Fluid Mechanics - MTF053

Lecture 17

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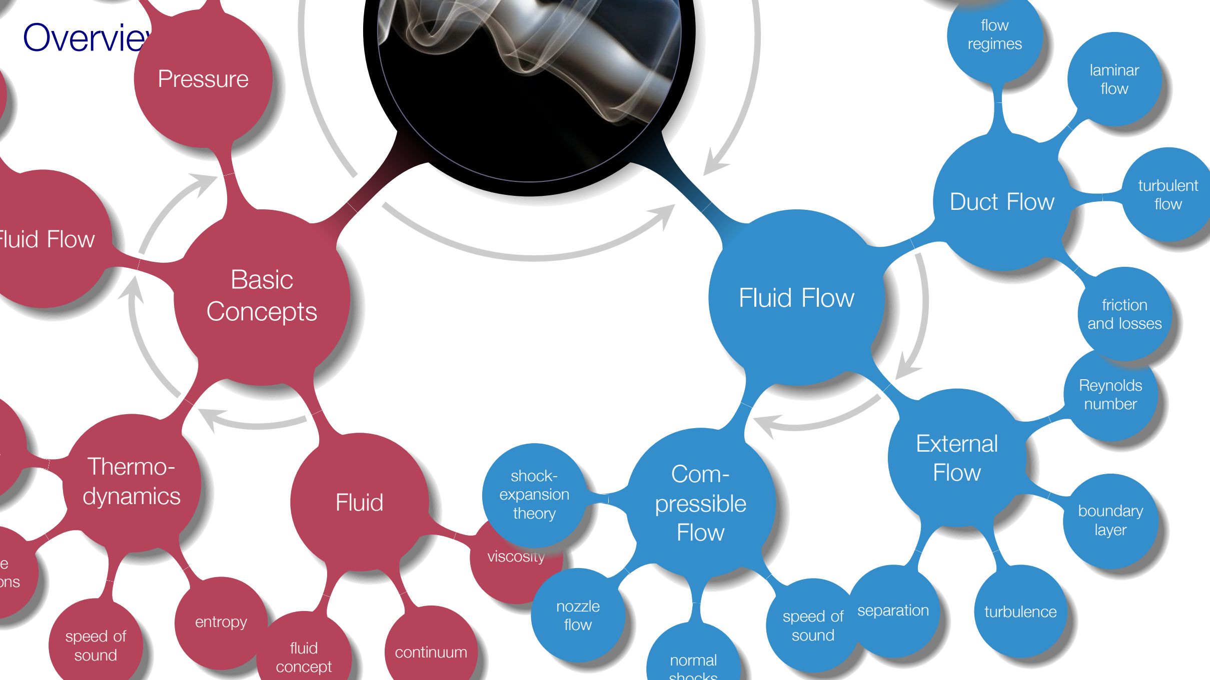
Chapter 7 - Flow Past Immersed Bodies


Overvie
Pressure
luid Flow
Basic Concepts
Thermo-dynamics
Fluid
viscosity
speed of sound
entropy
fluid concept
continuum
Fluid Flow
flow regimes
laminar flow
Duct 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

