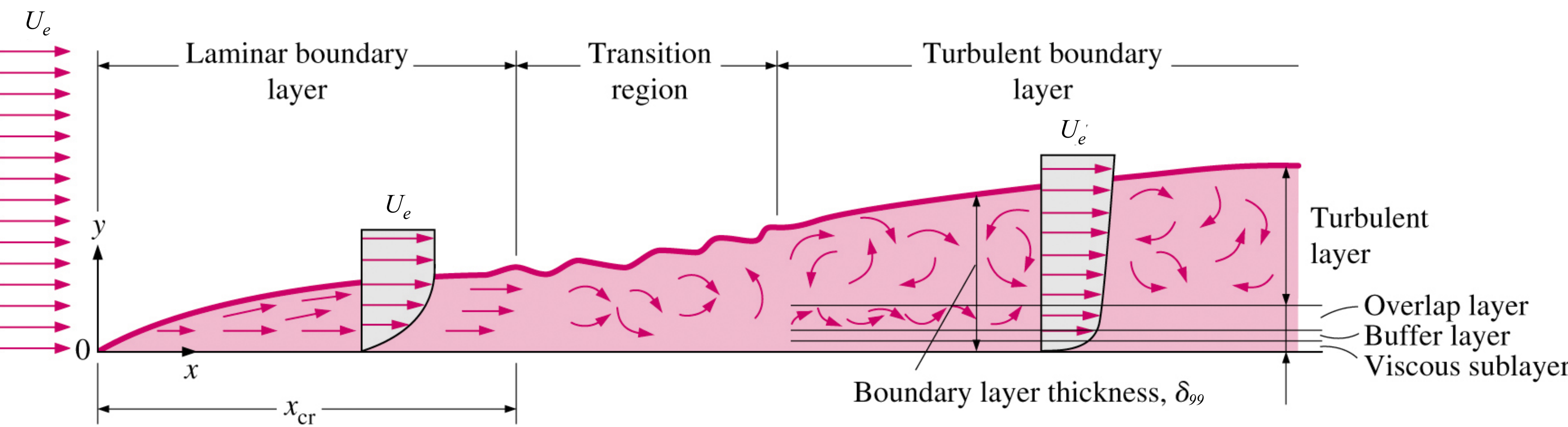


L/D	C_D
0.5	1.1
1	0.9
2	0.9
4	0.9
8	1.0

C_D of Common Geometries

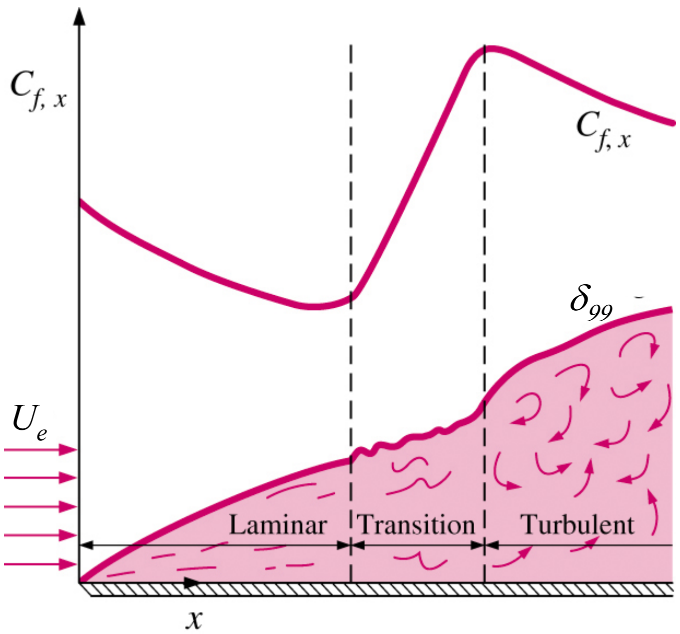


Flat Plate Drag



- Drag on flat plate is solely due to friction created by laminar, transitional, and turbulent boundary layers.

Flat Plate Drag



- Local friction coefficient
  - Laminar: $C_{f,x} = \frac{0.664}{Re_x^{1/2}}$
  - Turbulent: $C_{f,x} = \frac{0.059}{Re_x^{1/5}}$
- Average friction coefficient

