Offshore Hydromechanics Module 1

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5. Real Flows part 1

Introduction

Topics of Module 1

• Problems of interest	Chapter 1
• Hydrostatics	Chapter 2
• Floating stability	Chapter 2
• Constant potential flows	Chapter 3
• **Constant real flows**	**Chapter 4**
• Waves	Chapter 5

Learning Objectives

Chapter 4

- To understand basic real flow concepts, flow regimes in real flows, vortex induced vibrations
- To apply scaling laws to analyse hydromechanic model experiments
- Understand the concepts of lift and drag in real and in potential flows
- To perform basic computations on wind and current loads on floating structures
- To understand the concept of ship resistance and resistance components
- To understand the basic concepts of ship propulsion

Chapter 4 Constant Real Flow Phenomena

Introduction

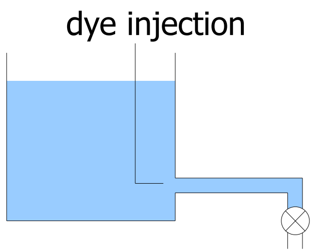
- Real fluids:

  - Now we deal with viscosity
  - Flows in water (current, forward speed) and air (wind)
  - Media still continuous and homogeneous

Basic Viscous Flow Concepts

Reynolds number

- Experiments with tank with drain:



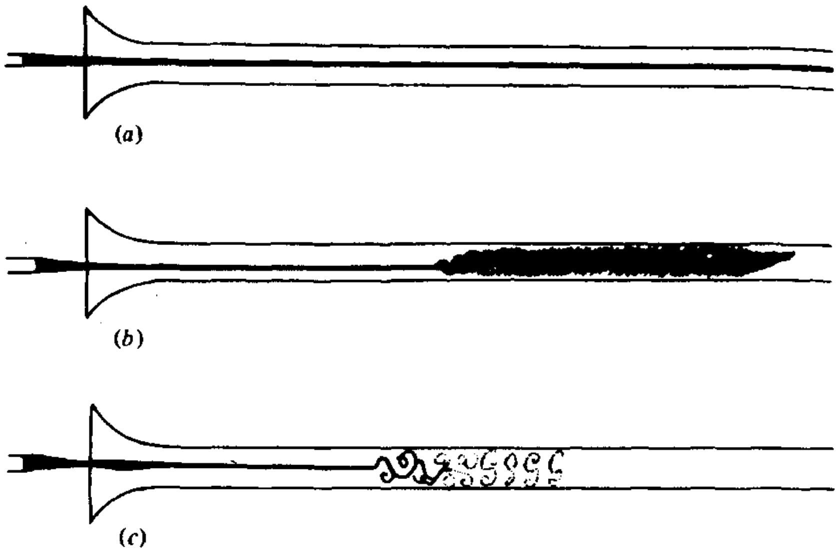


Fig. 9.2. Reynolds's drawings of the flow in his dye experiment.

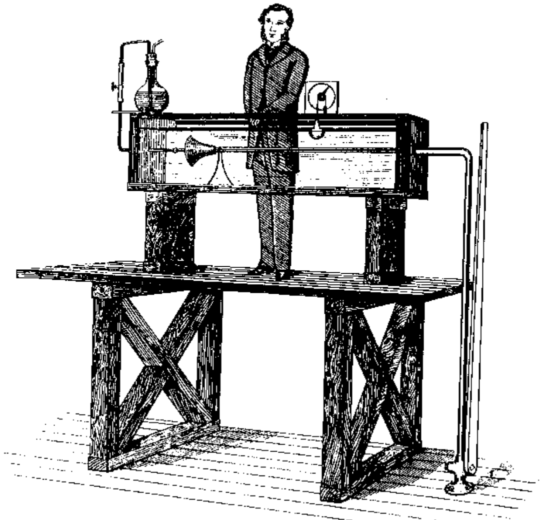


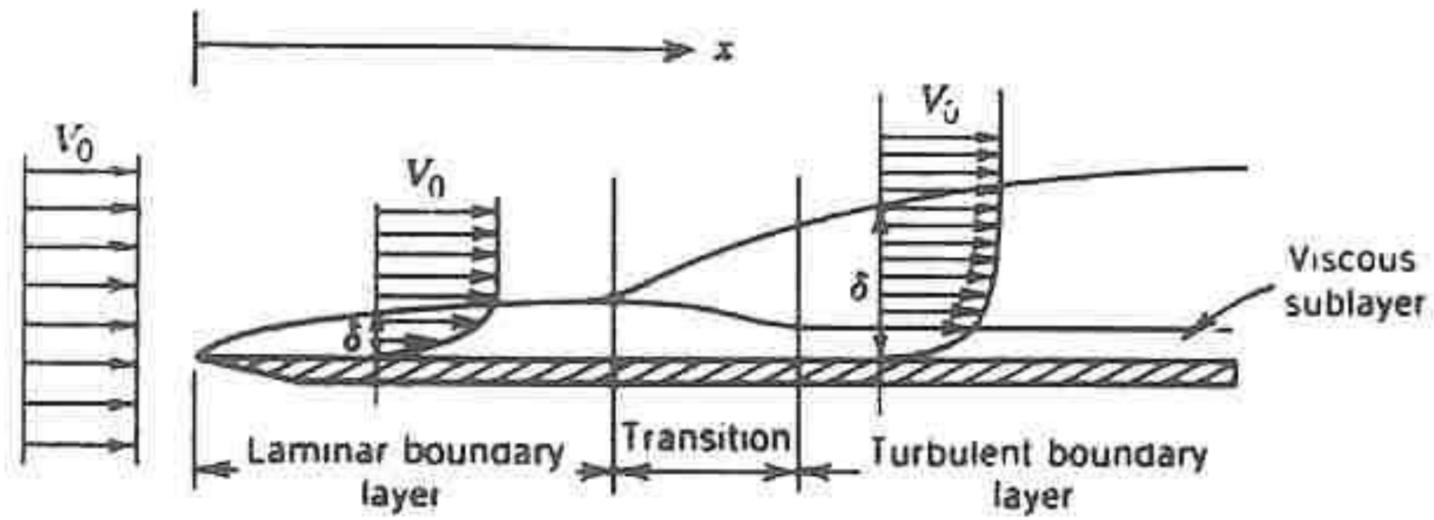
Fig. 9.1. Sketch of Reynolds's dye experiment, taken from his 1883 paper

- Clear influence of flow velocity on flow pattern and length transition laminar – turbulent flow

Basic Viscous Flow Concepts

Reynolds number

- Laminar and turbulent boundary layer:



Basic Viscous Flow Concepts

Reynolds number

- Reynolds found similar phenomena when following ratio was kept constant:

$$Re = \frac{V \cdot D}{\nu}$$

- With:
  - V Flow velocity [m/s]
  - D Pipe diameter [m]
  - ν Kinematic viscosity of fluid [m^2/s]
  - η Dynamic viscosity of fluid [kg /(ms)]

$$\nu = \frac{\eta}{\rho}$$

- Interpretation:

Reynoldsnumber = Inertia forces / Viscous forces

Basic Viscous Flow Concepts

Newton's Friction Force description

- Newton postulated the following for the tangential stress in a fluid:

$$\tau = \eta \cdot \frac{dV}{dy}$$

- With:
  - τ Shear stress [N/m^2]
  - η Dynamic viscosity of fluid [kg /(ms)]
  - dV/dy Velocity gradient [s^{-1}]

- Note: works only well for very low Reynolds numbers (<2000)

Reynolds number ship: $$Re = \frac{(20 \cdot 1852/3600) \cdot 100}{1 \cdot 10^{-6}} \approx 1 \cdot 10^{9}$$

Dimensionless Ratios and Scaling Laws

Physical Model Relationships

- Geometric Similitude:
  (Similitude=Similarity)
  - Fixed ratio between dimensions on model scale and on full scale
- Kinematic Similitude
  - Fixed ratio between velocities and velocity vectors (and components) on model scale and on full scale
- Dynamic Similitude
  - Fixed ratio between forces and force vectors (and components) on model scale and on full scale

Dimensionless Ratios and Scaling Laws

Scale factors

• Length	α_L	$L_p = \alpha_L \cdot L_m$
• Velocity	α_V	$V_p = \alpha_V \cdot V_m$
• Acceleration of gravity	α_g	$g_p = \alpha_g \cdot g_m$
• Density	α_ρ	$\rho_p = \alpha_\rho \cdot \rho_m$
• Viscosity	α_ν	$\nu_p = \alpha_\nu \cdot \nu_m$

Dimensionless Ratios and Scaling Laws

Scale factors

• Area	$\alpha_S = \alpha_L^2$
• Volume	$\alpha_\nabla = \alpha_L^3$
• Mass mom. of inertia	$\alpha_I = \alpha_\rho \cdot \alpha_L^5$
• Mass	$\alpha_M = \alpha_\rho \cdot \alpha_\nabla = \alpha_\rho \cdot \alpha_L^3$
• Time	$\alpha_T = \frac{\alpha_L}{\alpha_V}$
• Acceleration	$\alpha_a = \frac{\alpha_V}{\alpha_T} = \frac{\alpha_V^2}{\alpha_L}$
• Force	$\alpha_F = \alpha_M \cdot \alpha_a = \alpha_\rho \cdot \alpha_L^3 \cdot \frac{\alpha_V^2}{\alpha_L} = \alpha_\rho \cdot \alpha_V^2 \cdot \alpha_L^2$

Dimensionless Ratios and Scaling Laws

Newton's Similitude Law: application

$$\alpha_F = \alpha_M \cdot \alpha_a = \alpha_\rho \cdot \alpha_L^3 \cdot \frac{\alpha_V^2}{\alpha_L} = \alpha_\rho \cdot \alpha_V^2 \cdot \alpha_L^2$$

$$\alpha_F = \frac{F_p}{F_m} = \frac{\rho_p \cdot V_p^2 \cdot L_p^2}{\rho_m \cdot V_m^2 \cdot L_m^2}$$

$$\frac{F_p}{\rho_p \cdot V_p^2 \cdot L_p^2} = \frac{F_m}{\rho_m \cdot V_m^2 \cdot L_m^2} = C$$

$$F_p = C \cdot \frac{1}{2}\rho_p V_p^2 \cdot L_p^2 \qquad F_m = C \cdot \frac{1}{2}\rho_m V_m^2 \cdot L_m^2$$

- Constant C independent of scale!