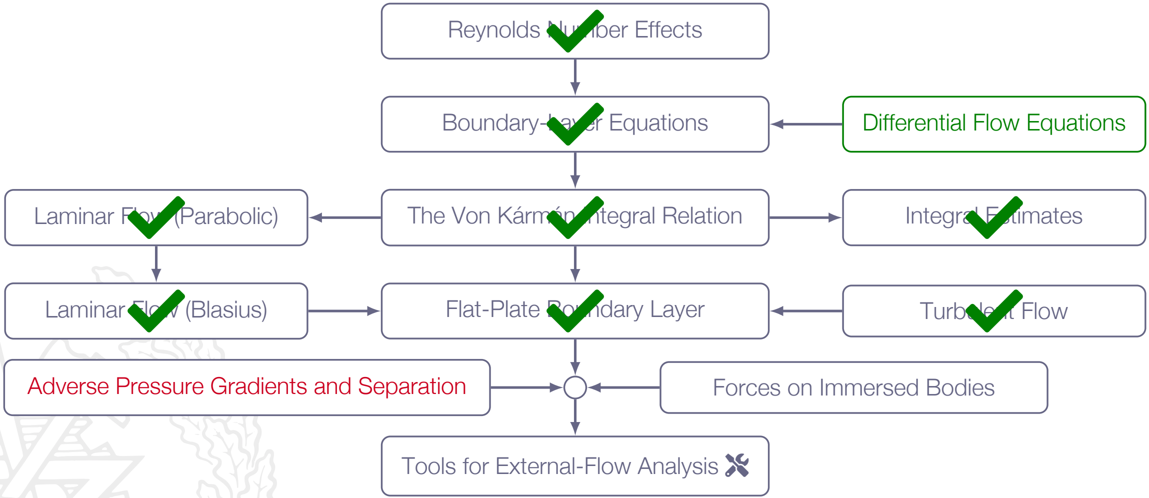
Complementary Course Material

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

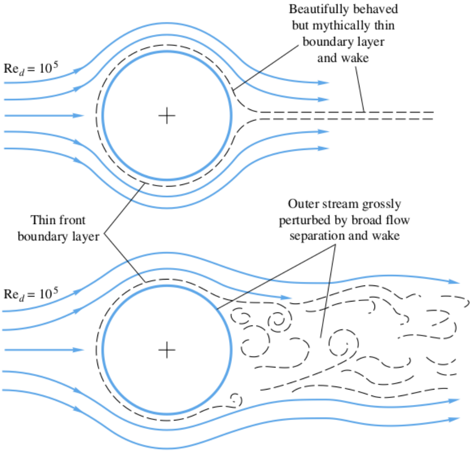
pressure increases in the flow direction
may lead to separation

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

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

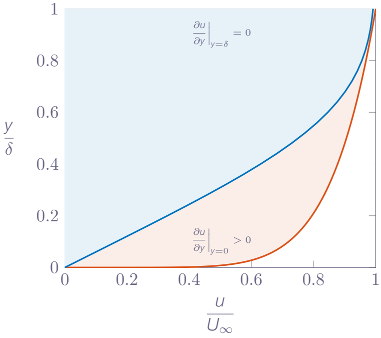
$$\frac{\partial u^2}{\partial y^2} \sim \frac{\left.\frac{\partial u}{\partial y}\right|_{y=\delta} - \left.\frac{\partial u}{\partial y}\right|_{y=0}}{\delta} < 0$$

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

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

$\frac{\partial^2 u}{\partial y^2} < 0$ in the outer layer ($y \to \delta$)