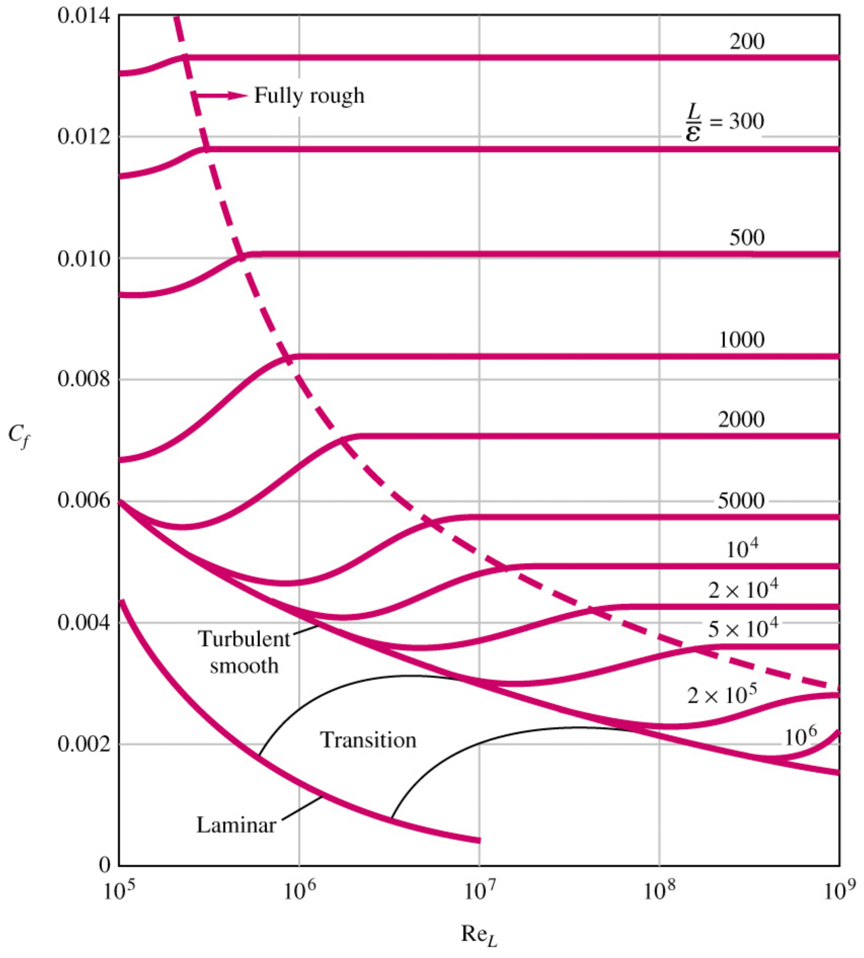
$$C_f = \frac{1}{L}\int_0^L C_{f,x}\,dx$$

  - Laminar: $C_f = \frac{1.33}{Re_L^{1/2}}$
  - Turbulent: $C_f = \frac{0.074}{Re_L^{1/5}}$

