Fall 2024

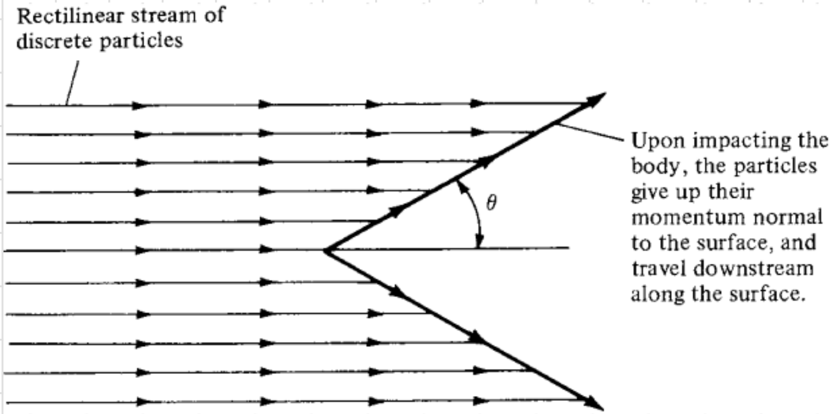
ME-445 AERODYNAMICS
01 - Introduction

K. Mulleners

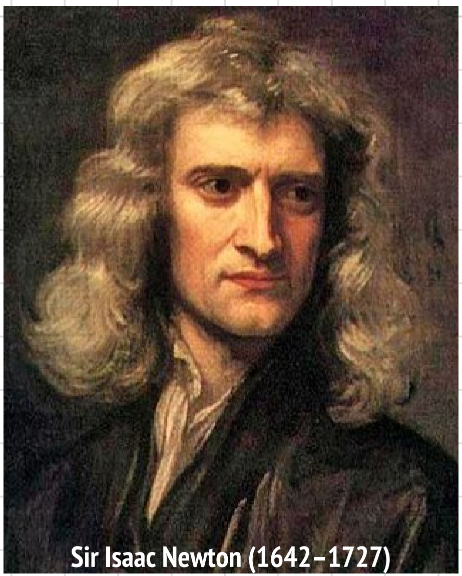
Introduction

- A bit of history
- Course summary
- Aerodynamic analysis
- Dimensional analysis and similarity
- Aerodynamic scaling
- Course roadmap

A little bit of history



Sir Isaac Newton's model of fluid flow (1687)
$\Rightarrow$ hydrodynamic force on a surface $\sim \sin^2\theta$

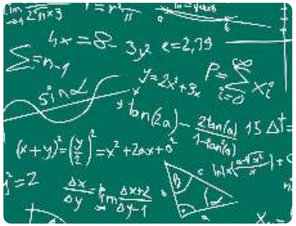


Sir Isaac Newton (1642–1727)

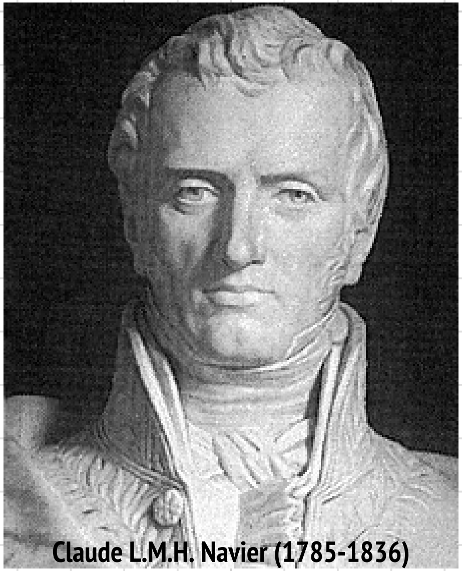
Jean-Baptiste d'Alembert (1717–1783)

Leonhard Euler (1707–1783)

A little bit of history



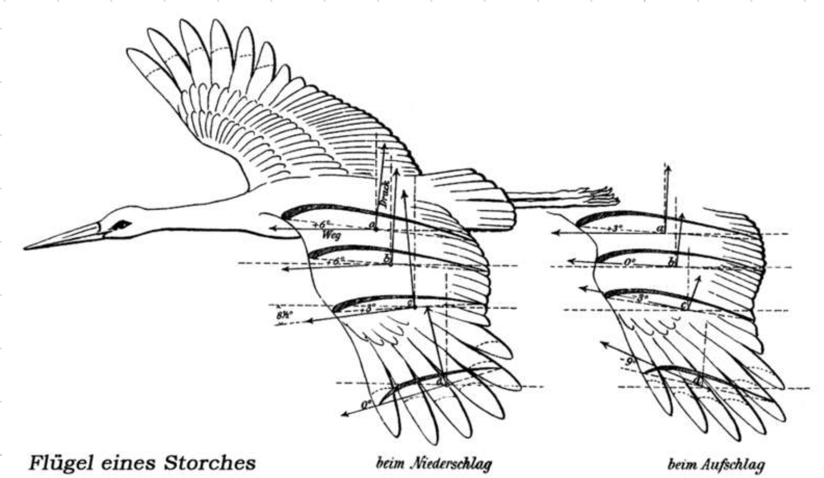
Daniel Bernoulli (1700-1782)



Claude L.M.H. Navier (1785-1836)

