Fluid Mechanics - MTF053

Lecture 17

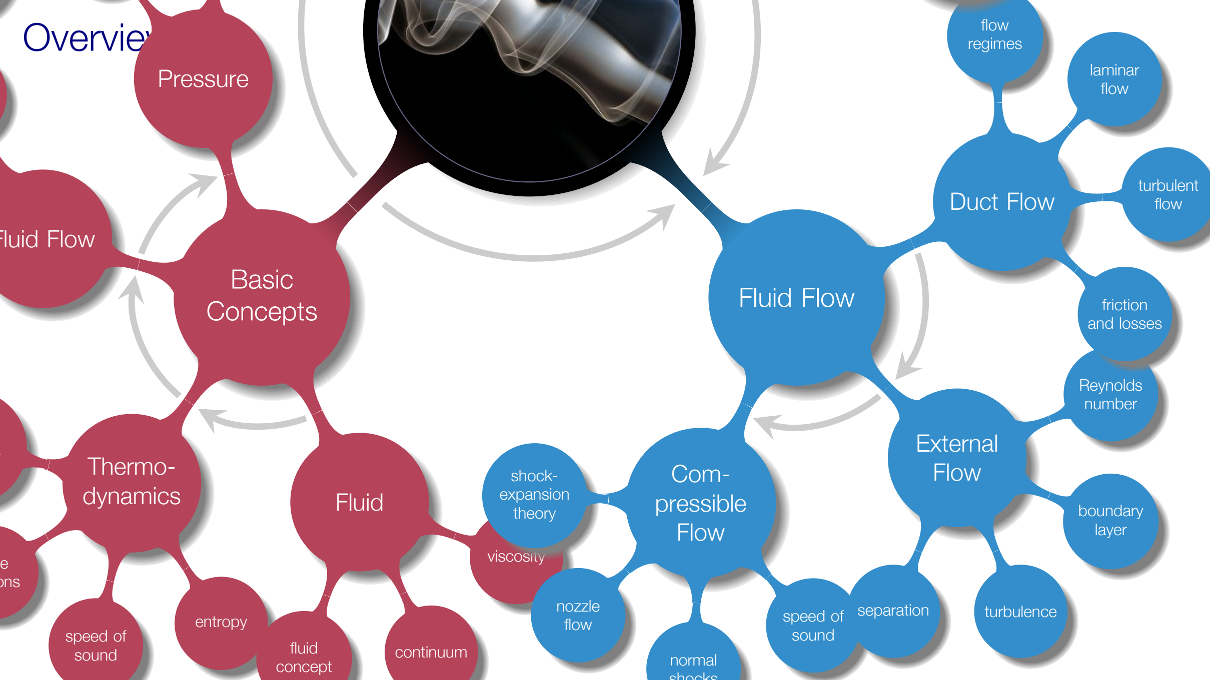
Niklas Andersson

Chalmers University of Technology
Department of Mechanics and Maritime Sciences
Division of Fluid Mechanics
Gothenburg, Sweden

niklas.andersson@chalmers.se

Chapter 7 - Flow Past Immersed Bodies

Overvie



Pressure
luid Flow
Basic Concepts
Thermo-dynamics
Fluid
viscosity
e
ons
speed of sound
entropy
fluid concept
continuum
Fluid Flow
Duct Flow
flow regimes
laminar flow
turbulent flow
friction and losses
Reynolds number
External Flow
boundary layer
turbulence
separation
Com-pressible Flow
shock-expansion theory
nozzle flow
normal
speed of sound

Learning Outcomes

4 Be **able to categorize** a flow and **have knowledge about** how to select applicable methods for the analysis of a specific flow based on category

6 **Explain** what a boundary layer is and when/where/why it appears

21 **Explain** how the flat plate boundary layer is developed (transition from laminar to turbulent flow)

22 **Explain** and use the Blasius equation

23 **Define** the Reynolds number for a flat plate boundary layer

24 **Explain** what is characteristic for a turbulent flow

29 **Explain** flow separation (separated cylinder flow)

30 **Explain** how to delay or avoid separation

31 **Derive** the boundary layer formulation of the Navier-Stokes equations

32 **Understand** and explain displacement thickness and momentum thickness

33 **Understand**, **explain** and **use** the concepts drag, friction drag, pressure drag, and lift