Dimensionless Ratios and Scaling Laws

Viscous forces and Inertia forces

- Newton's friction force:

$$F = \eta \cdot \frac{dV}{dy} A \qquad F_v \propto \eta \frac{V}{L} L^2 \qquad \alpha_{F_v} = \alpha_\eta \alpha_V \alpha_L$$

- Inertia force:

$$F = ma \qquad F_i \propto \rho L^3 \frac{V^2}{L} = \rho L^2 V^2 \qquad \alpha_{F_i} = \alpha_\rho \alpha_L^2 \alpha_V^2$$

- Gravity force:

$$F = mg \qquad F_g \propto \rho L^3 g \qquad \alpha_{F_g} = \alpha_\rho \alpha_L^3 \alpha_g$$

Dimensionless Ratios and Scaling Laws

Reynolds number and Froude number

- Reynolds number: dynamic similitude viscous forces and inertia forces

$$\alpha_\eta \alpha_V \alpha_L = \alpha_\rho \alpha_L^2 \alpha_V^2$$

$$\alpha_\eta = \alpha_\rho \alpha_L \alpha_V$$

$$\frac{\alpha_\rho \alpha_L \alpha_V}{\alpha_\eta} = 1$$

$$Re = \frac{V \cdot D \cdot \rho}{\eta} = \frac{V \cdot D}{\nu} = constant$$

- Froude number: dynamic similitude gravity forces and inertia forces

$$\alpha_\rho \alpha_L^3 \alpha_g = \alpha_\rho \alpha_L^2 \alpha_V^2$$

$$\alpha_L \alpha_g = \alpha_V^2$$

$$\frac{\alpha_V^2}{\alpha_L \alpha_g} = 1$$

$$Fr = \frac{V}{\sqrt{Lg}} = constant$$

Dimensionless Ratios and Scaling Laws

Reynolds number and Froude number

- For situations where gravity, inertia and viscosity play a role:
  - Model test should be performed at equal Re and Fr with respect to full scale!
  - Only then dynamic similitude for model scale and full scale

  - Example: ship resistance
    - Moving ship and water: inertia forces
    - Waves: gravity forces
    - Friction: viscous forces

$$Re = \frac{V \cdot D \cdot \rho}{\eta} = \frac{V \cdot D}{\nu} = constant \qquad Fr = \frac{V}{\sqrt{Lg}} = constant$$

- However is this really possible?

Cylinder Flow Regimes

Drag force

- The drag force of objects in a fluid is often expressed as:

$$F_D = C_D \cdot \frac{1}{2}\rho V^2 \cdot A \quad [N]$$

- Or for 2D cases per unit length (for instance D diameter of a cylinder):

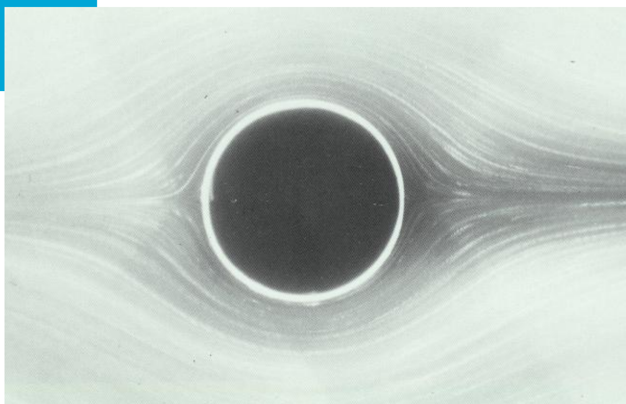
$$f_D = C_D \cdot \frac{1}{2}\rho V^2 \cdot D \quad [N/m]$$

- Newton's similitude law, but C_D is dependent on scale

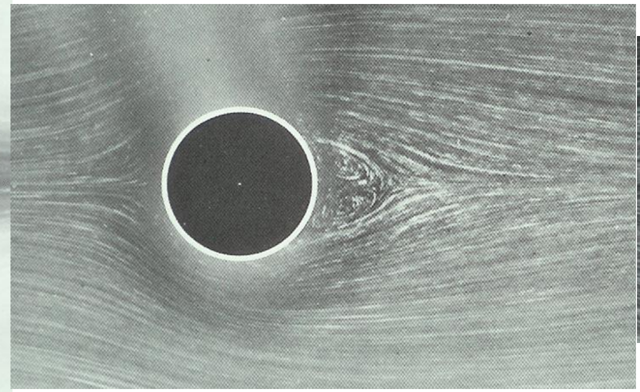
- Note: only (viscous) drag force in real or viscous flows: not in ideal or potential flows!

Cylinder Flow Regimes

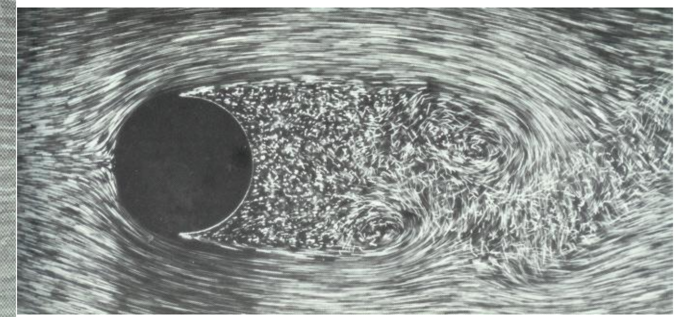
Dependence on Reynolds number



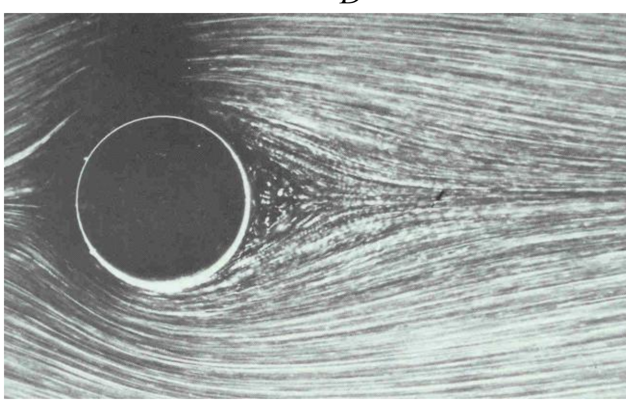
$Re < 1$, $C_D = 1.2$



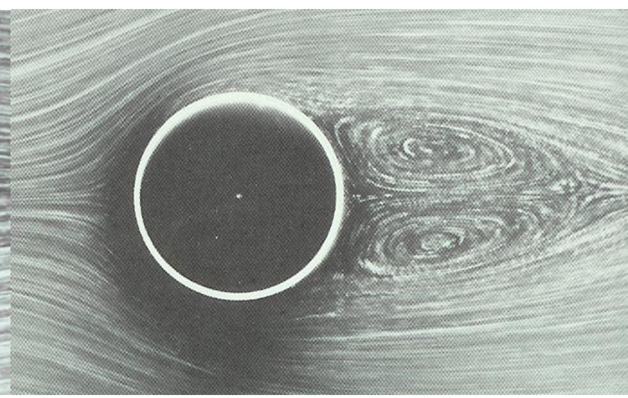
$Re = 13$, $C_D = 3.5$



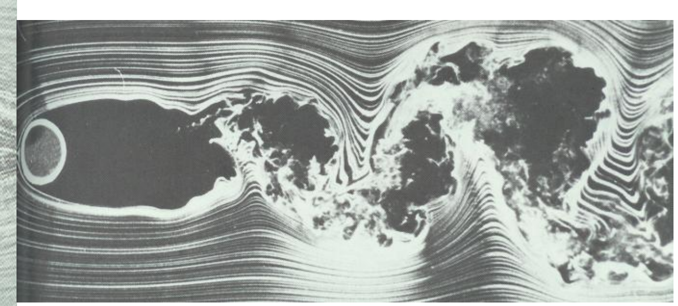
$Re = 2000$, $C_D = 1.3$



$Re = 9.6$, $C_D = 4.0$



$Re = 26$, $C_D = 2.0$



$\mathrm{Re} = 10000$, $C_D = 1.2$

Cylinder Flow Regimes

Critical flow

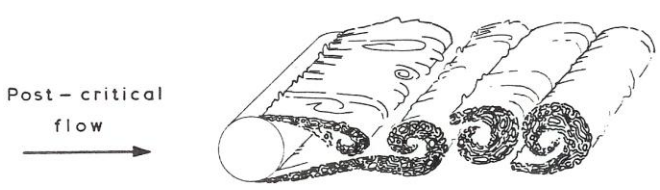
- Critical Reynoldsnumber: transition from laminar to turbulent flow