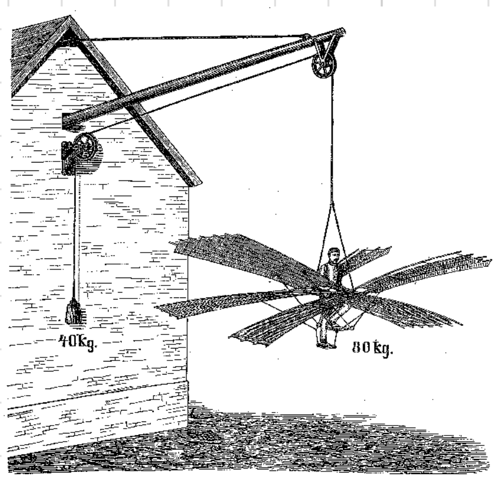
Sir George Gabriel Stokes (1819-1903)

A little bit of history

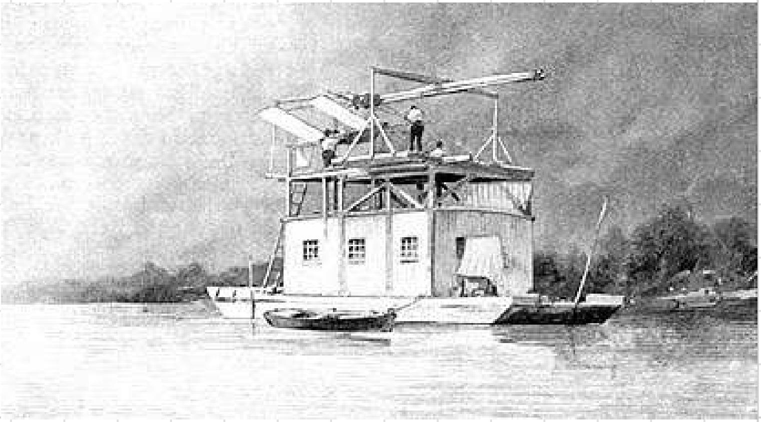


Der Vogelflug als Grundlage der Fliegekunst (1889)


Otto Lilienthal (1848–1896)

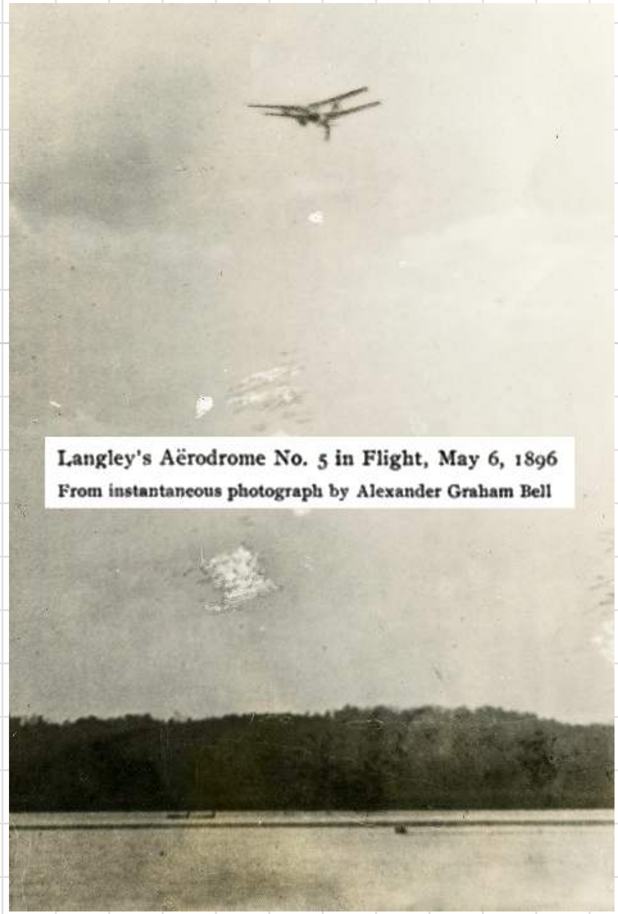


A little bit of history



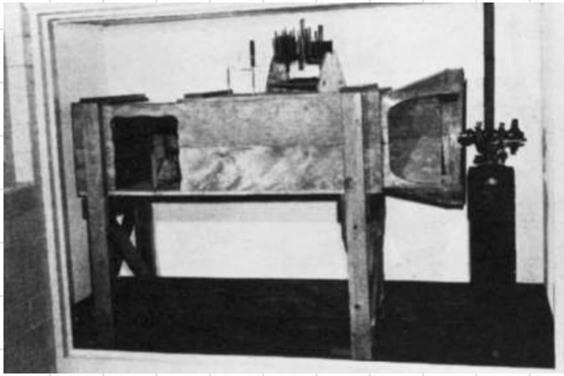
Otto Lilienthal (1848–1896)