Let's take a deep dive into boundary-layer theory

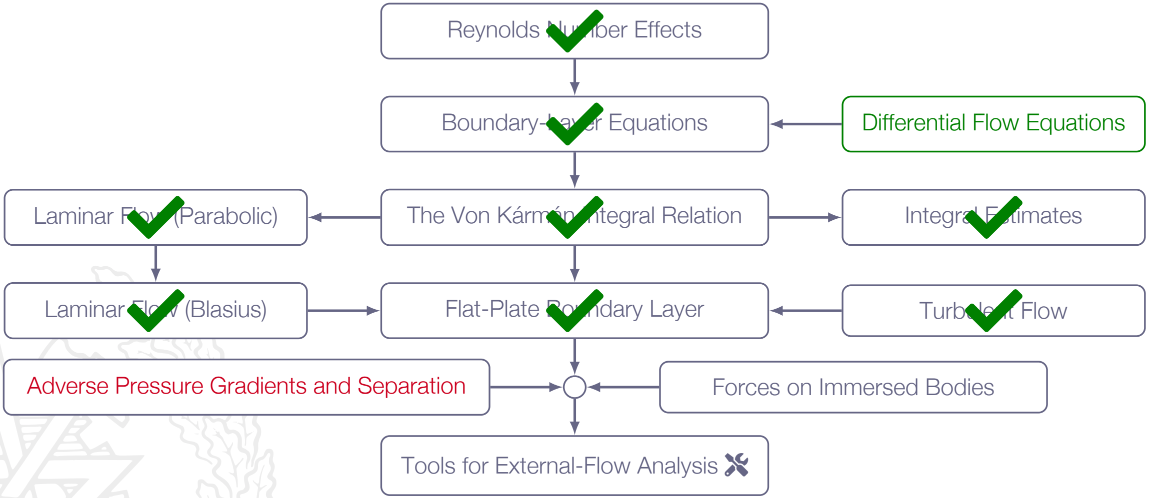
Complementary Course Material

These lecture notes covers chapter 7 in the course book and additional course material that you can find in the following documents

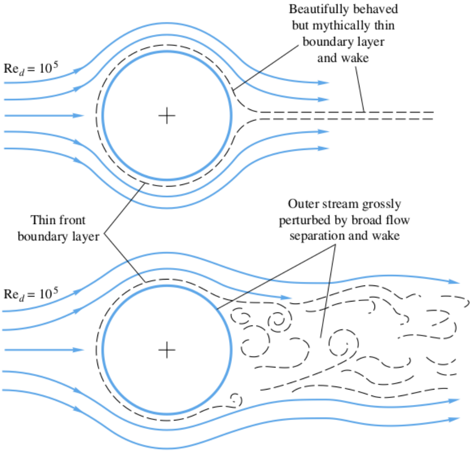
`MTF053_Equation-for-Boundary-Layer-Flows.pdf`

`MTF053_Turbulence.pdf`

Roadmap - Flow Past Immersed Bodies



Pressure Gradient



Adverse pressure gradient

- pressure increases in the flow direction
- may lead to separation

Favorable pressure gradient

- pressure decreases in the flow direction
- the flow will not separate

Separation mechanism

- loss of momentum near the wall
- adverse pressure gradient
- decelerated fluid will force flow to separate from the body

Pressure Gradient

Boundary layer formulation of the momentum equation:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{dp}{dx} + \frac{1}{\rho}\frac{\partial \tau}{\partial y}$$

with $u = v = 0$ close at the wall, we get

$$\left.\frac{\partial \tau}{\partial y}\right|_{wall} = \mu \left.\frac{\partial^2 u}{\partial y^2}\right|_{wall} \Rightarrow \left.\frac{\partial^2 u}{\partial y^2}\right|_{wall} = \frac{1}{\mu}\frac{dp}{dx}$$

Note! applies both for laminar and turbulent flow

Pressure Gradient

$$\left.\frac{\partial^2 u}{\partial y^2}\right|_{wall} = \frac{1}{\mu}\frac{dp}{dx}$$

Adverse pressure gradient ($\frac{dp}{dx} > 0$):