- For flow around a cylinder:

  - Subcritical ($C_D = 1.2$)
  - Critcal flow ($C_D = 0.3$)
  - Postcritical flow ($C_D = 0.7$)

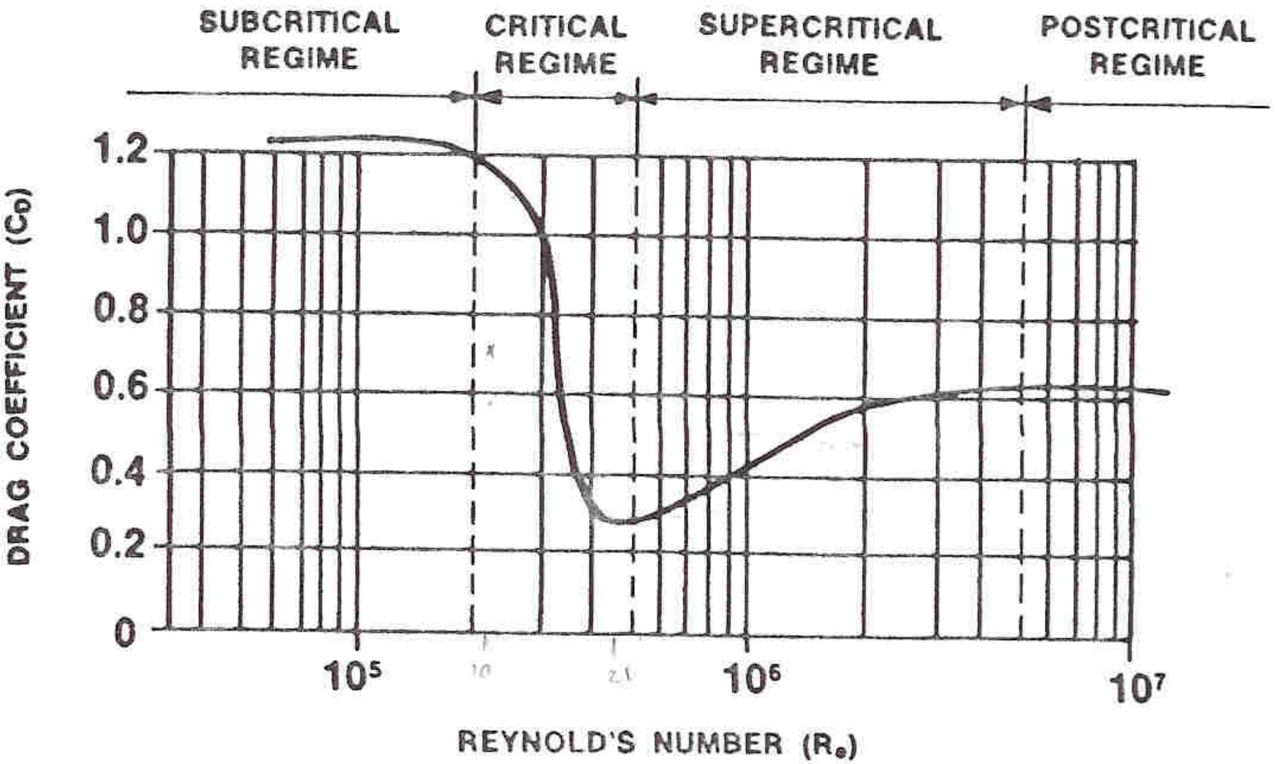
  - Critical $Re_D \approx 5 \cdot 105$

  - Large dependence of surface roughness



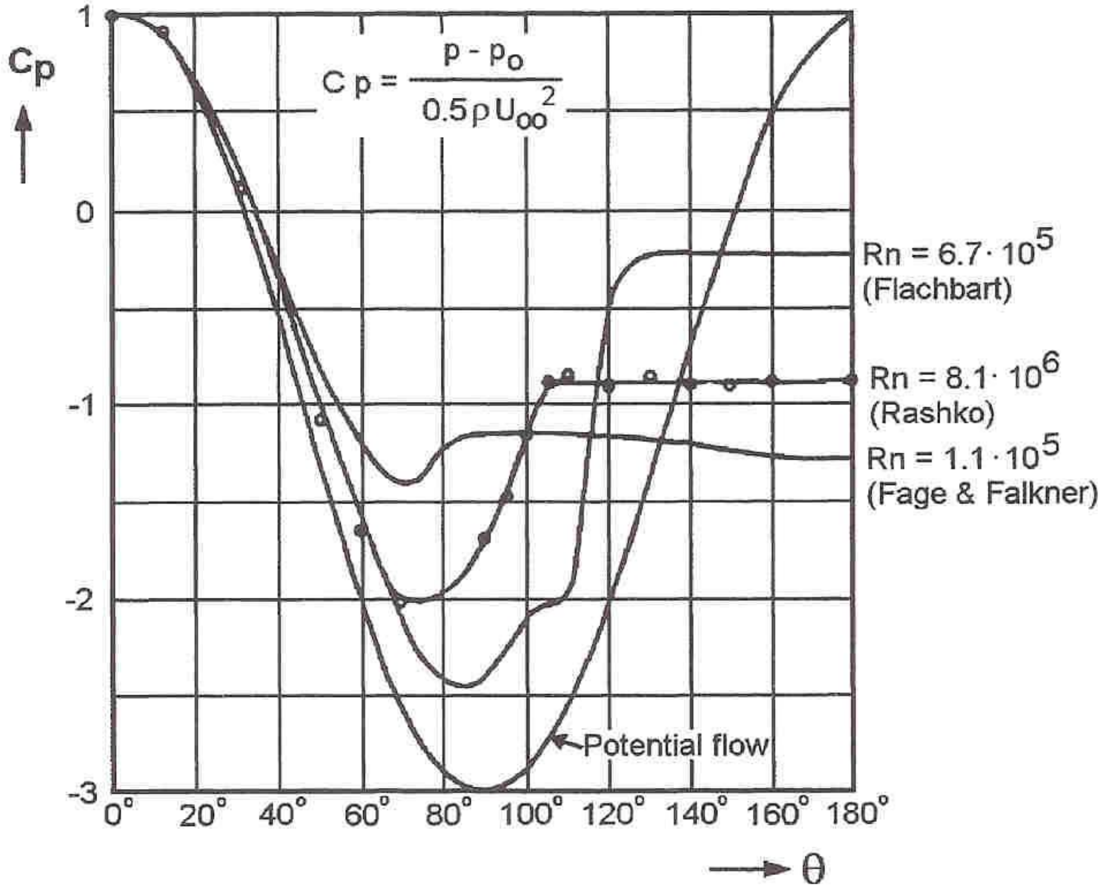
Cylinder Flow Regimes

Drag coefficient cylinder in cross flow



Cylinder Flow Regimes

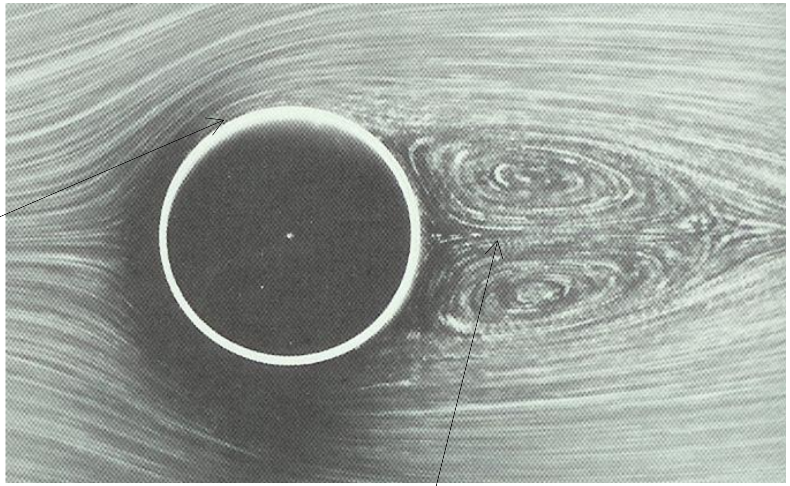
Pressure distribution cylinder in cross flow



Cylinder Flow Regimes

Drag components

- For (2D) submerged body has **two** components:



1) Frictional drag:

   - Related to skin friction due tangential stresses between fluid and body

2) Form drag: (aka: pressure drag or profile drag)

   - Related to separation region behind body: failure of pressure to recover to stagnation pressure