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



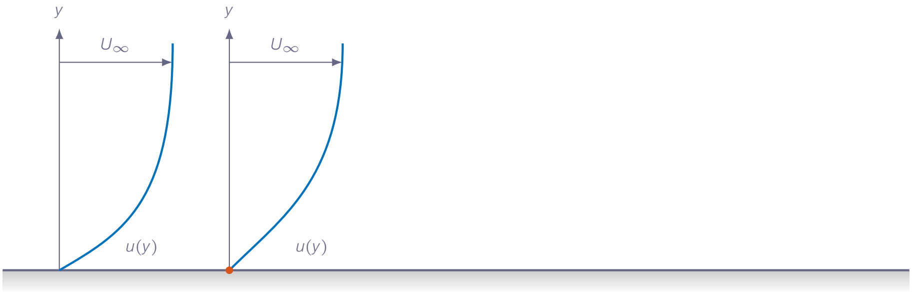
Pressure Gradient

Favorable gradient
$(dp/dx < 0)$

Point of inflection:
inside wall

No separation

Pressure Gradient



Favorable gradient
$(dp/dx < 0)$

Point of inflection:
inside wall

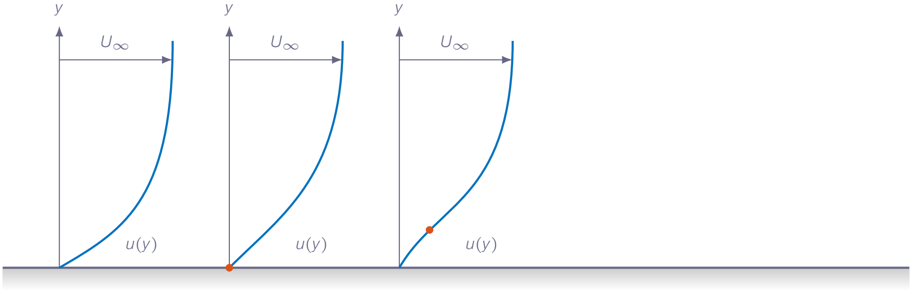
No separation

Zero gradient
$(dp/dx = 0)$

Point of inflection:
at the wall

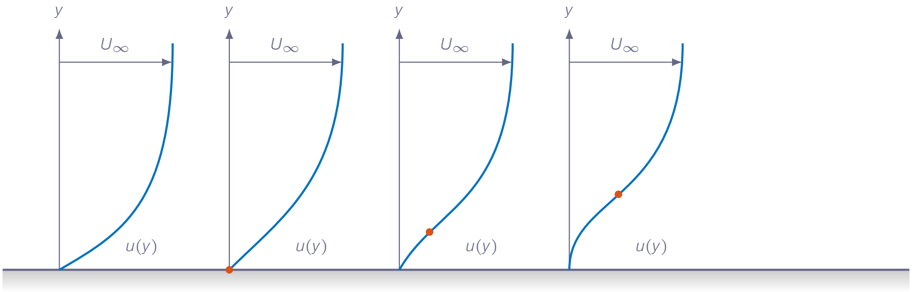
No separation

Pressure Gradient



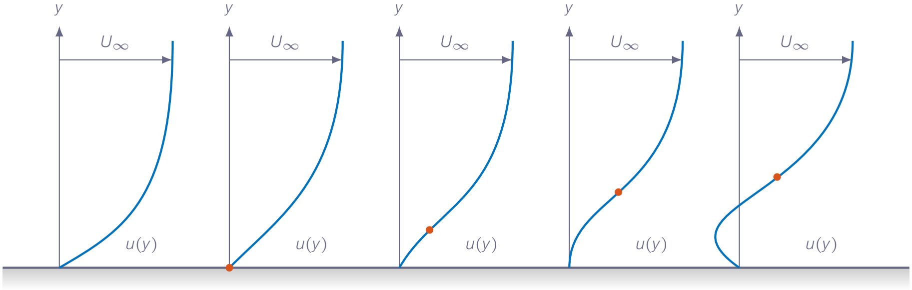
Favorable gradient ($dp/dx < 0$)	Zero gradient ($dp/dx = 0$)	Weak adverse gradient ($dp/dx > 0$)
Point of inflection: inside wall	Point of inflection: at the wall	Point of inflection: in the flow
No separation	No separation	No separation

Pressure Gradient



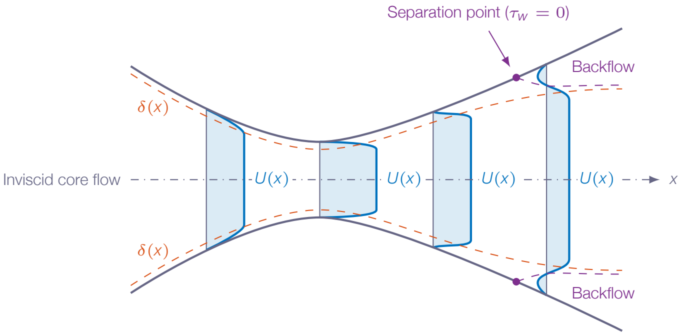
Favorable gradient $(dp/dx < 0)$	Zero gradient $(dp/dx = 0)$	Weak adverse gradient $(dp/dx > 0)$	Critical adverse gradient $(dp/dx > 0)$
Point of inflection: inside wall	Point of inflection: at the wall	Point of inflection: in the flow	Point of inflection: in the flow
No separation	No separation	No separation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