$\frac{\partial^2 u}{\partial y^2} > 0$ at the wall

$\frac{\partial^2 u}{\partial y^2} < 0$ at the outer layer $y = \delta$

thus $\frac{\partial^2 u}{\partial y^2} = 0$ somewhere in the boundary layer

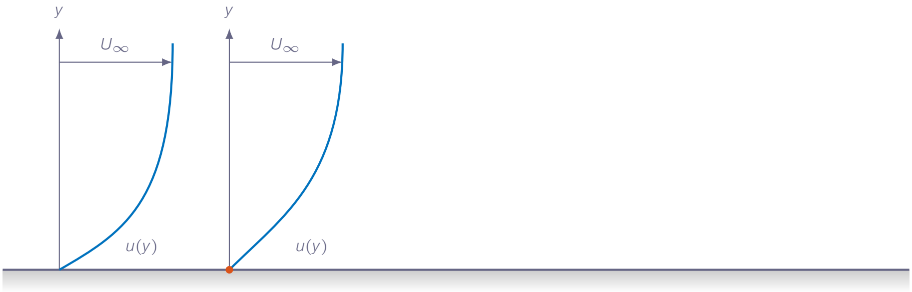
Pressure Gradient

Favorable gradient
$(dp/dx < 0)$

Point of inflection:
inside wall

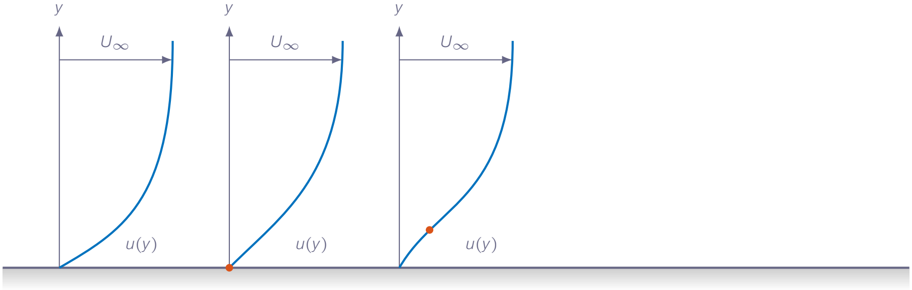
No separation

Pressure Gradient



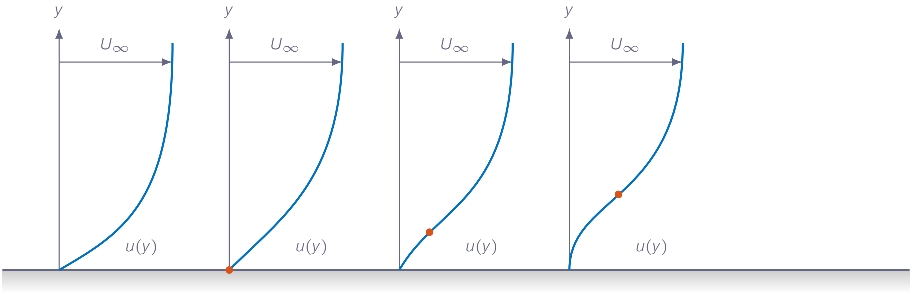
Favorable gradient	Zero gradient
$(dp/dx < 0)$	$(dp/dx = 0)$
Point of inflection: inside wall	Point of inflection: at the wall
No separation	No separation

Pressure Gradient



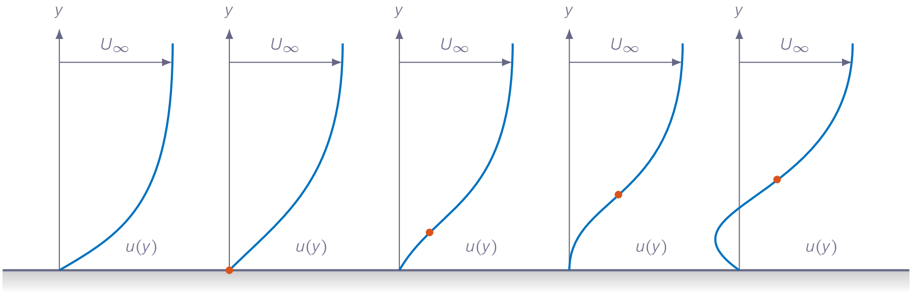
Favorable gradient $(dp/dx < 0)$	Zero gradient $(dp/dx = 0)$	Weak adverse gradient $(dp/dx > 0)$
Point of inflection: inside wall	Point of inflection: at the wall	Point of inflection: in the flow
No separation	No separation	No separation