Drag

Fall velocity

- When object falls through a fluid (or gas) it experiences drag

- At certain point drag equals weight and object has a constant flow velocity, the **fall velocity**
  - in 2D:

$$W_{subm} = C_D D \cdot \frac{1}{2} \rho V_f^2$$

  - C_D is dependent on Reynolds number: often iteration necessary

Drag

Fall velocity

- When object falls through a fluid (or gas) it experiences drag
- A … stant fl …
  - … ssary

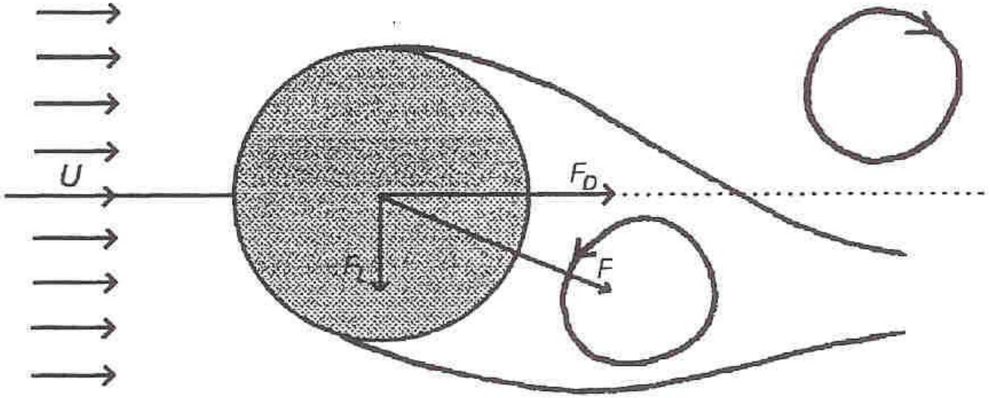
Quantity→ Object ↓	D (mm)	W_{sub} (N)	Rn (-)	V_f (m/s)
sand grain	0.2	$0.07 \cdot 10^{-6}$	≈2	0.02
gravel	20	0.07	20 000	1.00
stone	100	8.38	235 000	2.35
1 m wire rope	76	196	131 250	1.78
1 m chain	76	1079	396000	3.00

Common Fall Velocities

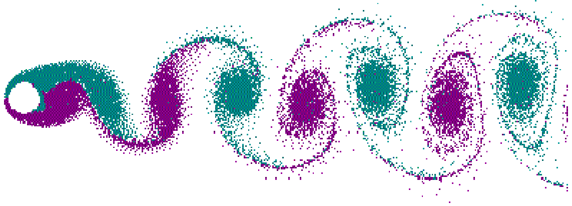
Cylinder Flow Regimes

Vortex shedding

- Vortex shedding → alternating circulation built up around the cylinder due to unsteady turbulent flow
  - (Or cyclic pressure variation behind cylinder)
  - Leads to alternating (transverse) lift force and (longitudinal) drag force



Von Karman vortex street



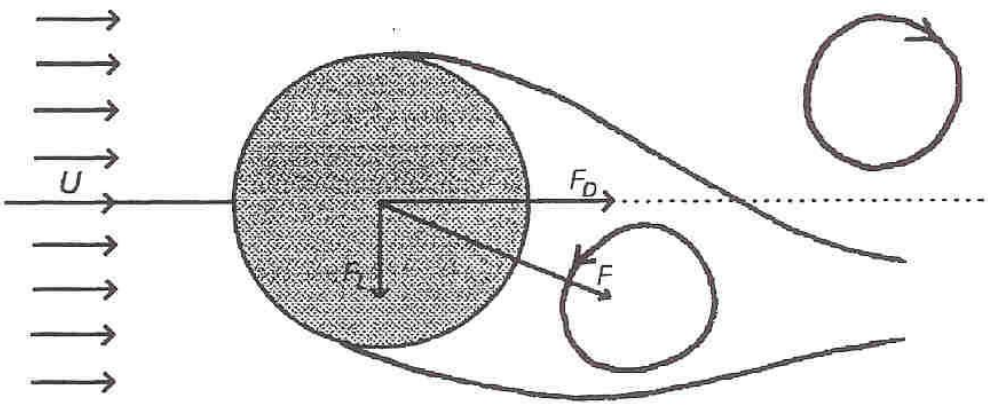
Cylinder Flow Regimes

Vortex shedding

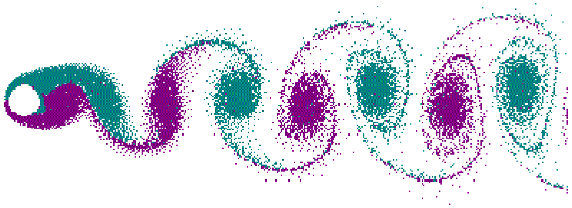
- This can be expressed as (very approx.):

$$F_L = C_L \cdot \frac{1}{2}\rho V^2 \cdot D \cdot \sin(2\pi f_v t + \varepsilon)$$

Vortex shedding frequency



Von Karman vortex street

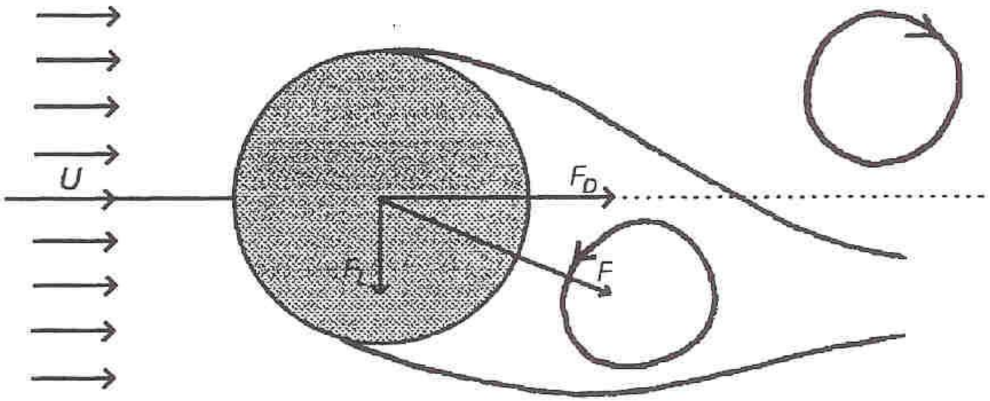


Cylinder Flow Regimes

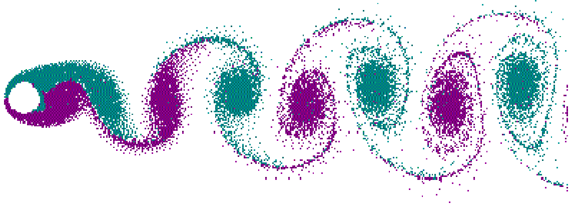
Vortex shedding

- Based on the vortex shedding frequency the Strouhal number is defined:

$$St = \frac{f_v \cdot D}{U}$$



Von Karman vortex street

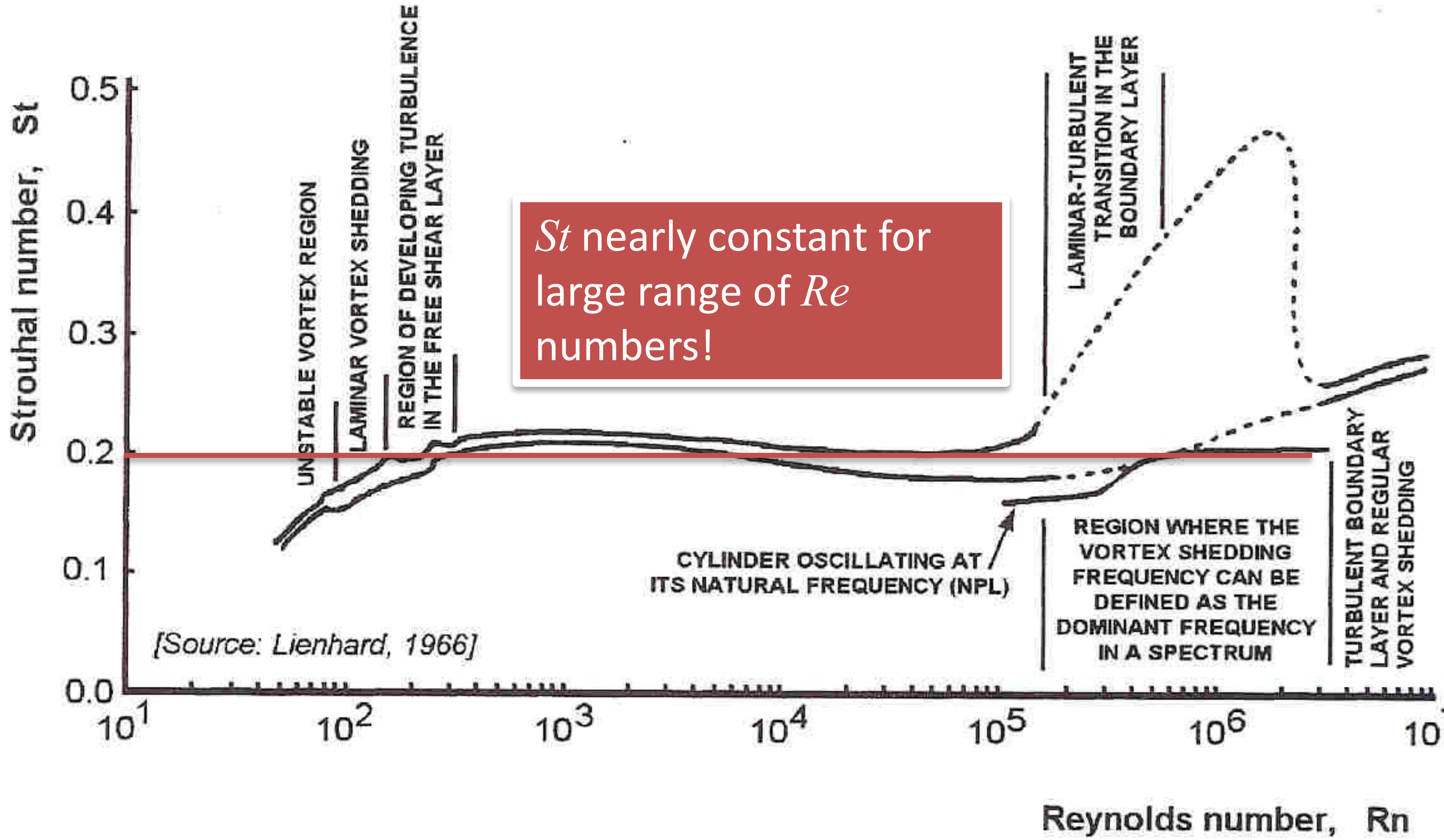


Cylinder Flow Regimes

Vortex shedding

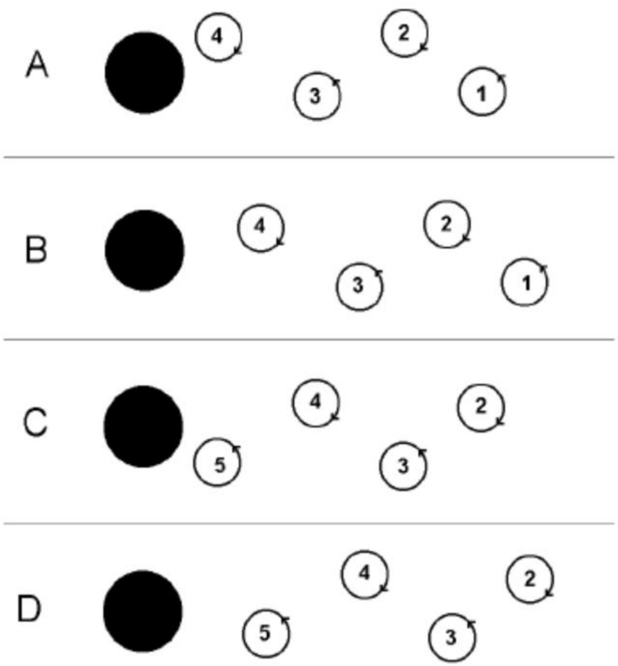
Cylinder Flow Regimes

Vortex shedding



Cylinder Flow Regimes

Vortex shedding



	L	D
A	+	+
B	0	
C	-	
D	0	-

Lift force oscillates with frequency f_v

Drag force oscillates with frequency $2f_v$

Cylinder Flow Regimes

Vortex shedding

- Usually only the total drag of interest:
  - Acts over the whole structure **in the same direction**

- The lift force is dependent on **local** vortex generation, that in turn is dependent on:
  - Local shape
  - Local velocities
  - **Randomness** in general

- However! In one case vortex shedding can become **important** and even **dangerous**:
  - When shedding takes place at the **natural frequency of the structure**
  - Spectacular **resonance** can be the result
  - As well as increased drag

Cylinder Flow Regimes

Vortex induced vibrations (VIV)

- Reduced frequency defined as:

$$U_r = \frac{U}{f_n \cdot D} \qquad f_n = \frac{U}{U_r \cdot D}$$

- Resonance when vortex shedding frequency equals natural frequency:

$$f_v = \frac{St \cdot U}{D} = f_n \qquad \frac{St \cdot U}{D} = \frac{U}{U_r \cdot D} \qquad St = \frac{1}{U_r}$$

- For large part flow regime $St = 0.2$, then the reduced frequency becomes:

$$St \approx 0.2 \rightarrow U_r = \frac{1}{St} \approx 5$$

Cylinder Flow Regimes

Vortex induced vibrations (VIV)

- Reduced frequency:

$$U_r = \frac{U}{f_n \cdot D} \qquad\qquad St \approx 0.2 \rightarrow U_r = \frac{1}{St} \approx 5$$

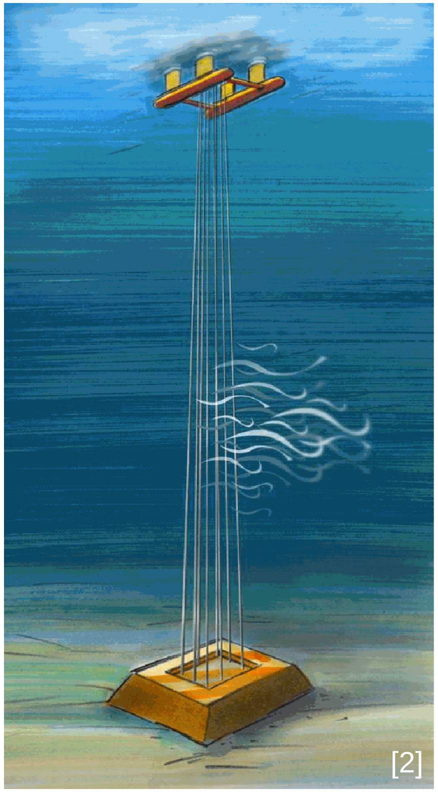
- Crosswise oscillations
  - Strong when Ur about 5
  - Lock in: the response of the cable/construction element (at its natural frequency) reinforces the process

- In-line oscillations
  - Due to slight oscillation of drag force (few percent of total drag)
  - Frequency **twice** the Strouhal frequency
  - Happen at lower U_r values
  - Seen at **half** the ambient velocity needed for crosswise oscillations

Cylinder Flow Regimes

Vortex induced vibrations (VIV)


[1]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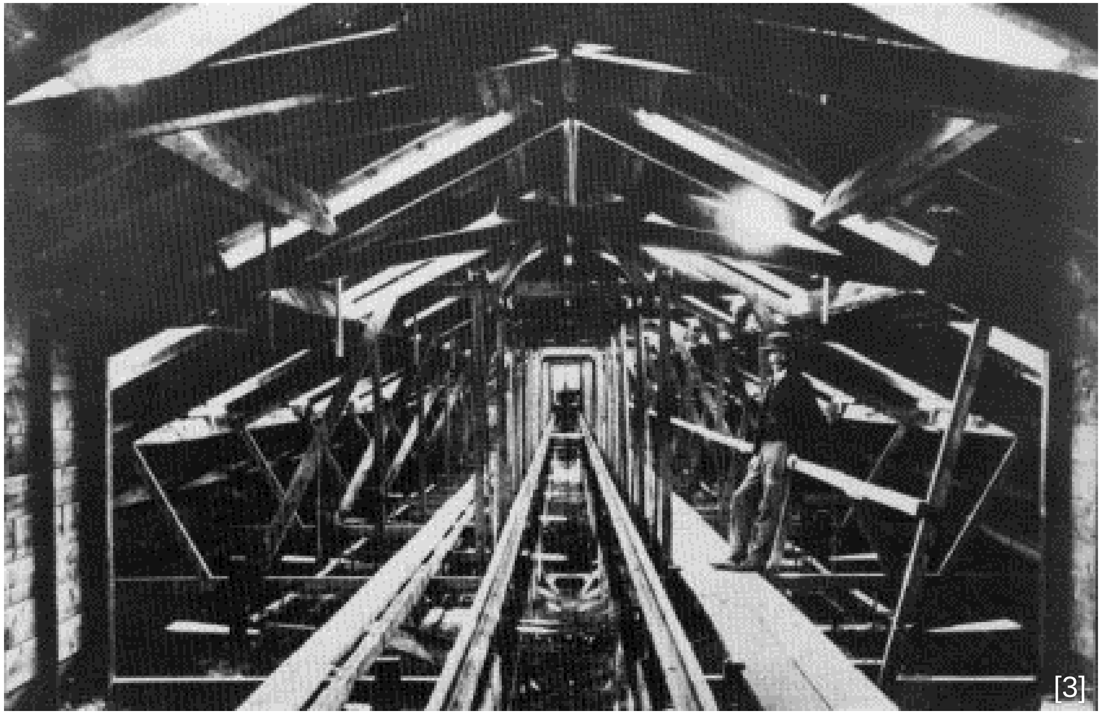
Ship Resistance

Froude's hypotheses

- World's First Towing tank (1872, Torquay UK)
- 85 x 11 x 3 m by W. Froude



Ship Resistance

Froude's hypotheses

- Froude's 1st hypothesis:
  - Resistance consists of 2 independent components:
    - Frictional resistance R_f
    - Residual resistance R_r

$$R_t = R_f + R_r$$

- Froude's 2nd hypothesis:
  - Frictional resistance can be estimated with the drag of a equivalent flat plate:
    - Same Reynolds number (same length and velocity)
    - Same wetted area

Ship Resistance

Froude's hypotheses

- Necessary due to difficulties retaining Dynamic Similitude
- Dynamic Similitude requires that Froude number and Reynolds number are identical for model and prototype

$$Fr = \frac{V}{\sqrt{gL}} \qquad Re = \frac{VL}{\nu}$$

- Physical meaning Froude number and Reynolds number?