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

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

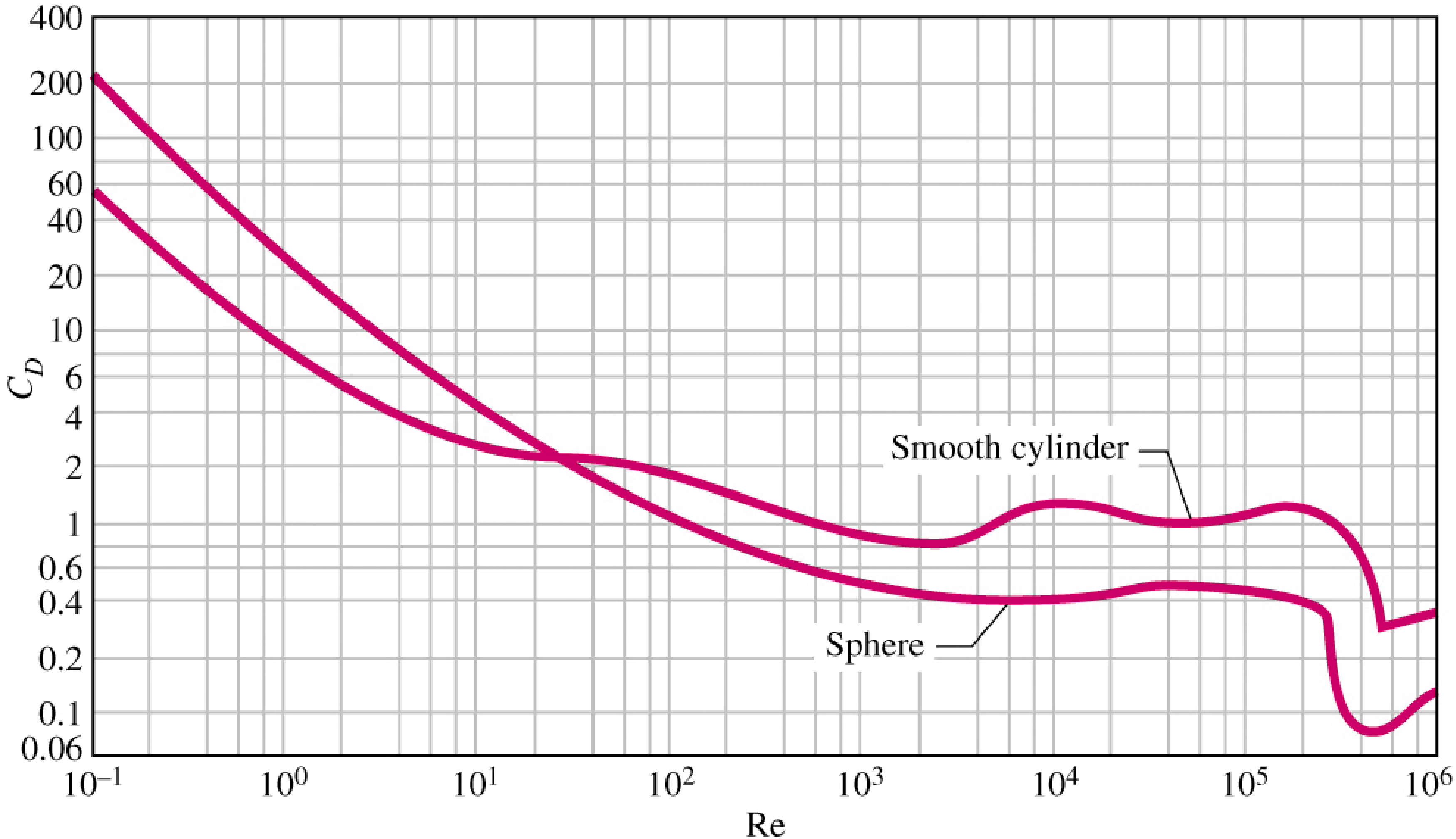
Effect of Roughness



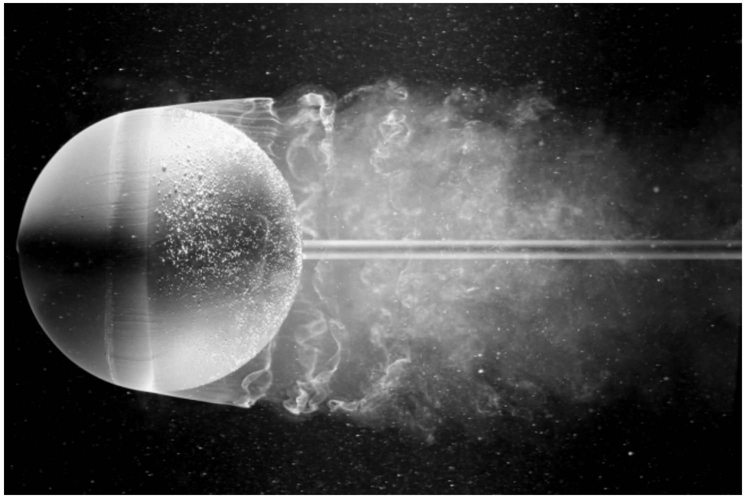
- Similar to Moody Chart for pipe flow
- Laminar flow unaffected by roughness
- Turbulent flow significantly affected: C_f can increase by 7 times for a given Re

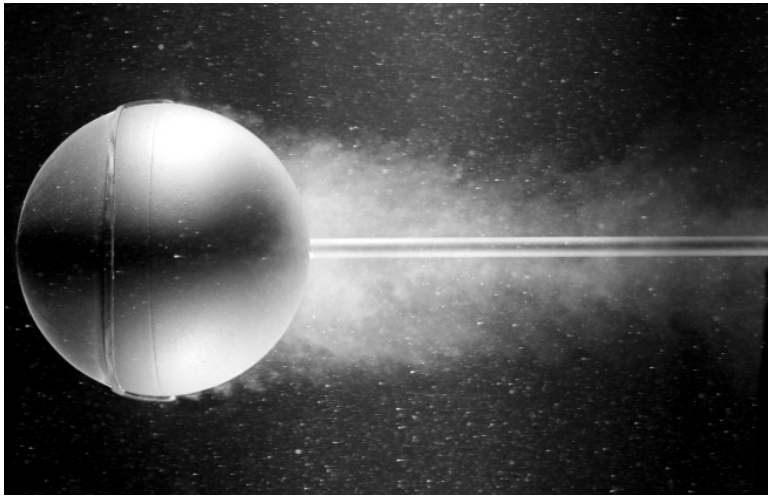
$$C_f = \left(1.89 - 1.62 log \frac{\epsilon}{L}\right)^{-2.5}$$