Pressure Gradient



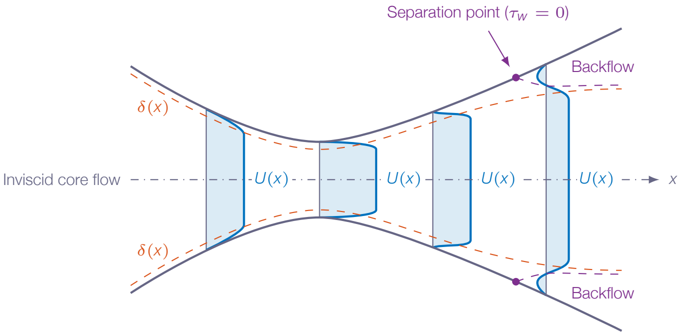
Favorable gradient ($dp/dx < 0$)	Zero gradient ($dp/dx = 0$)	Weak adverse gradient ($dp/dx > 0$)	Critical adverse gradient ($dp/dx > 0$)
Point of inflection: inside wall	Point of inflection: at the wall	Point of inflection: in the flow	Point of inflection: in the flow
No separation	No separation	No separation	Separation zero slope at wall $\tau_w = 0$

Pressure Gradient



Favorable gradient ($dp/dx < 0$)	Zero gradient ($dp/dx = 0$)	Weak adverse gradient ($dp/dx > 0$)	Critical adverse gradient ($dp/dx > 0$)	Excessive adverse gradient ($dp/dx > 0$)
Point of inflection: inside wall	Point of inflection: at the wall	Point of inflection: in the flow	Point of inflection: in the flow	Point of inflection: in the flow
No separation	No separation	No separation	Separation zero slope at wall $\tau_W = 0$	Separated flow backflow at wall

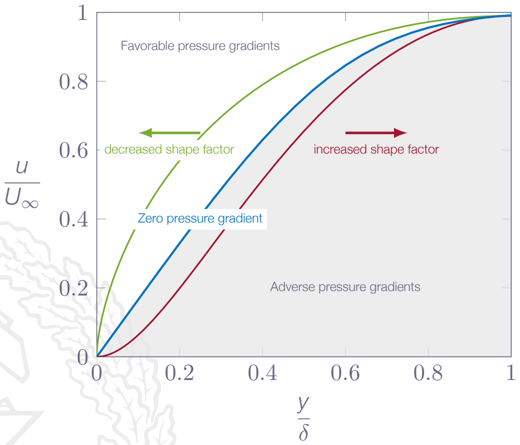
Pressure Gradient



Nozzle	Throat	Diffuser
decreasing area	minimum area	increasing area
favorable pressure gradient	zero pressure gradient	adverse pressure gradient
$dp/dx < 0$	$dp/dx = 0$	$dp/dx > 0$
$dU/dx > 0$	$dU/dx = 0$	$dU/dx < 0$

Shape Factor

Shape factor: $H = \dfrac{\delta^*}{\theta}$



Laminar flow:

No pressure gradient: $H \approx 2.6$

Separation: $H \approx 3.5$

Turbulent flow:

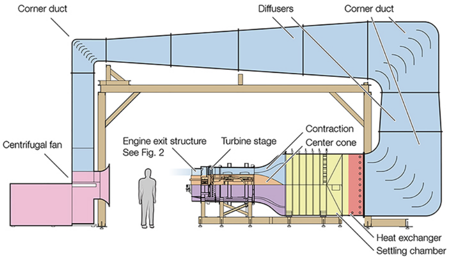
No pressure gradient: $H \approx 1.3$

Separation: $H \approx 2.4$

Avoid or Delay Separation

Decrease magnitude of adverse pressure gradient

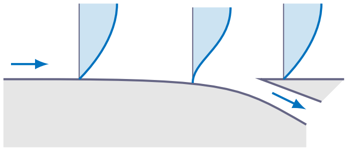
- Guide vanes
- Streamlining



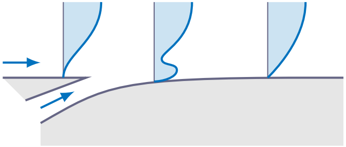
Avoid or Delay Separation

Remove decelerated fluid

Boundary layer suction



Avoid or Delay Separation



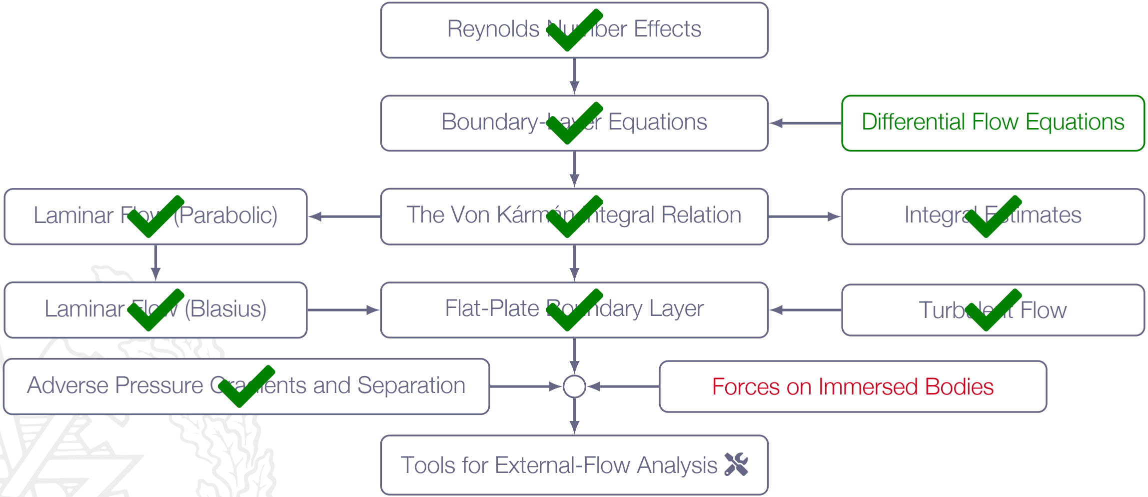
Increase near-wall momentum

Forced **transition to turbulence**

- surface roughness
- surface irregularities (dimples on the surface of a golf ball)
- trip wires

Negative consequence: comes with **increased friction**

Roadmap - Flow Past Immersed Bodies

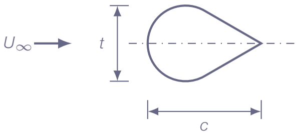


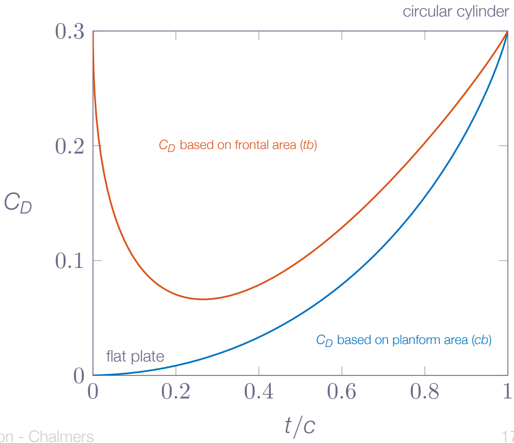
Drag of Immersed Bodies

$$C_D = \frac{drag}{\frac{1}{2}\rho U_\infty^2 A} = f\left(\frac{U_\infty L}{\nu}\right)$$

Characteristic area A:

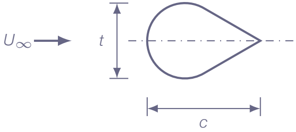
1. Frontal area
   blunt objects: *cylinders, cars*
2. Planform area
   wide flat bodies: *wings, hydrofoils*
3. Wetted area
   ships





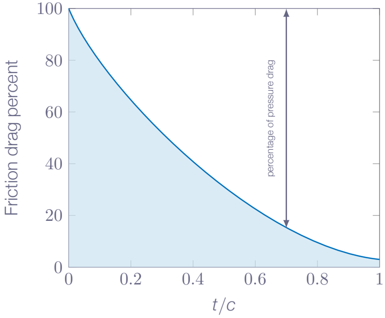
Drag of Immersed Bodies

$$C_D = C_{D_{pressure}} + C_{D_{friction}}$$



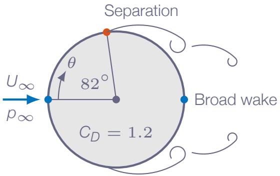
- Pressure drag
  - difference between the high front stagnation pressure and the low wake pressure on the backside of the body
  - often larger than the friction drag

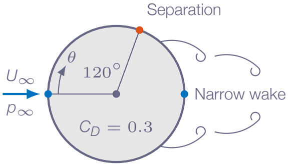
- The relative importance of friction and pressure drag depends on
  - shape
  - surface roughness



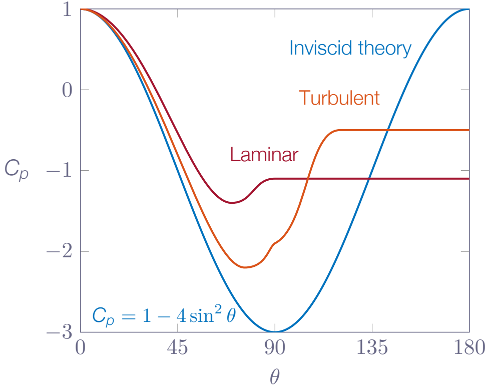
Note! for a cylinder, friction drag can be as low as a few percent of the total drag