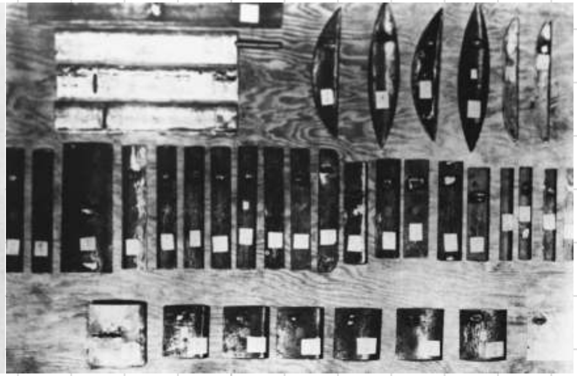
Samuel P. Langley (1834–1906)

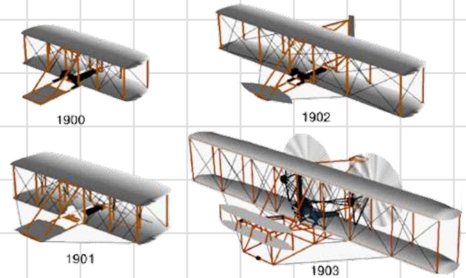


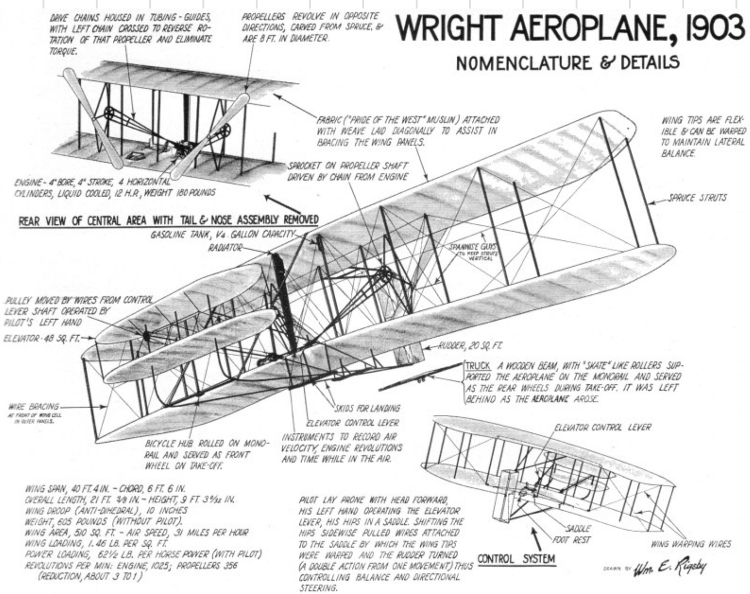
Langley's Aërodrome No. 5 in Flight, May 6, 1896
From instantaneous photograph by Alexander Graham Bell

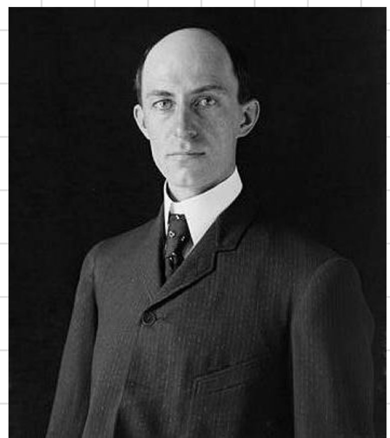
A little bit of history





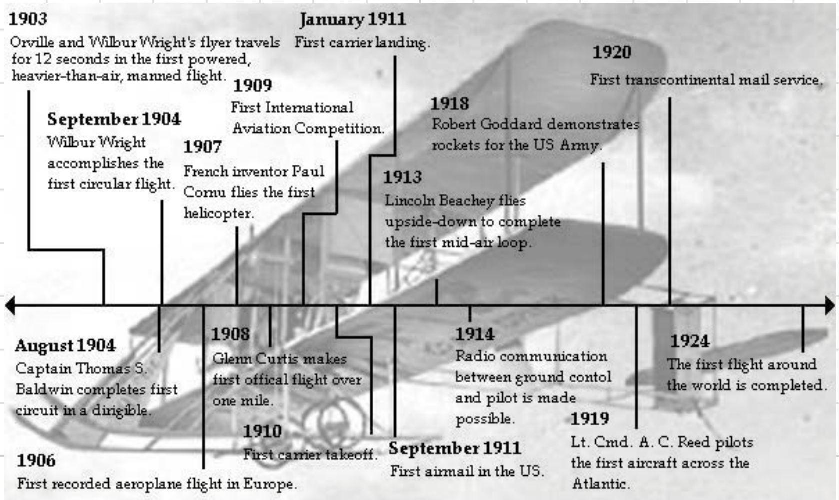





Wilbur Wright (1867-1912)


Orville Wright(1871-1948)