Cylinder and Sphere Drag



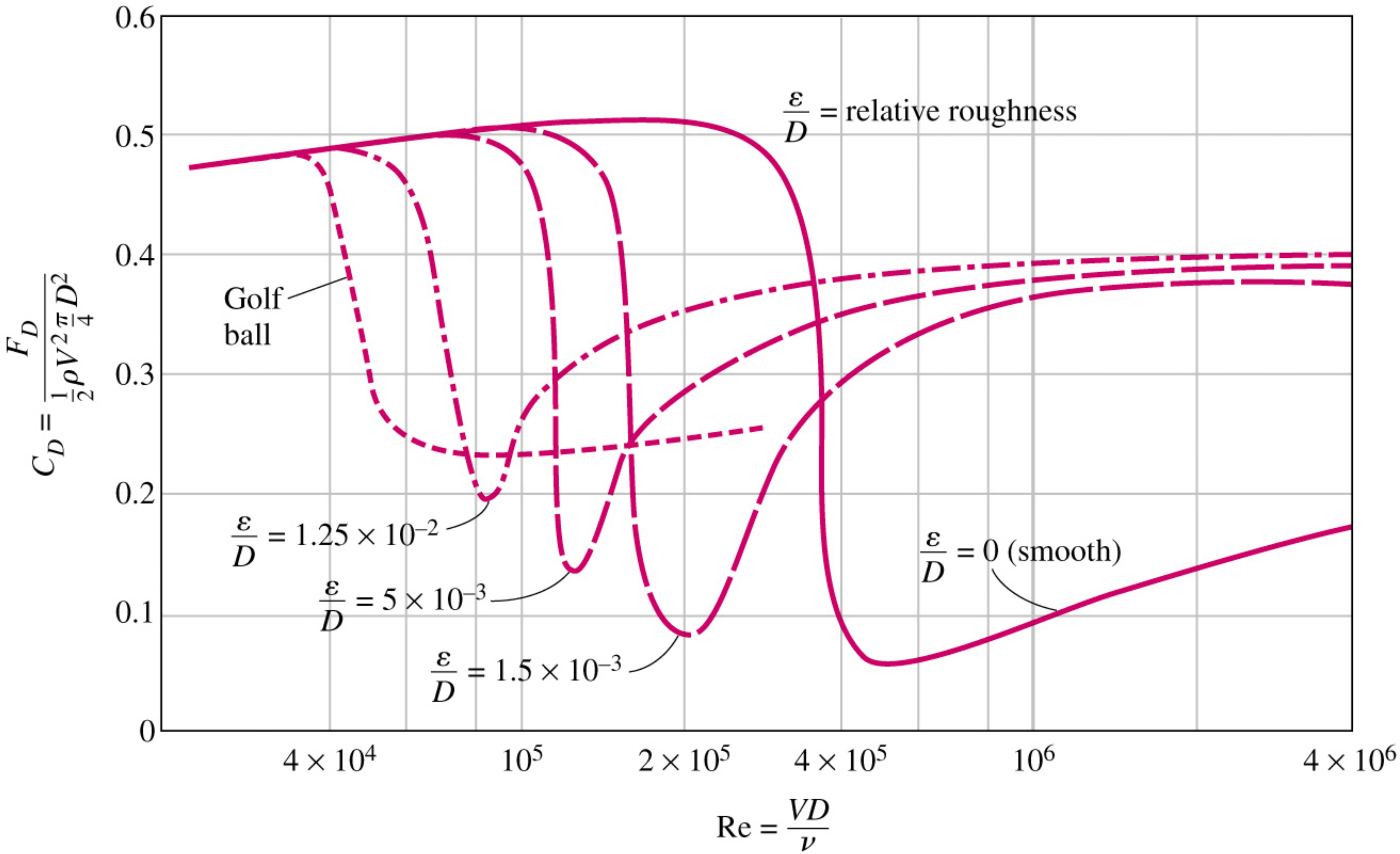
Cylinder and Sphere Drag



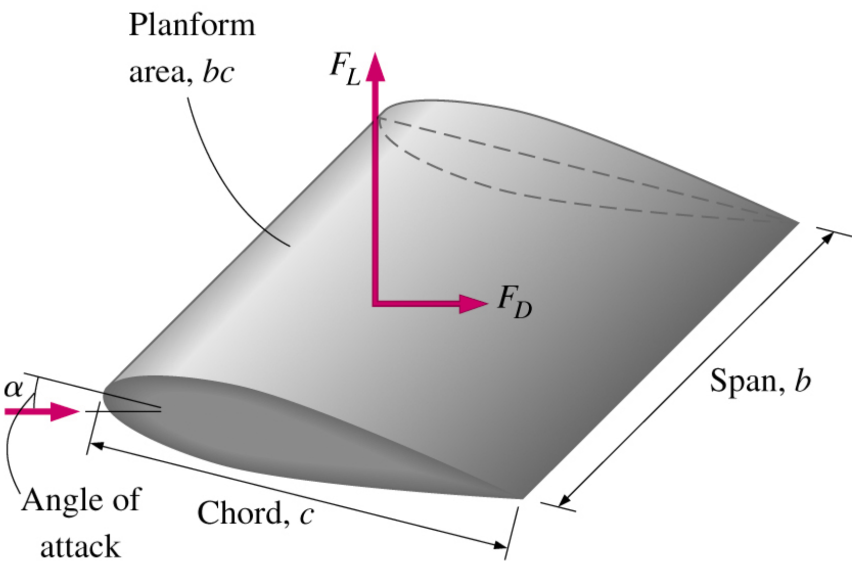


- Flow is strong function of Re.
- Wake narrows for turbulent flow since TBL (turbulent boundary layer) is more resistant to separation due to adverse pressure gradient.
- $\theta_{sep,turb} \approx 80^\circ$
- $\theta_{sep,lam} \approx 140^\circ$