Ship Resistance

Froude's hypotheses

- Froude number: ratio inertia forces and gravity forces:
  - Related to wave making: wave making causes resistance

$$Fr = \frac{V}{\sqrt{gL}}$$

- Reynolds number: ratio inertia forces and viscous forces
  - Related to friction

$$Re = \frac{VL}{\nu}$$

- Why not possible to keep both constant?

Ship Resistance

Frictional Resistance

- Flat plate: produces (almost) no wave, therefore no wave resistance, thus:
    - Resistance flat plate independent of Froude number
- In formula:

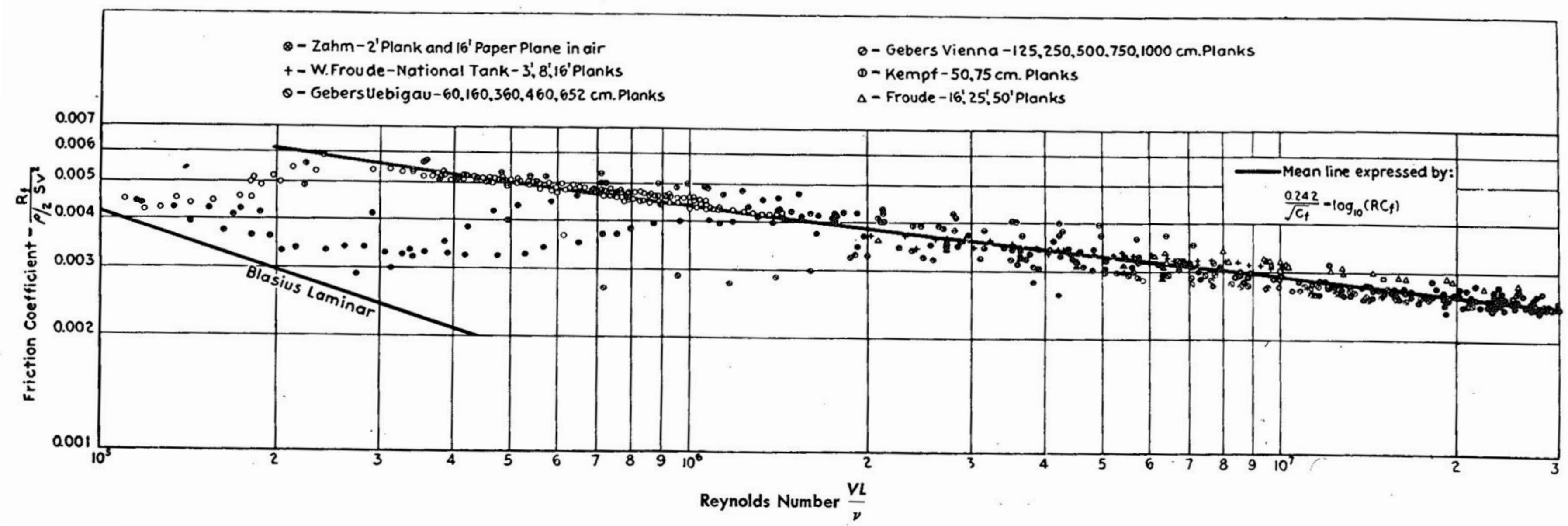
$$R_f = C_f \cdot \frac{1}{2}\rho V^2 \cdot S$$

- Frictional resistance coefficient flat plate empirically determined
    - Most widely used for ships is the ITTC-57 plate friction line:

$$C_f = \frac{0.075}{(\log_{10}(Rn) - 2)^2}$$

Ship Resistance

Frictional Resistance



Ship Resistance

Residual Resistance

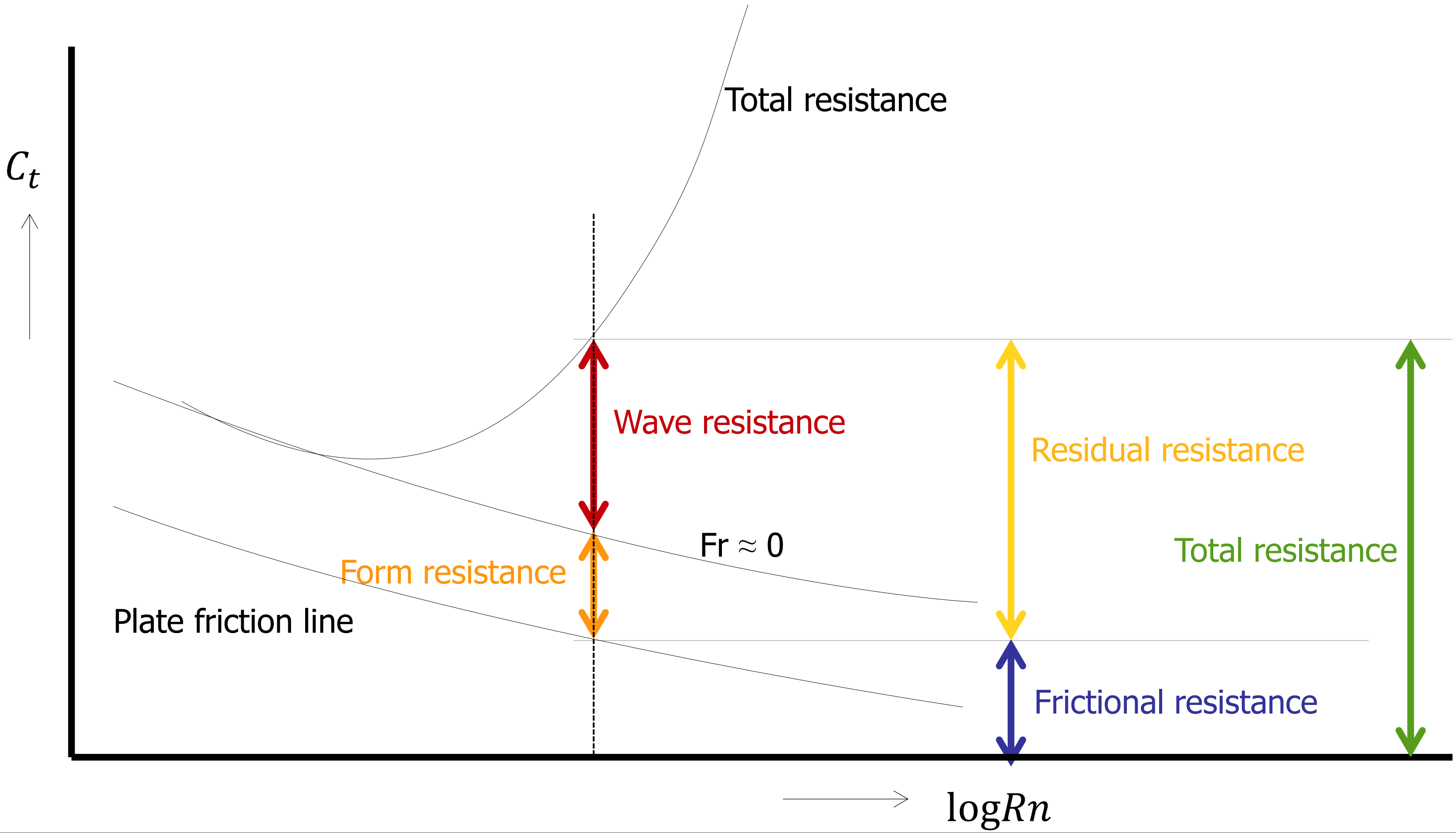
- Part of resistance that is not frictional resistance:

$$R_t = R_f + R_r \qquad R_r = C_r \cdot \frac{1}{2}\rho V^2 \cdot S$$

- Components:
  - Wave resistance: energy is lost by the production of waves around the ship traveling through the water
  - Form resistance: part of resistance that difference between total resistance and frictional resistance as $Fr \rightarrow 0$

Ship Resistance

Resistance Components



Ship Resistance

Form Resistance

- Resistance coefficients “Simon Bolivar” model family

- Test performed at **different scales** and **same Froude number → different Reynolds number**

- C_t dependent on scale! (No dynamic similarity)