A little bit of history




Otto Lilienthal (1848–1896)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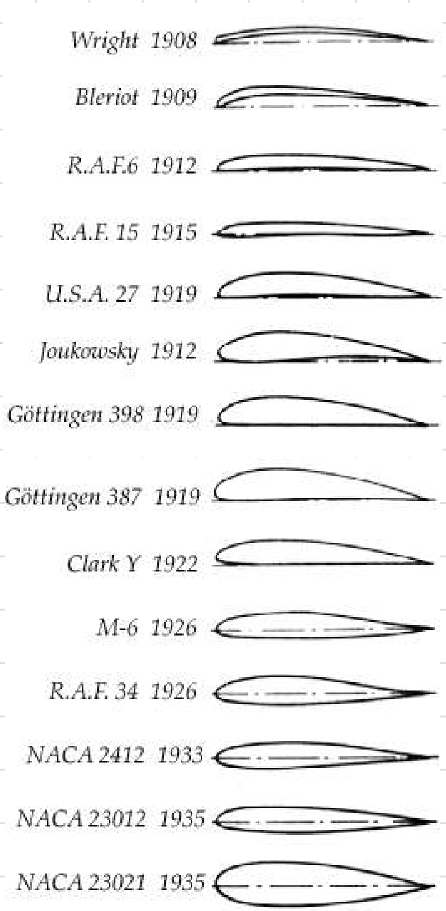
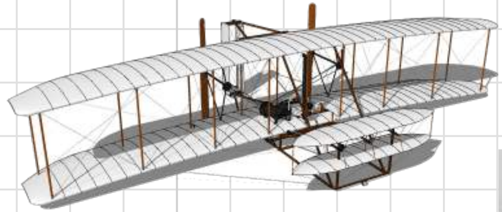
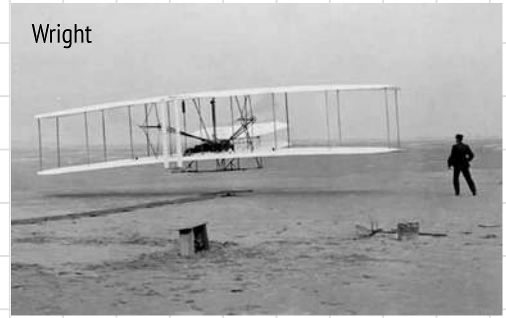
A little bit of history

Airfoil shapes







WWII →

Course summary

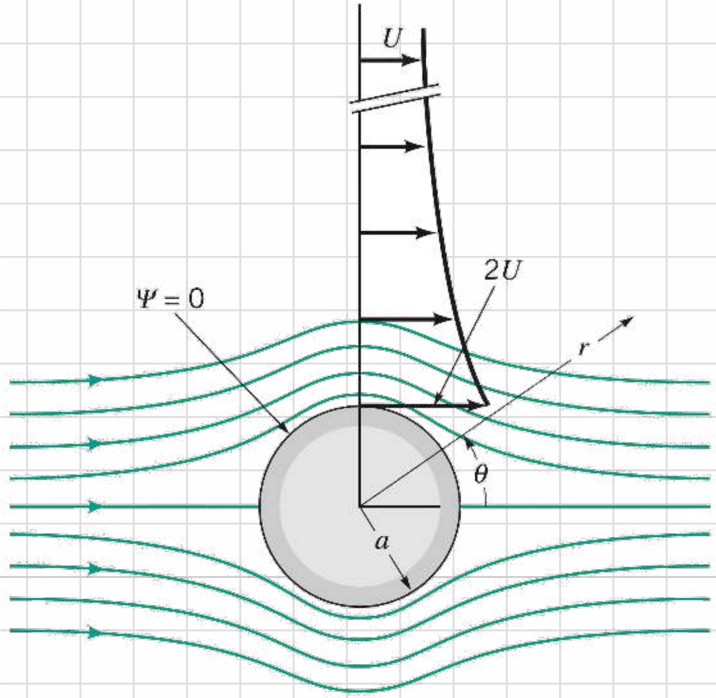
This course will provide the fluid dynamic background to understand how air flows around two- and three-dimensional wings and bodies and to understand the aerodynamics forces and moments acting on the objects as a result of the air flow.

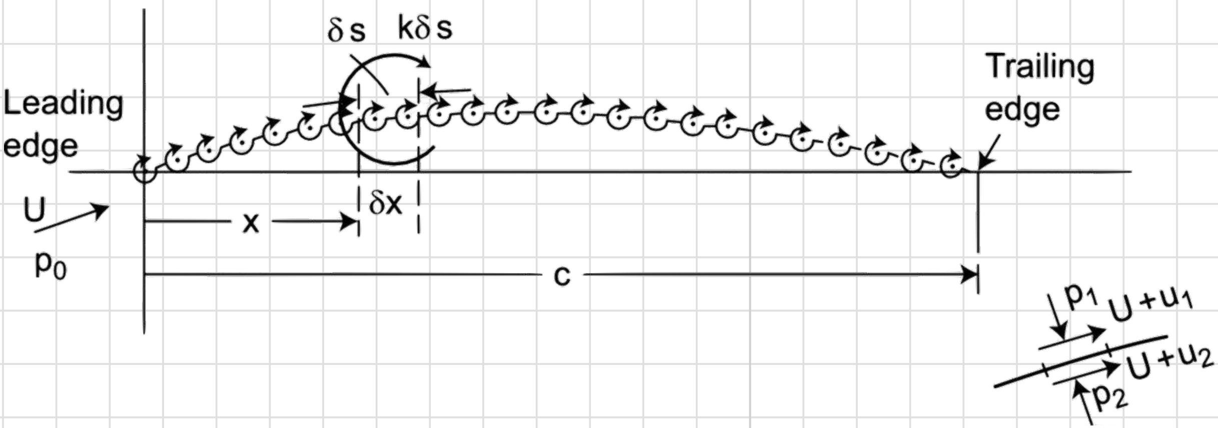
Aerodynamic analysis

- theoretical analysis
- numerical simulations (CFD)
- experimental testing

Aerodynamic analysis

- theoretical analysis
  - potential flow theory
  - thin airfoil theory
  - lifting line theory