Effect of Surface Roughness



Lift

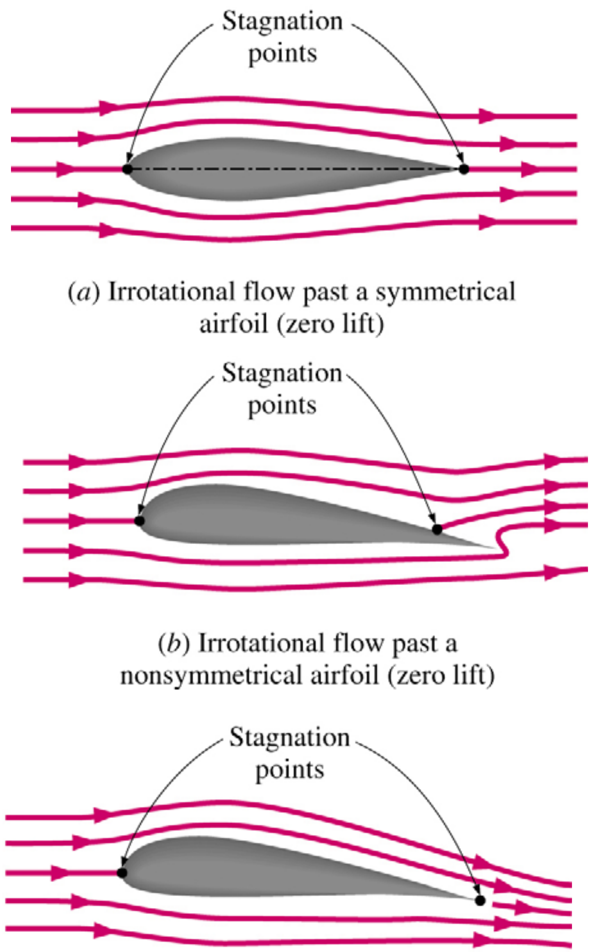


- Lift is the net force (due to pressure and viscous forces) perpendicular to flow direction.
- Lift coefficient

$$C_L = \frac{F_L}{\frac{1}{2}\rho V^2 A}$$

- $A=bc$ is the planform area

Computing Lift



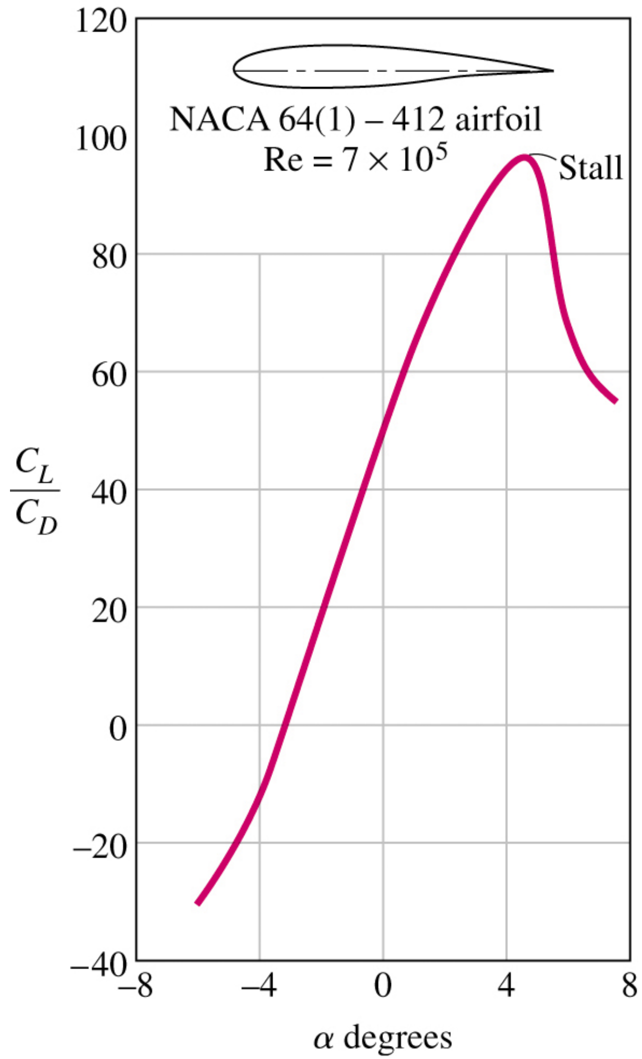
(*a*) Irrotational flow past a symmetrical airfoil (zero lift)

(*b*) Irrotational flow past a nonsymmetrical airfoil (zero lift)

(*c*) Actual flow past a nonsymmetrical airfoil (positive lift)