Cylinder Surface Pressure

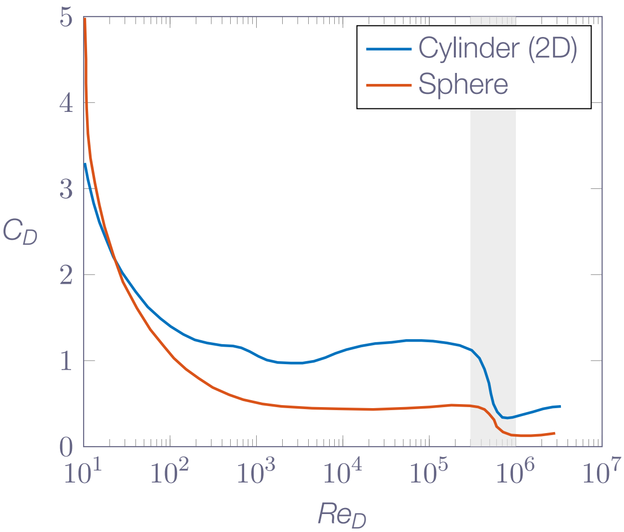




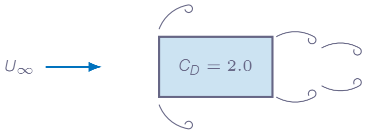
$$C_p = \frac{p - p_\infty}{\rho U_\infty^2 / 2}$$



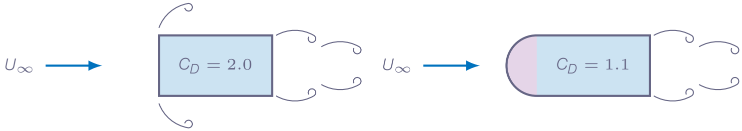
Cylinder Drag



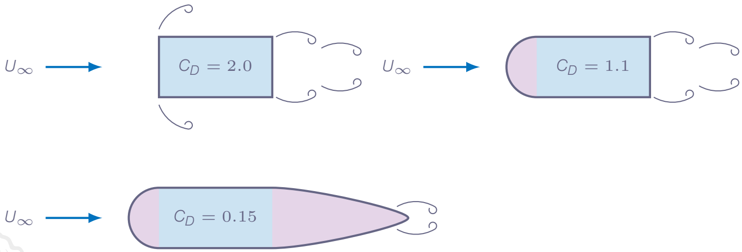
Streamlining



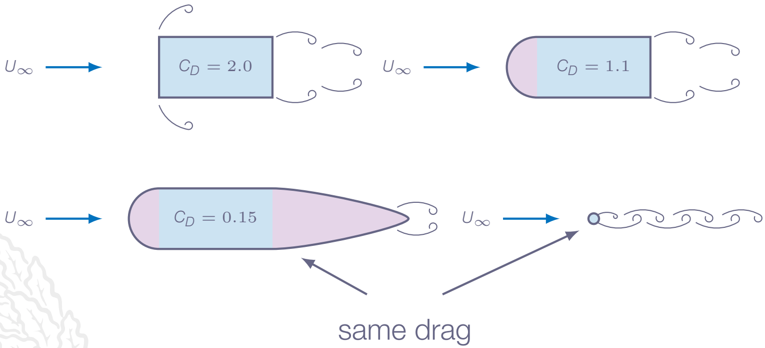
Streamlining



Streamlining



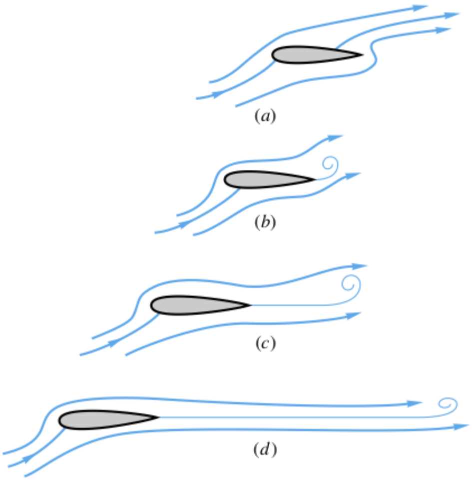
Streamlining



Drag Prediction

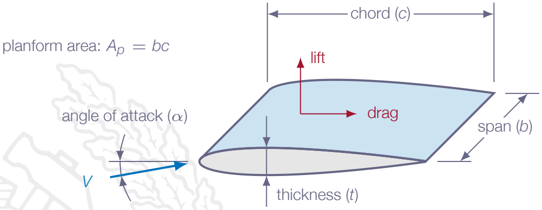
- No reliable theory for drag prediction (with the exception of flat plates)
- The separation point can be predicted with some accuracy but not the wake flow
- CFD or experiments needed