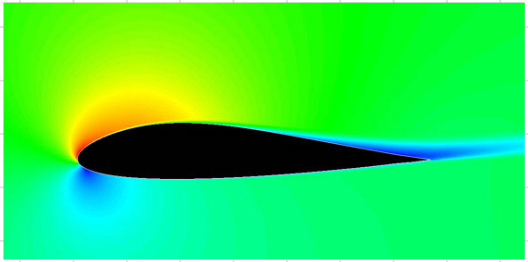


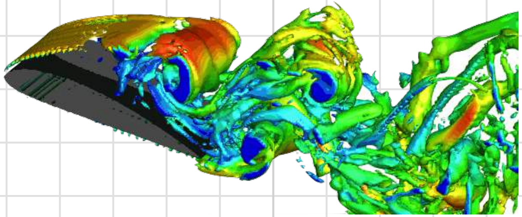


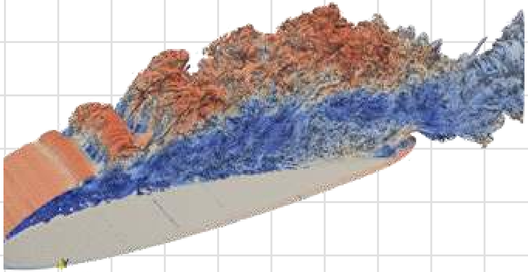
Aerodynamic analysis

- numerical simulations (CFD)
  - Reynolds-averaged Navier–Stokes equations (RANS) simulations
  - Large eddy simulation (LES)
  - Direct numerical simulation (DNS)

  - (machine learning)

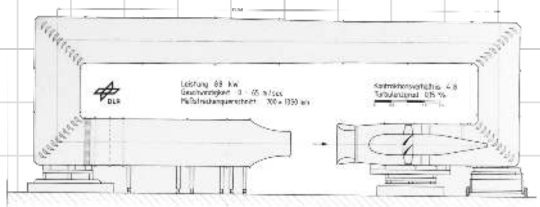


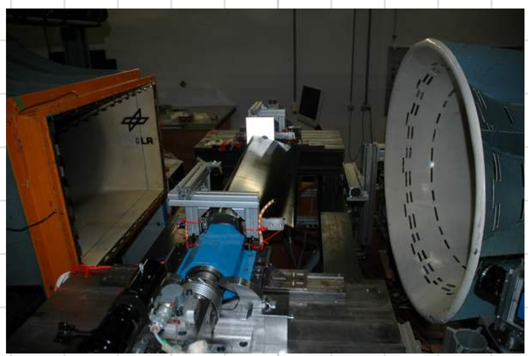


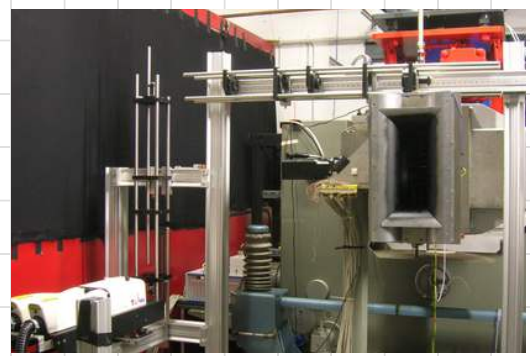


Aerodynamic analysis

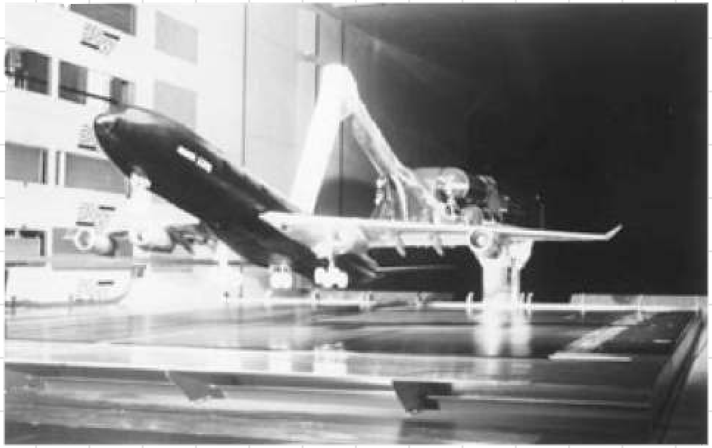
- experimental testing
  - Full-scale (in-flight) testing
  - Model-based testing ⇒ **proper aerodynamic scaling required**
    - windtunnel
    - waterchannel / tow tank