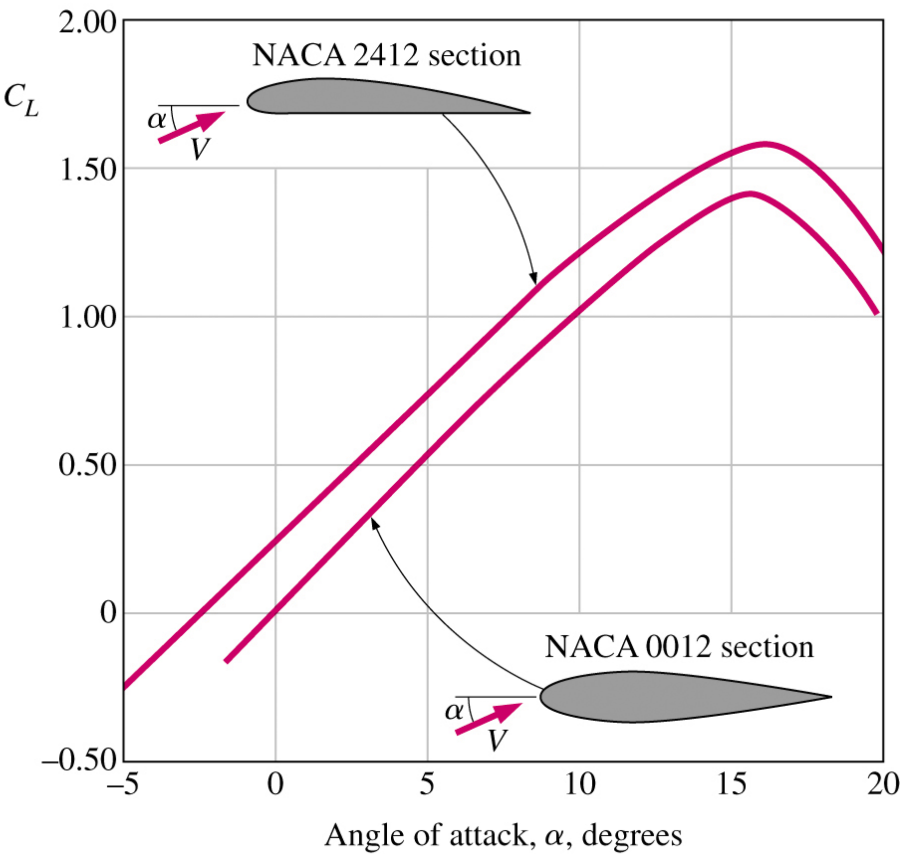
- Potential-flow approximation gives accurate C_L for angles of attack below stall: boundary layer can be neglected.
- Thin-foil theory: superposition of uniform stream and vortices on mean camber line.
- Java-applet panel codes available online: http://www.aa.nps.navy.mil/~jones/online_tools/panel2/
- ***Kutta condition*** required at trailing edge: fixes stagnation point at TE.

Effect of Angle of Attack



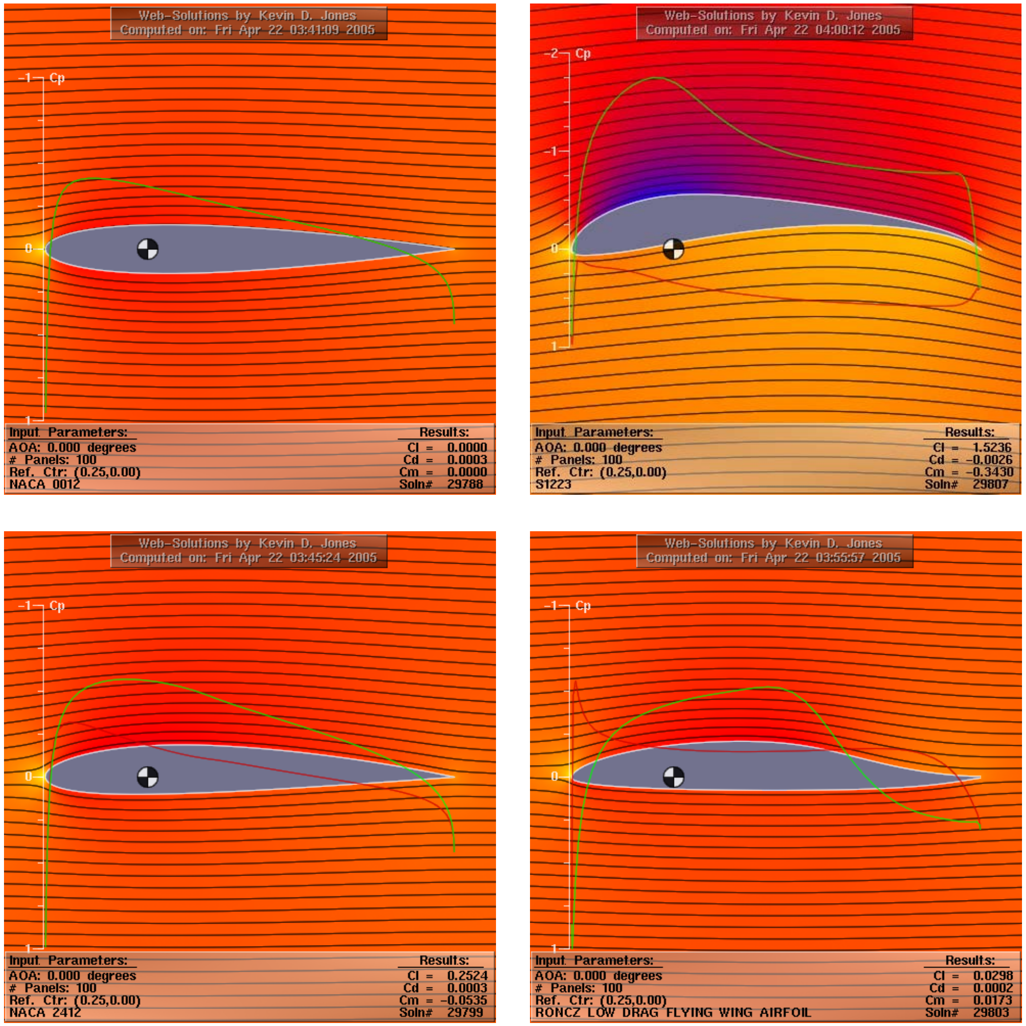
- Thin-foil theory shows that $C_L \approx 2\pi\alpha$ for $\alpha < \alpha_{stall}$
- Therefore, lift increases linearly with α
- Objective for most applications is to achieve maximum C_L/C_D ratio.
- C_D determined from wind-tunnel or CFD (BLE or NSE).
- C_L/C_D increases (up to order 100) until stall.