Pressure Gradient



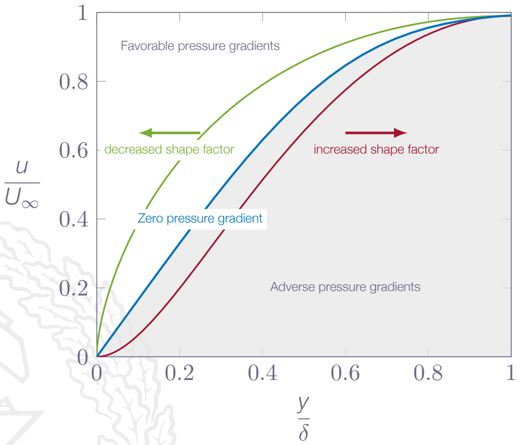
Favorable gradient $(dp/dx < 0)$	Zero gradient $(dp/dx = 0)$	Weak adverse gradient $(dp/dx > 0)$	Critical adverse gradient $(dp/dx > 0)$	Excessive adverse gradient $(dp/dx > 0)$
Point of inflection: inside wall	Point of inflection: at the wall	Point of inflection: in the flow	Point of inflection: in 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: $H = \frac{\delta^*}{\theta}$

Laminar flow:

No pressure gradient: $H \approx 2.6$

Separation: $H \approx 3.5$

Turbulent flow:

No pressure gradient: $H \approx 1.3$

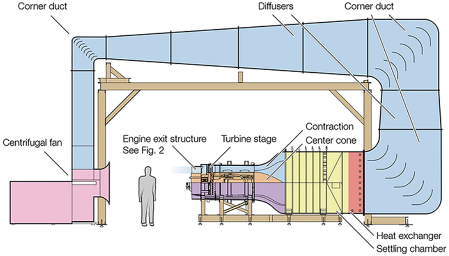
Separation: $H \approx 2.4$

Avoid or Delay Separation

Decrease magnitude of adverse pressure gradient

Guide vanes

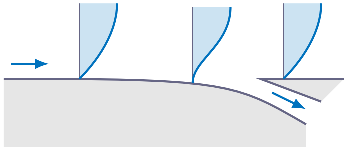
Streamlining



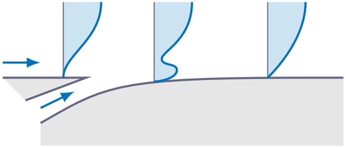
Avoid or Delay Separation

Remove decelerated fluid

Boundary layer suction



Avoid or Delay Separation



Increase near-wall momentum

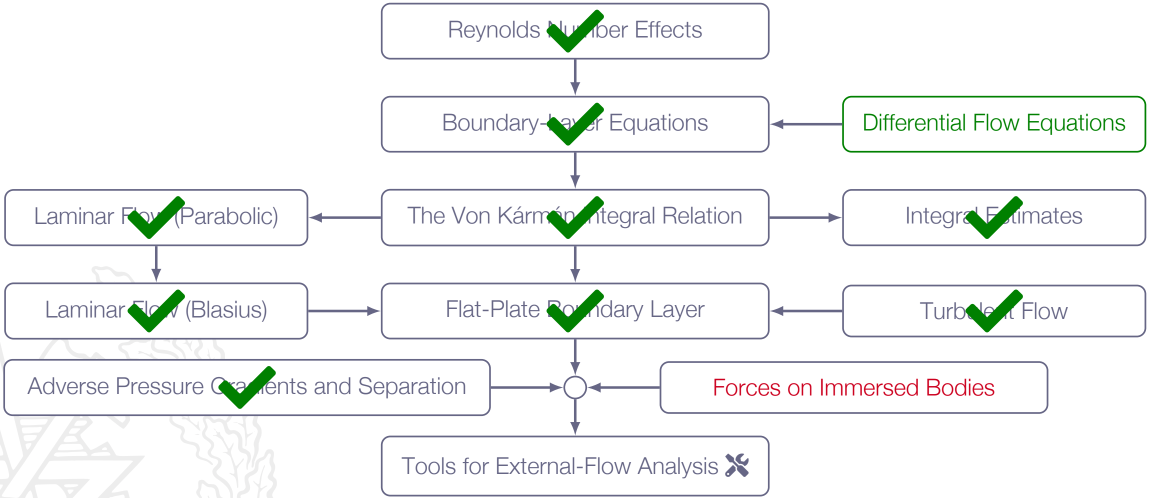
Injection of high-velocity fluid

Forced **transition to turbulence**

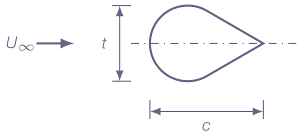
- surface roughness
- surface irregularities (dimples on the surface of a golf ball)
- trip wires

Negative consequence: comes with **increased friction**

Roadmap - Flow Past Immersed Bodies



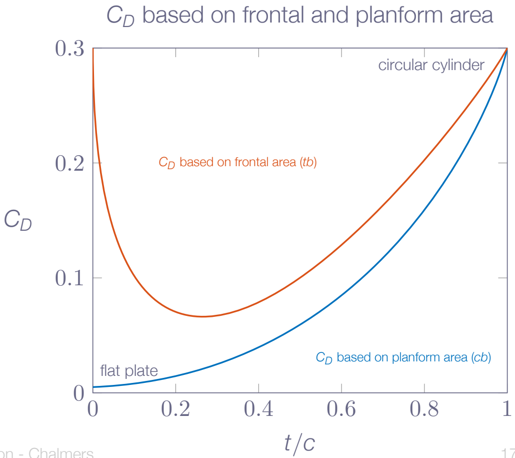
Drag of Immersed Bodies



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

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

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

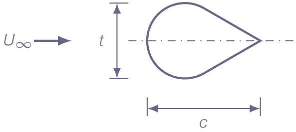
Pressure drag:

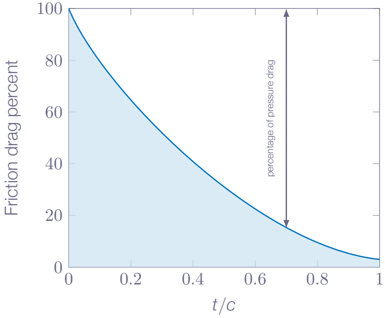
"the difference between the high front stagnation pressure and the low wake pressure on the backside of the body"

"often larger than the friction drag"

The relative importance of friction and pressure drag depends on:

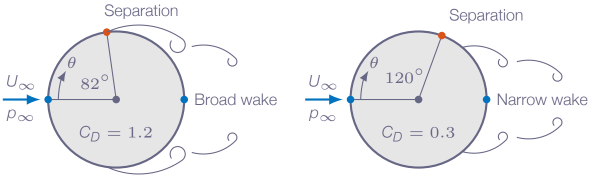
1. body shape
2. surface roughness



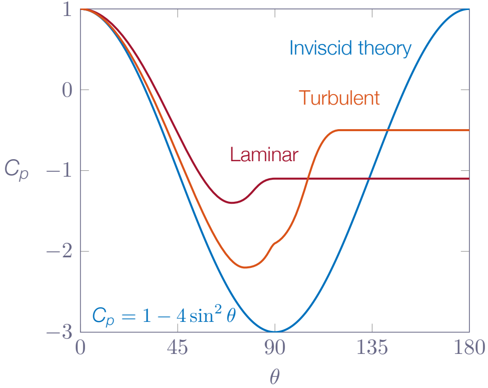


Note! for a cylinder, friction drag can be as low as a few percent of the total drag