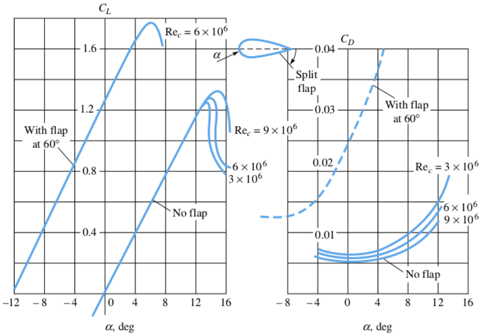
Wing Lift and Drag



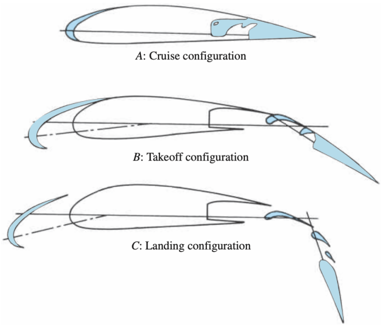
Wing Lift and Drag

$$C_D = \frac{F_D}{\frac{1}{2}\rho U_\infty^2 A_p} \qquad C_L = \frac{F_L}{\frac{1}{2}\rho U_\infty^2 A_p}$$

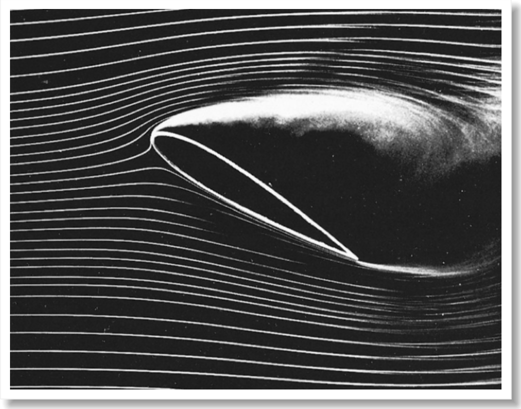




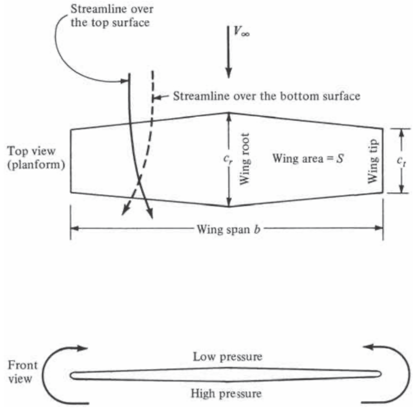
Wing Lift and Drag - High-Lift Devices

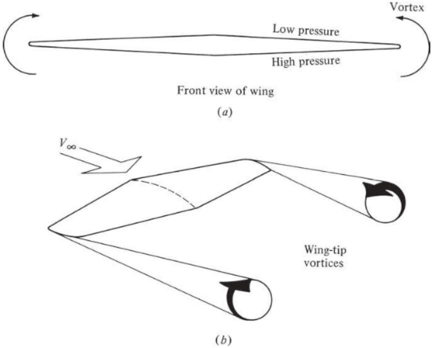


Wing Lift and Drag - Wing Stall

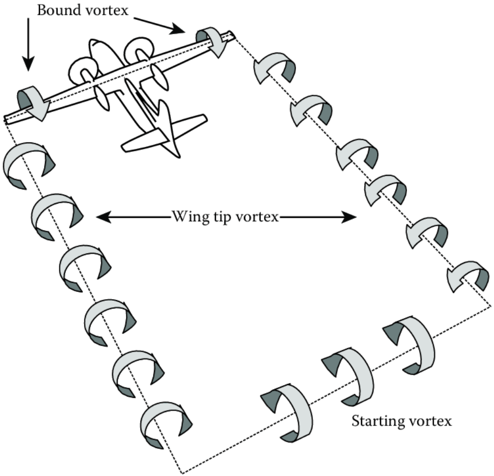


Wing Lift and Drag - Induced Drag



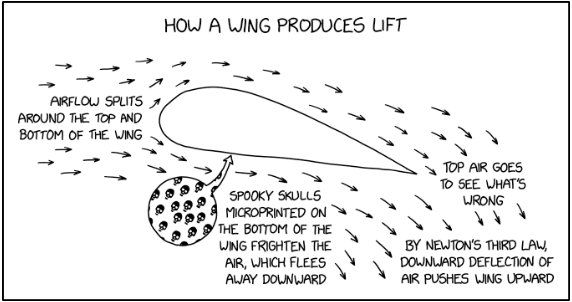


Wing Lift and Drag - Induced Drag

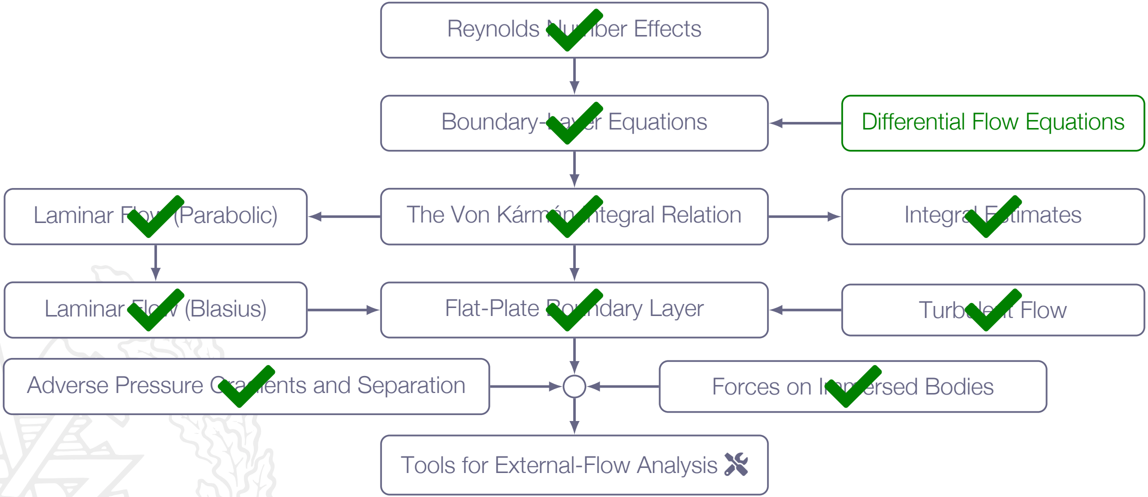