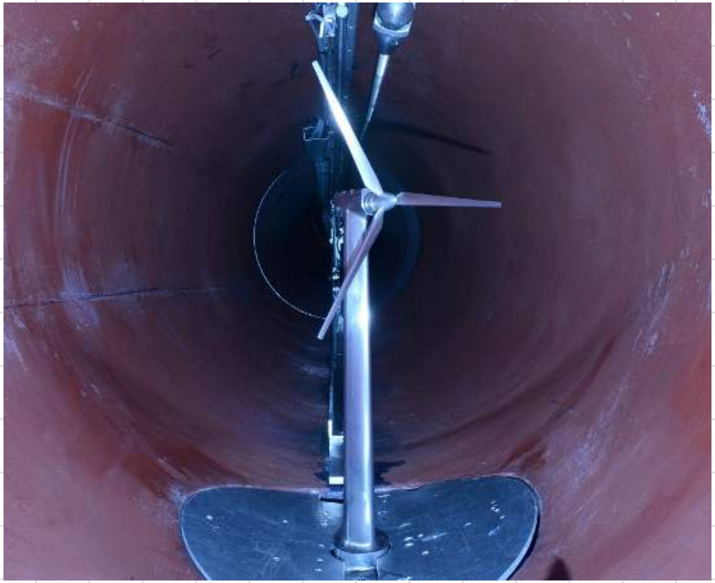






Dimensional analysis and similarity





Dimensions matter ...

Dimensions matter ...

Fundamental dimensions

dimension	symbol	unit
length	L	m
mass	M	kg
time	T	s
temperature	Θ	°K
current	I	A

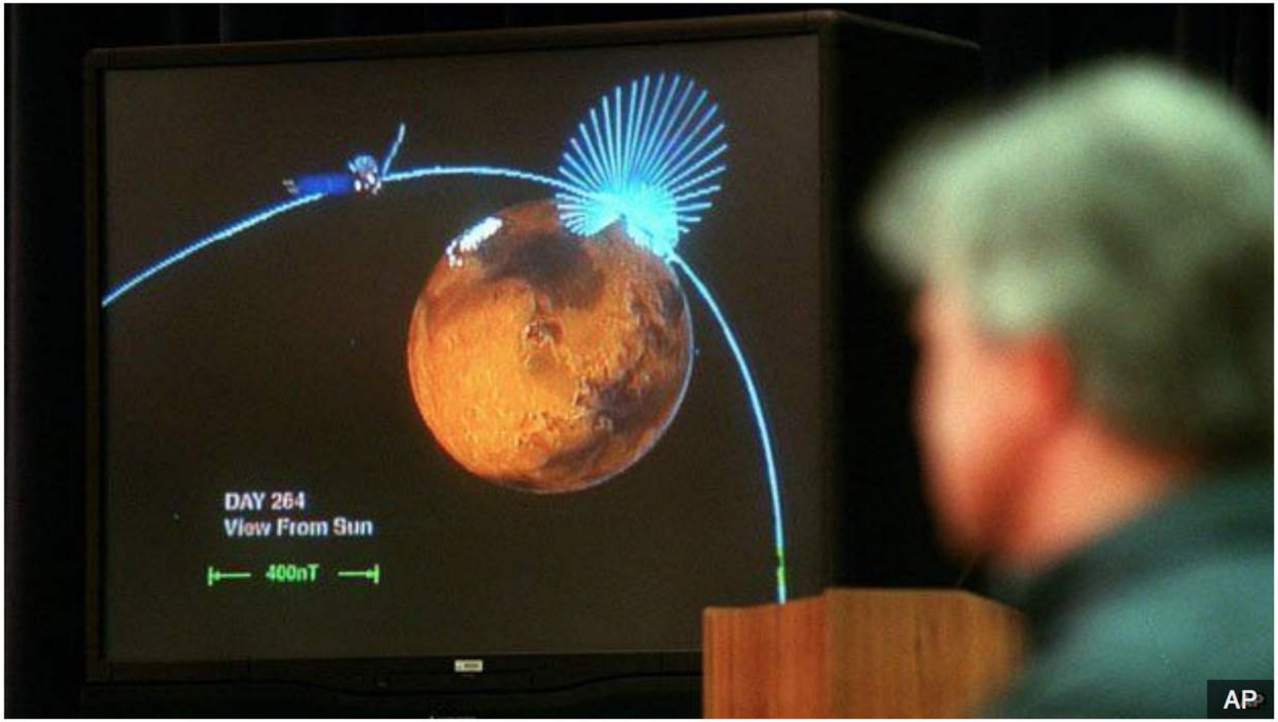
Derived dimensions

quantity	dimension
area	L^2
volume	L^3
velocity	L/T
acceleration	L/T^2
mass density	M/L^3
force	ML/T^2
pressure	$M/(LT^2)$
mechanical energy	ML^2/T^2

The principal use of dimensional analysis is to deduce from a study of the dimensions of the variables in any physical system certain limitations on the form of any possible relationship between those variables. The method is of great generality and mathematical simplicity.

Bridgman (1969)

... units too



Designed to orbit Mars as the first interplanetary weather satellite, the Mars Orbiter was lost in 1999 because the Nasa team used metric units while a contractor used imperial. The $125m probe came too close to Mars as it tried to manoeuvre into orbit, and is thought to have been destroyed by the planet's atmosphere. An investigation said the "root cause" of the loss was the "failed translation of English units into metric units" in a piece of ground software.

Course summary

This course will provide the fluid dynamic background to understand how air flows around two- and three-dimensional wings and bodies and to understand the aerodynamics forces and moments acting on the objects as a result of the air flow.