Effect of Foil Shape



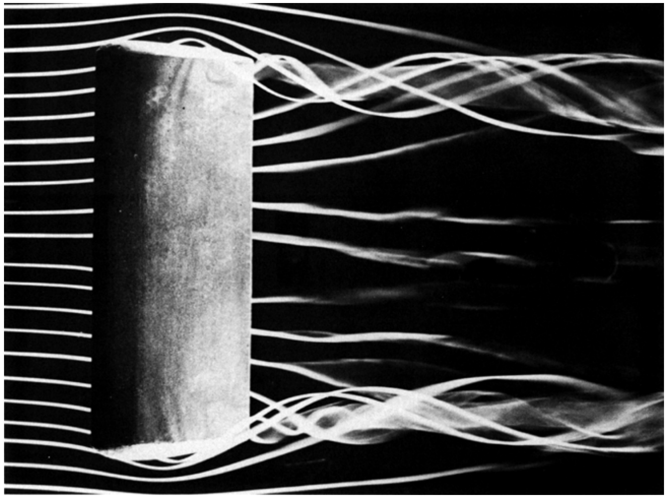
- Thickness and camber influence pressure distribution (and load distribution) and location of flow separation.
- Foil database compiled by Selig (UIUC)
  http://www.aae.uiuc.edu/m-selig/ads.html

Effect of Foil Shape



- Figures from NPS airfoil java applet.
  - Color contours of pressure field
  - Streamlines through velocity field
  - Plot of surface pressure
- Camber and thickness shown to have large impact on flow field.