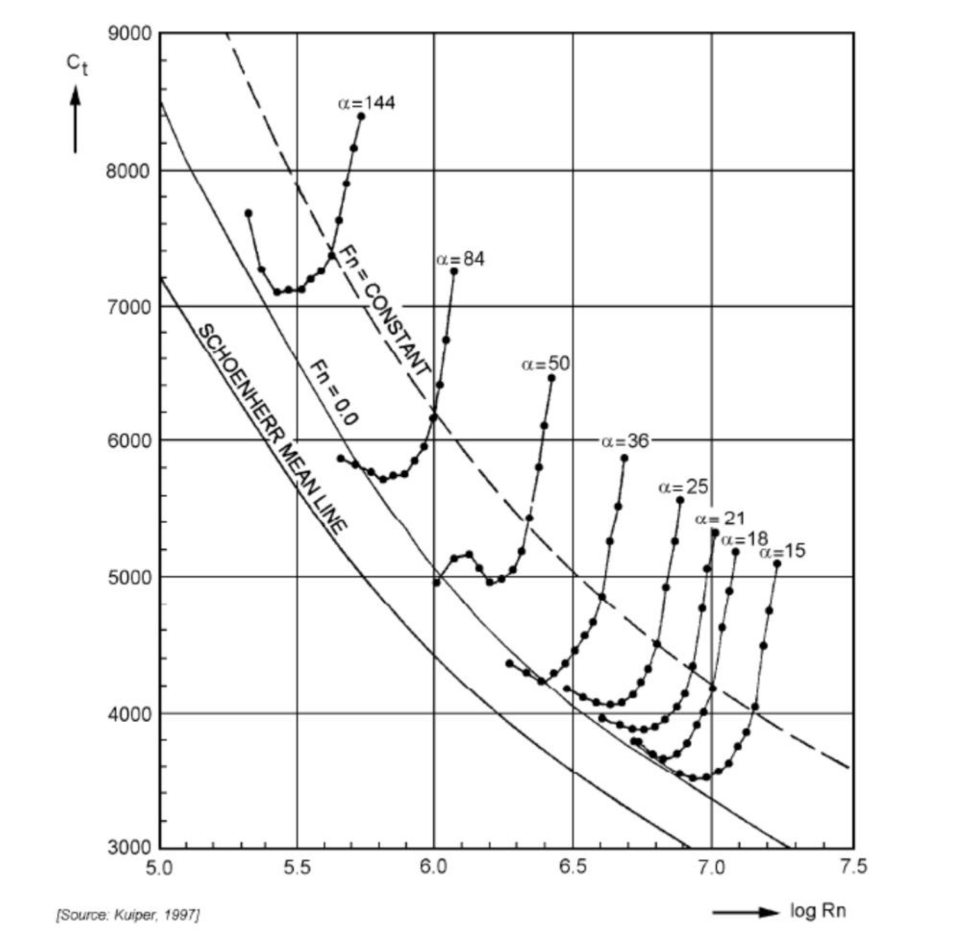
- $C_r = C_t$ - C_f independent of scale

- Difference **line Fn = 0** and **plate friciton line** = **form resistance**

Ship Resistance

Form Resistance

- Resistan ... nily
- Test perf ... **roude number**
- C_t deper
- $C_r = C_t$ - (
- Differenc ... = **form resistar**



Ship Resistance

Resistance Components

- Froude assumed form resistance independent of Reynolds number:

$$C_t = C_f + C_r = C_f + \left(C_w + C_{form}\right)$$

- Hughes instead assumed that form resistance was proportional to frictional resistance and came up with a form factor k:

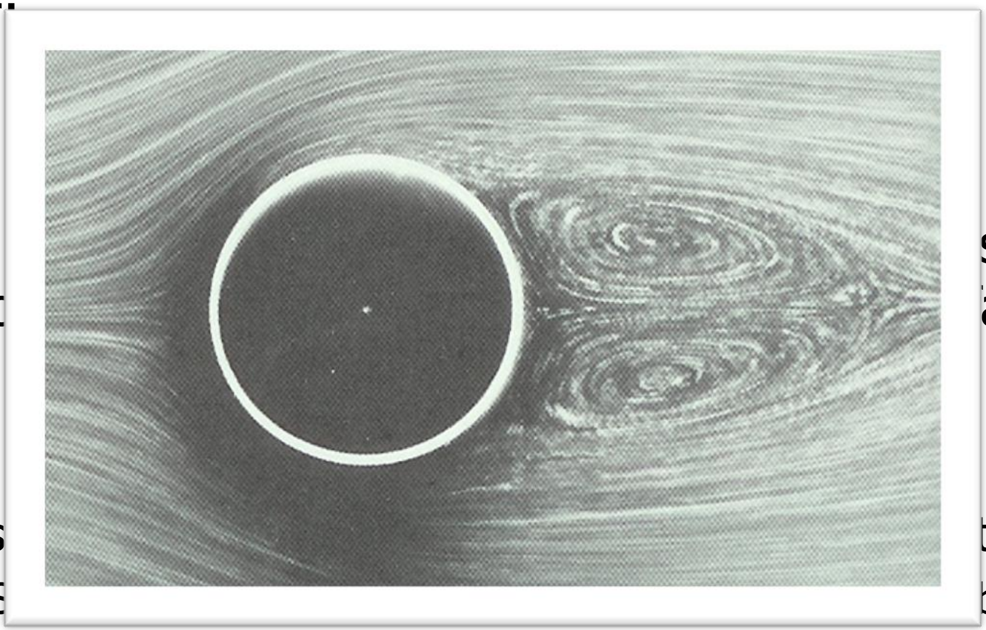
$$C_t = C_v + C_w = C_f(1 + k) + C_w$$

  - Reasoning: form resistance associated with separation of flow
    - Separation prevents pressure recovery at aft side of body: therefore drag
    - Flow separation is due to viscosity!
    - Thus form drag is associated with viscous flow

Ship Resistance

Resistance Components

- Froude assumed form resistance independent of Reynolds number:



- Hughes s proportional to frictic actor k:

  - Reas tion of flow
    - S body: therefore drag
    - Flow separation is due to viscosity!
    - Thus form drag is associated with viscous flow

Ship Resistance

Resistance Components

- Froude assumed form resistance independent of Reynolds number:

C_B	1+k
<0.7	1.10-1.15
0.7-0.8	1.15-1.20
>0.8	1.20-1.30

- Hughes … s proportional to frictio … factor k:
  - Reas … tion of flow
    - S … body: therefore drag
    - Flow separation is due to viscosity!
    - Thus form drag is associated with viscous flow

Ship Resistance

$$R = C \cdot \frac{1}{2}\rho V^2 \cdot S$$

$$Fn = \frac{V}{\sqrt{gL}} \qquad Rn = \frac{VL}{\nu}$$

Resistance Extrapolation

- Froude

$$Rn_{model} \neq Rn_{prototype}$$
$$Fn_{model} = Fn_{prototype}$$
$$V_{prototype} = \sqrt{\alpha_L} V_{model}$$

1 measure

2 calculate: $C_f = \frac{0.075}{(\log_{10}(Rn_{model}) - 2)^2}$

3 calculate: $C_r = C_t - C_f$

$$C_{t\,model} = C_{f\,model} + C_{r\,model}$$

4 extrapolate: $C_{r\,prototype} = C_{r\,model}$

$$C_{t\,prototype} = C_{f\,prototype} + C_{r\,prototype}$$

5 calculate: $C_f = \frac{0.075}{\left(\log_{10}\left(Rn_{prototype}\right) - 2\right)^2}$

6 calculate: $C_t = C_f + C_r$

TU Delft

Ship Resistance

$$R = C \cdot \frac{1}{2}\rho V^2 \cdot S$$

$$Fn = \frac{V}{\sqrt{gL}} \qquad Rn = \frac{VL}{\nu}$$

Resistance Extrapolation

- Hughes

$$Rn_{model} \neq Rn_{prototype}$$
$$Fn_{model} = Fn_{prototype}$$
$$V_{prototype} = \sqrt{\alpha_L} V_{model}$$

1 measure

2 calculate: $C_f = \frac{0.075}{(\log_{10}(Rn_{model}) - 2)^2}$

3 calculate: $C_w = C_t - C_f(1+k)$

$$C_{t\,model} = (1+k)C_{f\,model} + C_{w\,model}$$

4 extrapolate: $C_{w\,prototype} = C_{w\,model}$

$$C_{t\,prototype} = (1+k)C_{f\,prototype} + C_{w\,prototype}$$

5 calculate: $C_f = \frac{0.075}{\left(\log_{10}\left(Rn_{prototype}\right) - 2\right)^2}$

6 calculate: $C_t = C_f(1+k) + C_w$

Wind and Current loads

Forces and moments

- Forces and moments calculated using drag coefficients:

$$X = C_X(\alpha_r) \cdot \frac{1}{2}\rho V_r^2 \cdot A_T$$
$$Y = C_Y(\alpha_r) \cdot \frac{1}{2}\rho V_r^2 \cdot A_L$$
$$N = C_N(\alpha_r) \cdot \frac{1}{2}\rho V_r^2 \cdot A_L \cdot L$$

- X, Y, N Longitudinal, lateral and horizontal wind/current moment
- C_X, C_Y, C_N Drag coefficients dependent on relative wind angle
- ρ Density (of air for wind, of water for current)
- A_T, A_L Frontal and lateral projected area (above water for wind, below for current)
- L Length of ship
- V_r, α_r Relative wind speed and angle