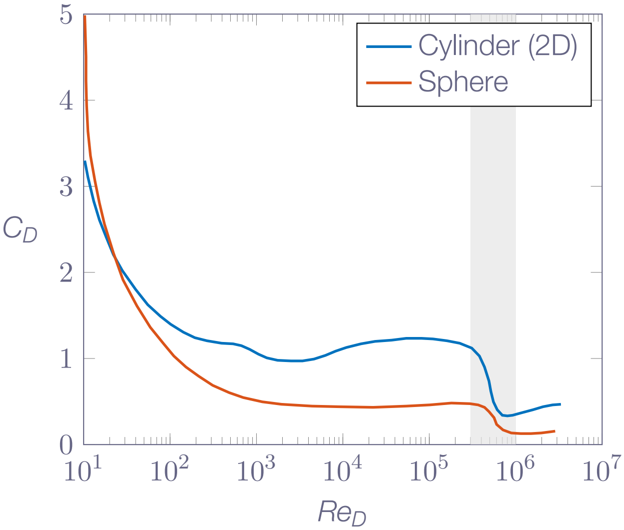
Cylinder Surface Pressure



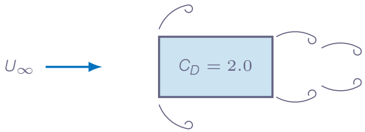
$$C_p = \frac{p - p_\infty}{\rho U_\infty^2 / 2}$$



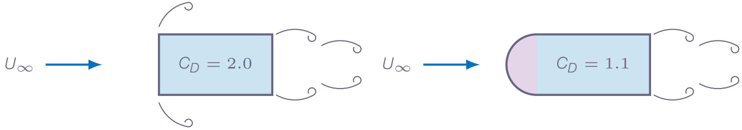
Cylinder Drag



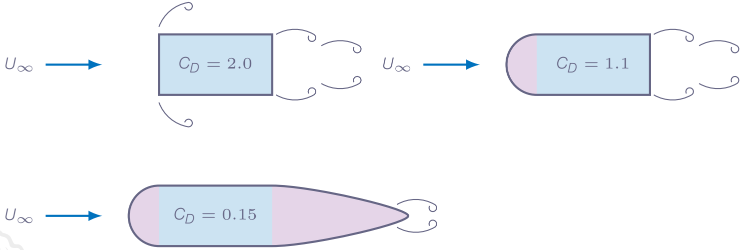
Streamlining



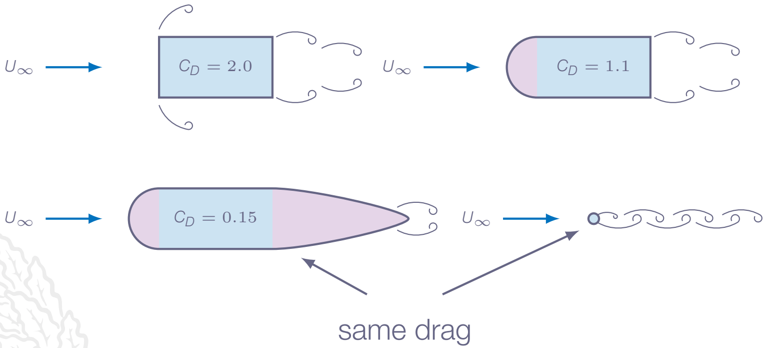
Streamlining



Streamlining



Streamlining



Drag Prediction

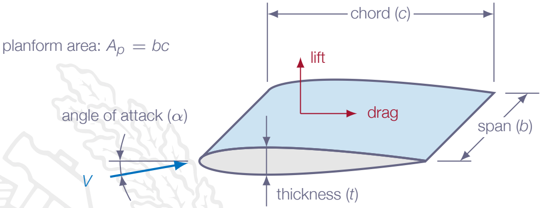
No reliable theory for drag prediction (with the exception of flat plates)