Wing Lift and Drag - Induced Drag

Wing Lift and Drag

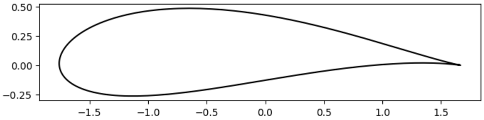


Roadmap - Flow Past Immersed Bodies



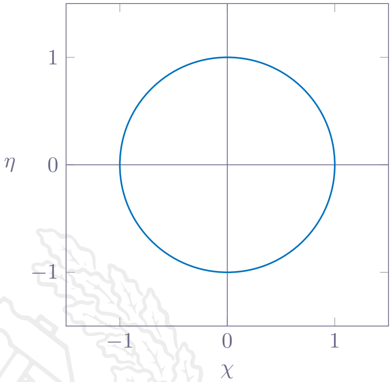
Joukowsky Transform

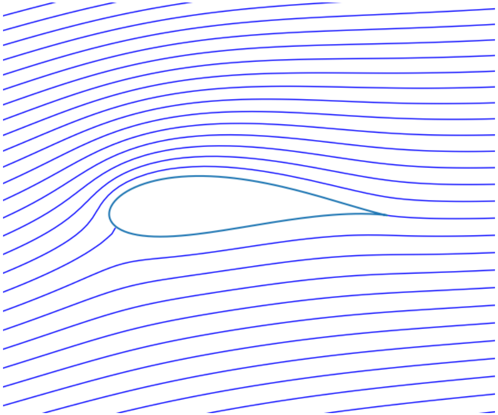
A Joukowsky wing is generated in the complex plane by applying the Joukowsky transform to a cylinder



Since the potential flow around a cylinder is well known it is by using so-called conformal mapping possible to get the flow around the wing profile from the cylinder solution

Joukowsky Transform





$$\zeta = \chi + i\eta$$

$$z = \zeta + \frac{1}{\zeta} = x + iy$$

Complex Conjugate