End Effects of Wing Tips

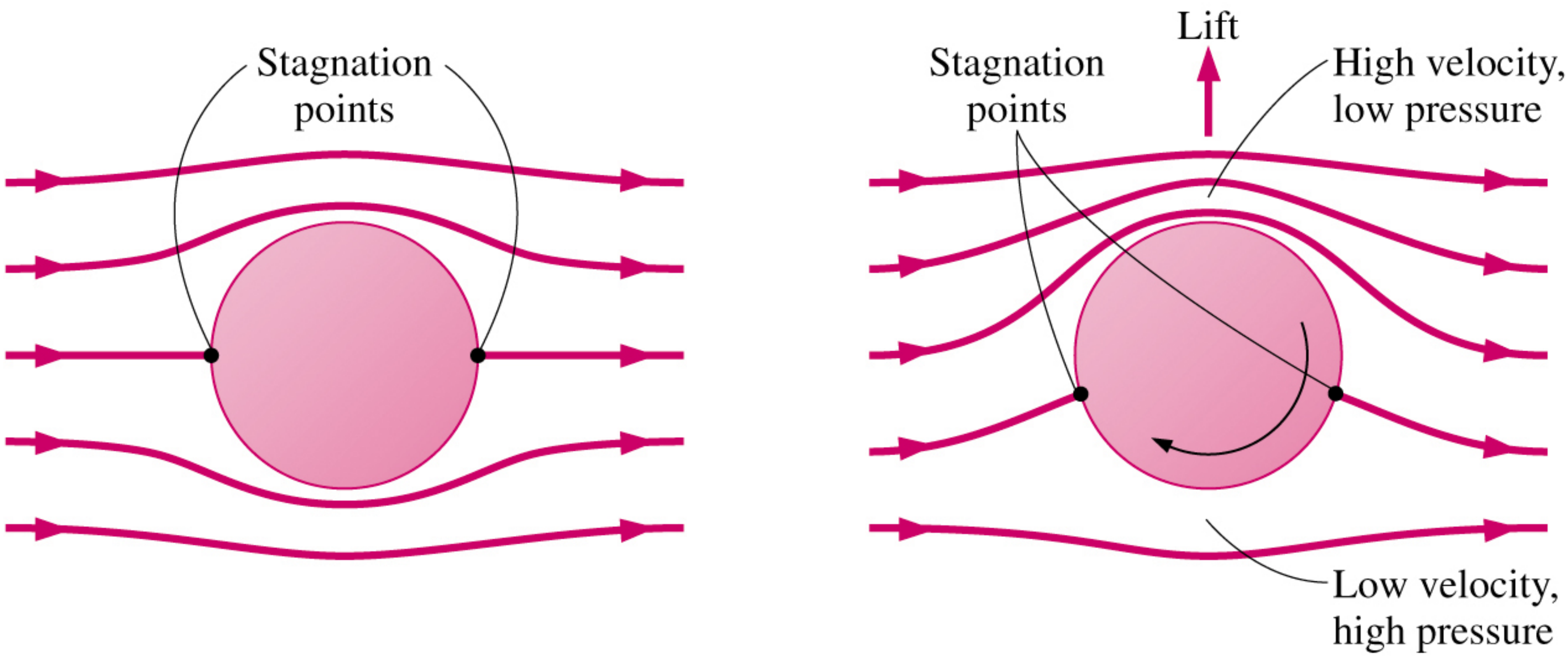


- Tip vortex created by leakage of flow from high-pressure side to low-pressure side of wing.
- Tip vortices from heavy aircraft persist far downstream and pose danger to light aircraft. Also sets takeoff and landing separation times at busy airports.

End Effects of Wing Tips

- Tip effects can be reduced by attaching *endplates* or *winglets.*
- Trade-off between reducing induced drag and increasing friction drag.
- Wing-tip feathers on some birds serve the same function.

Lift Generated by Spinning

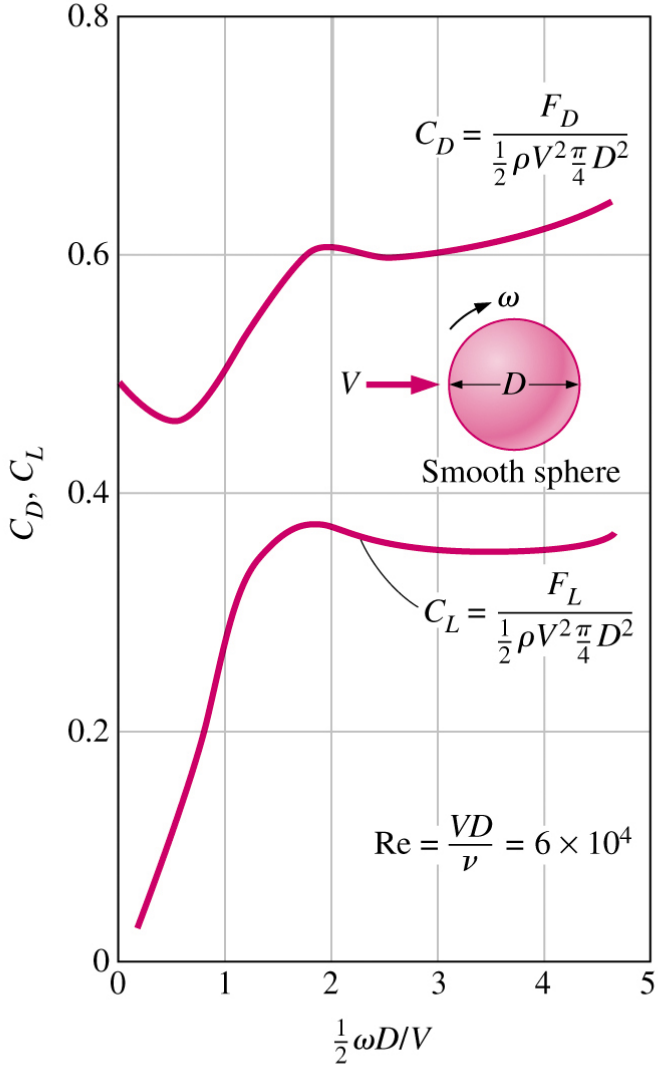


(*a*) Potential flow over a stationary cylinder

(*b*) Potential flow over a rotating cylinder

Superposition of Uniform stream + Doublet + Vortex

Lift Generated by Spinning



- C_L strongly depends on rate of rotation.
- The effect of rate of rotation on C_D is smaller.
- Baseball, golf, soccer, tennis players utilize spin.
- Lift generated by rotation is called the *Magnus Effect*.