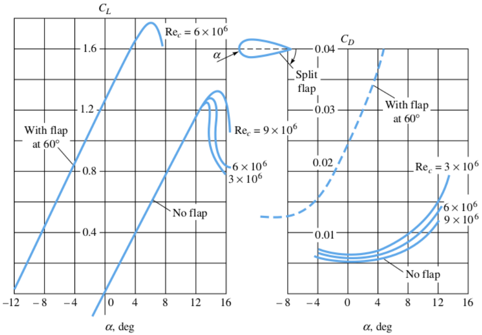
The separation point can be predicted with some accuracy but not the wake flow

CFD or experiments needed

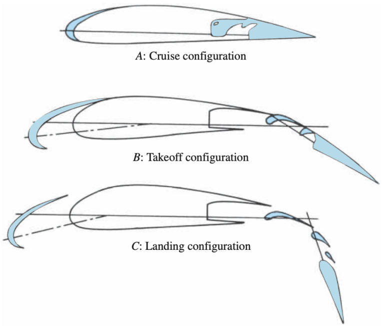
Wing Lift and Drag

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

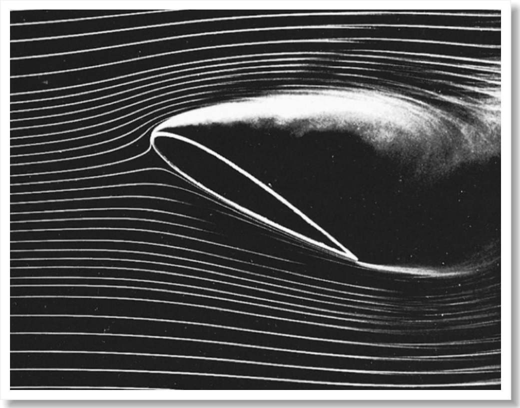




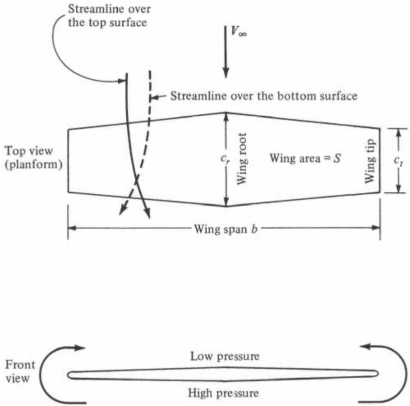
Wing Lift and Drag - High-Lift Devices

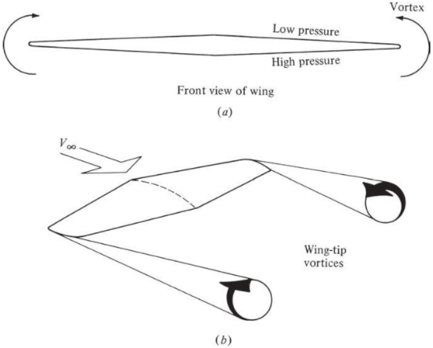


Wing Lift and Drag - Wing Stall

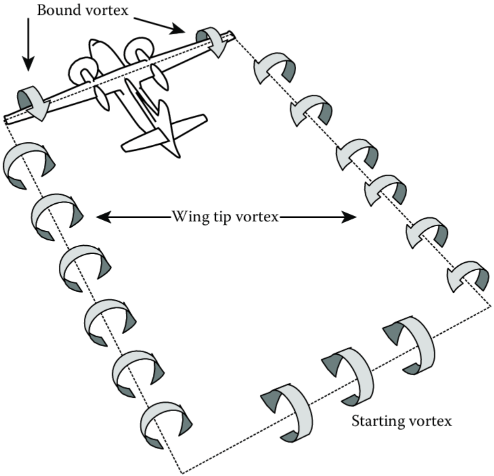


Wing Lift and Drag - Induced Drag