Three main ingredients in an aerodynamic analysis:

- the medium or the fluid
- the geometry or configuration of the model
- the relative motion or the flow

Describing an aerodynamic problem

	dimensional quantities
Medium	
Model	
Motion	

Buckingham Π theorem

Let K equal the number of fundamental dimensions required to describe the physical variables. Let P_1, P_2,...,P_N represent N physical variables in the physical relation:

$$f_1(P_1, P_2, ..., P_N) = 0$$

Then, this physical relation may be re-expressed as a relation of $(N-K)$ dimensionless products (called Π groups)

$$f_2(\Pi_1, \Pi_2, ..., \Pi_{N-K}) = 0$$

where each Π group is a dimensionless product of a set of K physical variables plus one other physical variable. Let P_1, P_2,...,P_K be the selected set of K physical variables. Then

$$\begin{aligned}
\Pi_1 &= f_3(P_1, P_2, ..., P_K, P_{K+1}) \\
\Pi_2 &= f_4(P_1, P_2, ..., P_K, P_{K+2}) \\
&\cdots \\
\Pi_{N-K} &= f_5((P_1, P_2, ..., P_K, P_N)
\end{aligned}$$

The choice of the repeating variables P_1, P_2,...,P_K should be such that they include all the K dimensions used in the problem. Also, the dependent variable should appear in only one of the Π products.

Special Π groups

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

Variables: Acceleration of gravity, g; Bulk modulus, E_v; Characteristic length, ℓ; Density, ρ; Frequency of oscillating flow, ω; Pressure, p (or Δp); Speed of sound, c; Surface tension, σ; Velocity, V; Viscosity, μ

Dimensionless Groups	Name	Interpretation (Index of Force Ratio Indicated)	Types of Applications
$\frac{\rho V \ell}{\mu}$	Reynolds number, Re	$\frac{\text{inertia force}}{\text{viscous force}}$	Generally of importance in all types of fluid dynamics problems
$\frac{V}{\sqrt{g\ell}}$	Froude number, Fr	$\frac{\text{inertia force}}{\text{gravitational force}}$	Flow with a free surface
$\frac{p}{\rho V^2}$	Euler number, Eu	$\frac{\text{pressure force}}{\text{inertia force}}$	Problems in which pressure, or pressure differences, are of interest
$\frac{\rho V^2}{E_v}$	Cauchy number,[a] Ca	$\frac{\text{inertia force}}{\text{compressibility force}}$	Flows in which the compressibility of the fluid is important
$\frac{V}{c}$	Mach number,[a] Ma	$\frac{\text{inertia force}}{\text{compressibility force}}$	Flows in which the compressibility of the fluid is important
$\frac{\omega \ell}{V}$	Strouhal number, St	$\frac{\text{inertia (local) force}}{\text{inertia (convective) force}}$	Unsteady flow with a characteristic frequency of oscillation
$\frac{\rho V^2 \ell}{\sigma}$	Weber number, We	$\frac{\text{inertia force}}{\text{surface tension force}}$	Problems in which surface tension is important

Describing an aerodynamic problem

	dimensional quantities	non-dimensional parameters
Medium		
Model		
Motion		

Buckingham Π theorem example

Step 1
$\Delta p_\ell = f(D, \rho, \mu, V)$

Step 2
$\Delta p_\ell = FL^{-3}, \ldots$

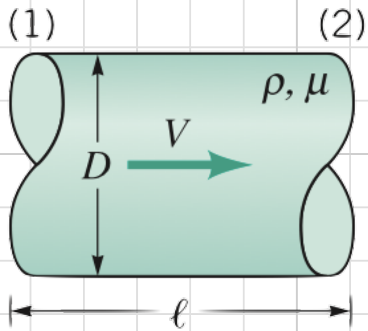
Step 3
N - K = 2

Step 4
D, V, ρ

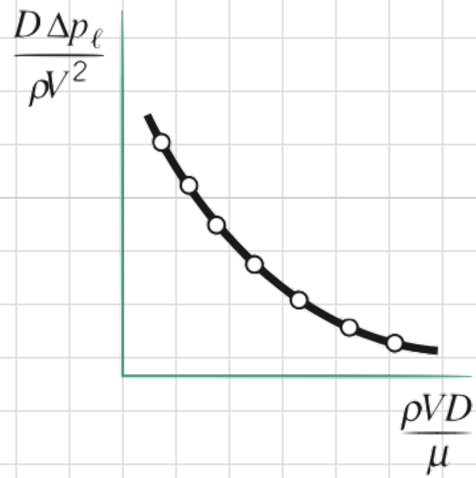
Step 5
$\Pi_1 = \Delta p_\ell D^a V^b \rho^c$

Step 6
$\Pi_2 = \mu D^a V^b \rho^c$

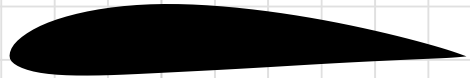
Step 7
$$\frac{\Delta p_\ell D}{\rho V^2} = \tilde{\phi}\left(\frac{\mu}{DV\rho}\right)$$



$$\Delta p_\ell = (p_1 - p_2)/\ell$$



Aerodynamic scaling



What physical quantities determine the variation of the resultant aerodynamic force R on an airfoil with a given shape and a given angle of attack in a constant free stream flow?