TU Delft

Wind and Current loads

Apparent (or Relative) Wind and True Wind

- Vector combination of vessel speed with with speed

$$\alpha_{rw} = \arctan\left[\frac{V_{tw}\sin\alpha_{tw}}{V_s + V_{tw}\cos\alpha_{tw}}\right]$$

$$V_{rw} = \sqrt{(V_{tw}\sin\alpha_{tw})^2 + (V_s + V_{tw}\cos\alpha_{tw})^2}$$

$$V_{rw} = \sqrt{V_s^2 + V_{tw}^2 + 2V_sV_{tw}\cos(\alpha_{tw})}$$

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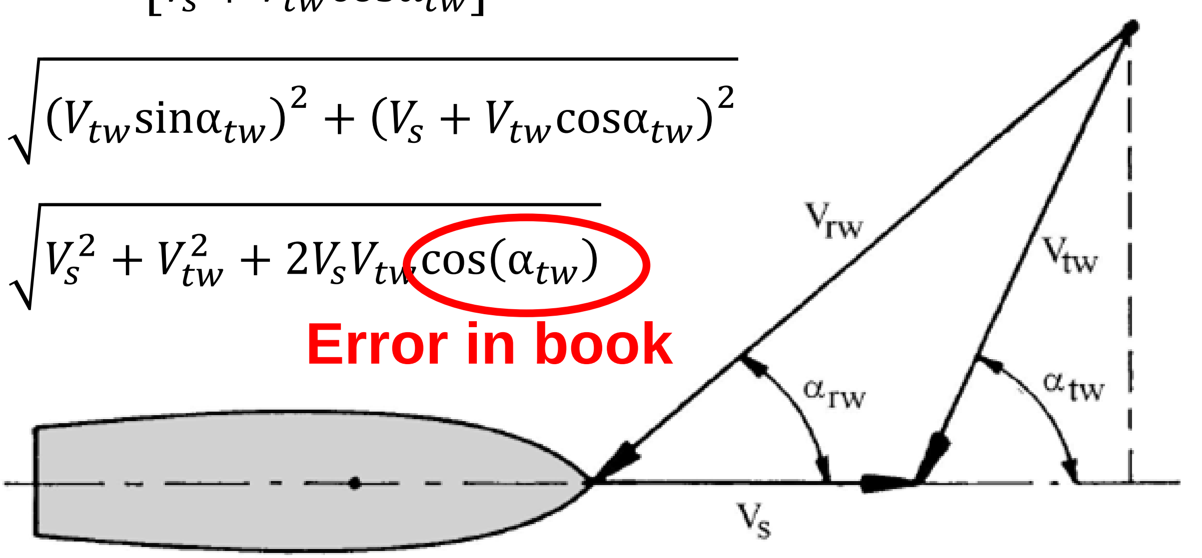


Wind and Current loads

Values for Drag Coefficients

- Difficult to calculate: viscous effects significant, as well as flow separation
  - Wind loads: done with wind tunnel model testing
  - Current loads: done with towing tank testing or testing in basin with current simulation
- Based on previous performed model testing:
  - Empirical estimation methods available (for instance Remery and Van Oortmerssen, 1973)

Wind and Current loads

Values for Drag Coefficients

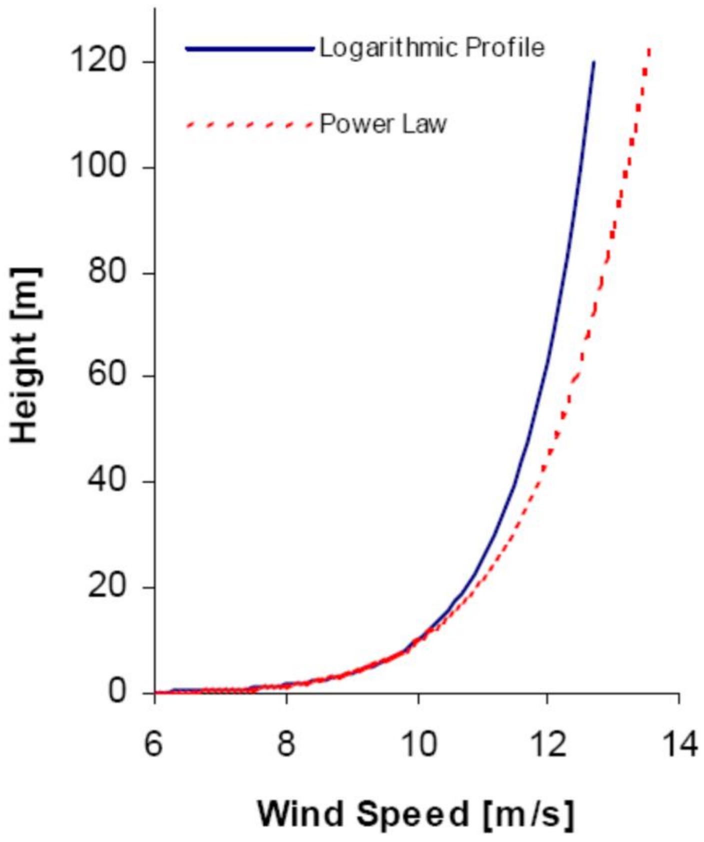
$$V_w(z) = V_{wrefheight} \cdot \left(\frac{z}{z_{refheight}}\right)^{\alpha_{shear}}$$

- Typical values:

$$z_{refheight} = 10m$$

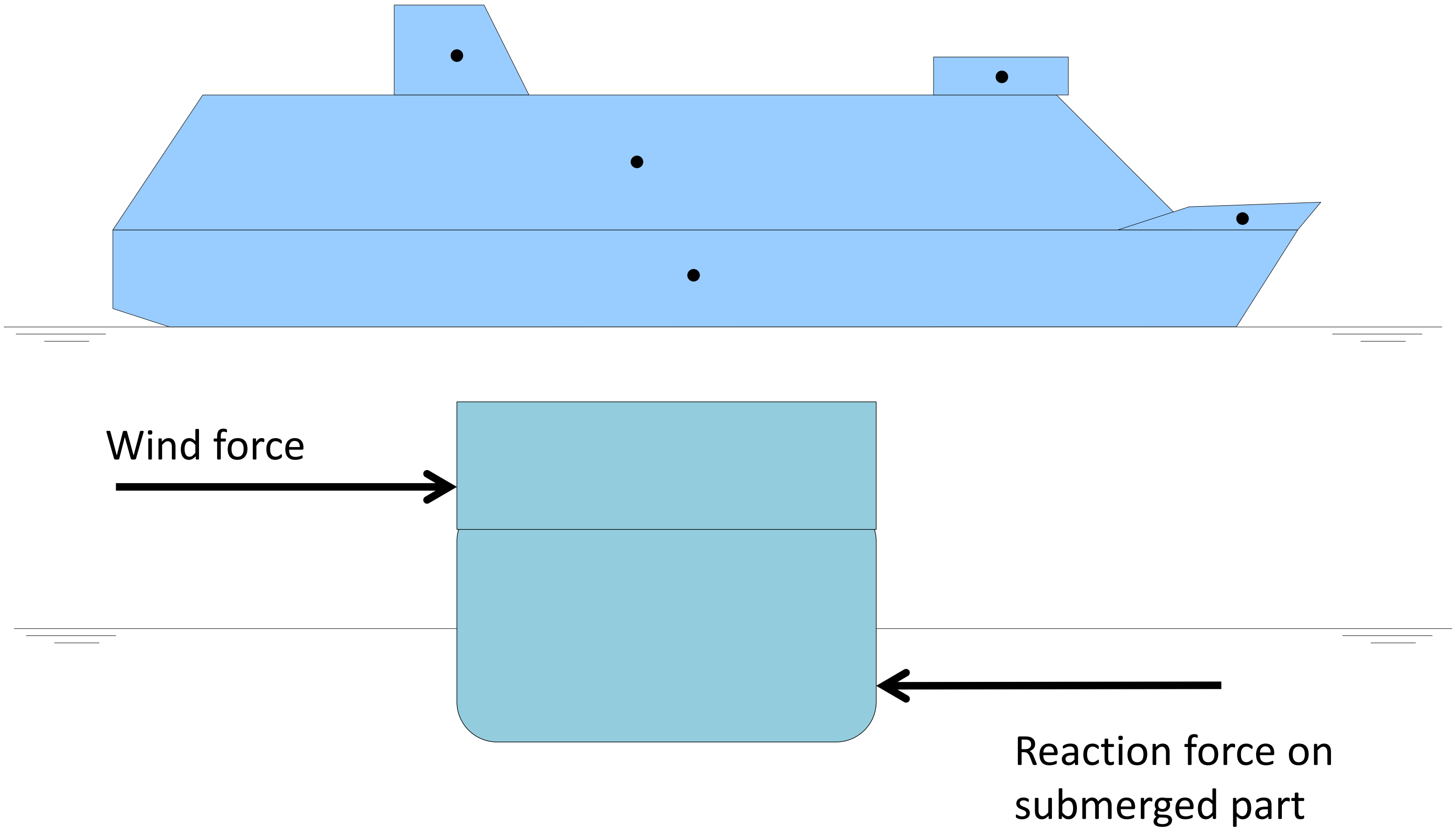
$$\alpha_{sea} = 0.11$$

$$\alpha_{land} = 0.16$$



Wind and Current loads

Lateral area and force balance



Sources images

[1] (Vortex Induced Vibration) VIV Suppressors Strakes, source: http://www.marktool.com/splashtron/SPLASHTRON-VIV-Supression-Strakes
[2] Vortex Induced Vibration (VIV), source: CeSOS
[3] View of the first naval test tank constructed by the civil engineer and naval architect, William Froude, source: Imperial War Museum London