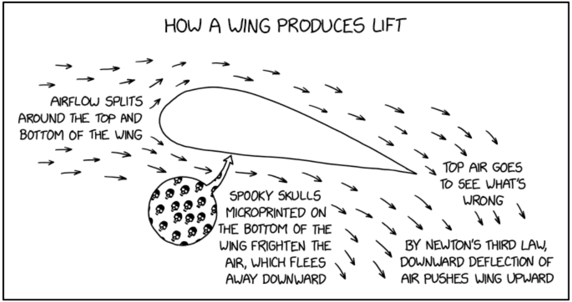


Wing Lift and Drag - Induced Drag

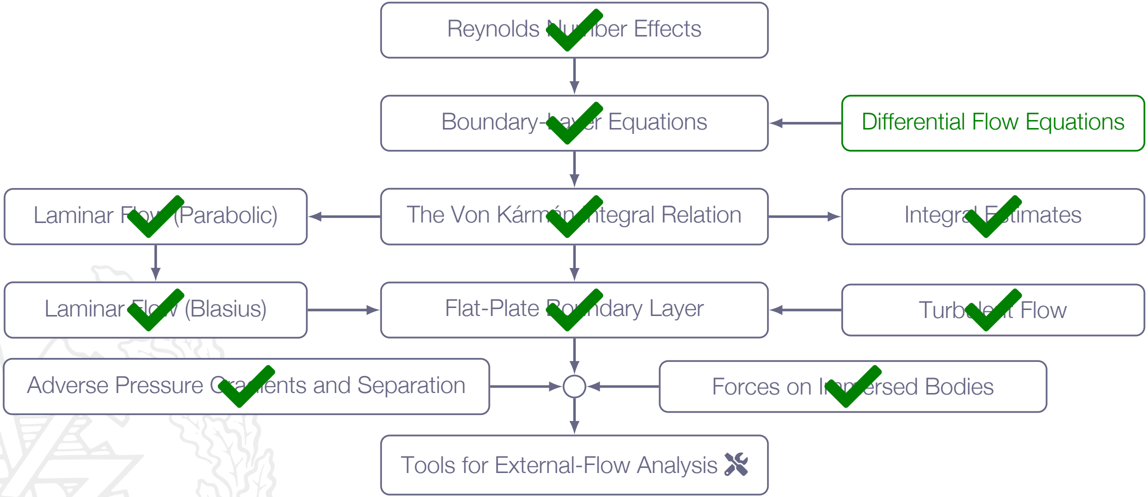


Wing Lift and Drag - Induced Drag

Wing Lift and Drag

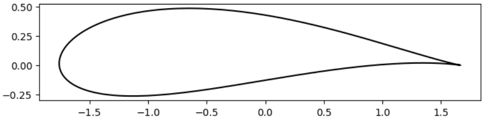


Roadmap - Flow Past Immersed Bodies



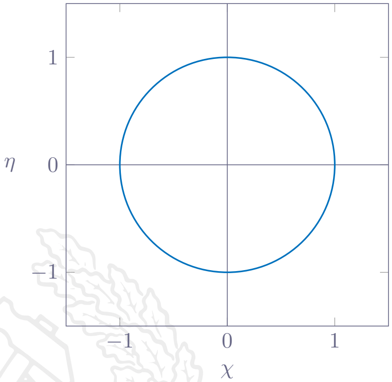
Joukowsky Transform

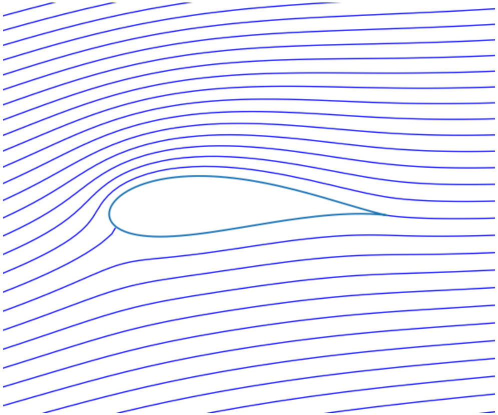
A Joukowsky wing is generated in the complex plane by applying the Joukowsky transform to a cylinder



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