Step 1

Step 2

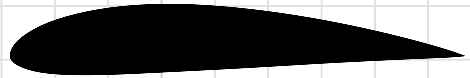
Step 3

Step 4

Step 5

Step 6

Aerodynamic scaling



What physical quantities determine the variation of the resultant aerodynamic force R on an airfoil with a given shape and a given angle of attack in a constant free stream flow?

Step 1

$$R = f_1(\rho_\infty, \mathrm{U}_\infty, c, \mu_\infty, a_\infty) \rightarrow g_1(R, \rho_\infty, \mathrm{U}_\infty, c, \mu_\infty, a_\infty) = 0$$

Step 2

Step 3

$$6 - 3 = 3$$

Step 4

$$\rho_\infty, \mathrm{U}_\infty, c$$

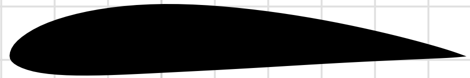
Step 5

$$\Pi_1 = \frac{R}{0.5\rho_\infty \mathrm{U}_\infty^2 S}, \quad \Pi_2 = \frac{\rho_\infty \mathrm{U}_\infty c}{\mu_\infty}, \quad \Pi_3 = \frac{\mathrm{U}_\infty}{a_\infty}$$

Step 6

$$g_2(C_\mathrm{R}, \mathrm{Re}, \mathrm{Ma}) = 0 \rightarrow C_\mathrm{R} = (\mathrm{Re}, \mathrm{Ma})$$

Aerodynamic scaling



What physical quantities determine the variation of the resultant aerodynamic force R on an airfoil with a given shape and a given angle of attack in a constant free stream flow?

Step 1

$$R = f_1(\rho_\infty, U_\infty, c, \mu_\infty, a_\infty) \rightarrow g_1(R, \rho_\infty, U_\infty, c, \mu_\infty, a_\infty) = 0$$

Ste

Ste

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ρ_∞, U_∞, c

Step 5

$$\Pi_1 = \frac{R}{0.5\rho_\infty U_\infty^2 S}, \quad \Pi_2 = \frac{\rho_\infty U_\infty c}{\mu_\infty}, \quad \Pi_3 = \frac{U_\infty}{a_\infty}$$

Step 6

$$g_2(C_R, \mathrm{Re}, \mathrm{Ma}) = 0 \rightarrow C_R = (\mathrm{Re}, \mathrm{Ma})$$

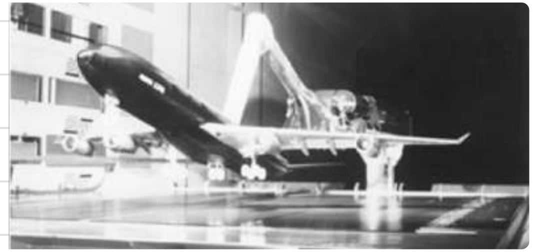
Conclusions of the dimensional analysis:

1. the force can be expressed in terms of a dimensionless force coefficient

$$C_R = \frac{R}{0.5\rho_\infty U_\infty^2 S}$$

2. C_R is a function of only Re and Ma if the shape and angle of attack are given

Similarity



Consider two different flow fields over two different bodies. By definition, different flows are dynamically similar if:

1. The streamline patterns are geometrically similar.
2. The distributions of U/U_∞, p/p_∞, T/T_∞, etc. throughout the flow field are the same when plotted against common non-dimensional coordinates.
3. The force coefficients are the same.

Two flows will be dynamically similar if:

1. The bodies and any other solid boundaries are **geometrically similar** for both flows.
2. The **similarity parameters** are the same for both flows

$$\Pi_1^o = \Pi_1^m \ , \ \Pi_2^o = \Pi_2^m \ , \ \dots \ , \ \Pi_k^o = \Pi_k^m$$

$$\Downarrow$$

$$f^o(\Pi_1^o, \Pi_2^o, \dots, \Pi_K^o) \quad = \quad f^m(\Pi_1^m, \Pi_2^m, \dots, \Pi_K^m)$$

Course roadmap

basic concepts & definitions

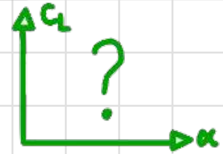
- easy to calculate
- fundamental insights

2D inviscid incompressible flows → ideal flows

potential flow theory

cylinder

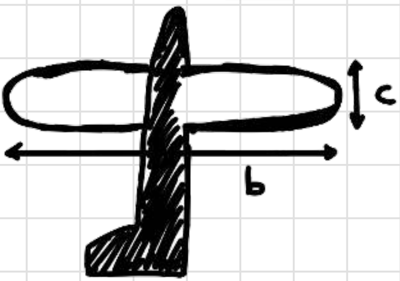
conformal mapping



2D thin airfoil theory

finite wing effects

AR $= \frac{b}{c}$



finite wing ↔ infinite wing
tip vortices

Prandtl lifting line theory

viscous effects

Re $= \frac{U_\infty c}{\nu}$

- boundary layer
- flow separation
- drag

unsteady flow effects

St $= \frac{fc}{U_\infty}$

- insect flight / animal propulsion
- helipter, wind turbine rotors

compressible effects

Ma $= u/a$

ME-343 Compressible fluid dynamics
by Dr. Noca - spring semester