Main aspects of the flow around bluff bodies

PEF 6000 - Special topics on dynamics of structures

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Objectives

- To present the physical aspects of the flow of incompressible fluids around bidimensional bluff bodies. Focus on the flow around a cylinder and the vortex-shedding phenomenon!

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- Examples of references: Textbooks by Blevins (2001), Païdoussis et al (2011), Naudascher & Rockwell (2005), the reviews by Sarpkaya (2004) and Williamson & Govardhan (2004), habilitation thesis Franzini (2019) and selected papers.

1. Objetivos
2. Flow around immersed bodies - introduction
3. Flow around a fixed cylinder

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- Full-slip condition: The component in the direction of the normal to the surface of the relative velocity is null.

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- Real fluids: Non-null viscosity $\rightarrow$ No-slip condition;
- Ideal fluids: Inviscid fluid $\rightarrow$ Full-slip condition (basic hypothesis for the potential flow theory.)

Equation of motion for the fluid particles:

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}.\boldsymbol{\nabla})\boldsymbol{u} = -\frac{\nabla p}{\rho} + \boldsymbol{g} + \nu \nabla^2 \boldsymbol{u} \tag{1}$$

Continuity equation for non-compressible flows:

$$\boldsymbol{\nabla}.\boldsymbol{u} = 0 \tag{2}$$

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- Far from the body (far from the boundary layer), the viscous effects are irrelevant and the solution from the potential theory leads to acceptable results;

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- The presence of corners defines the separation points;
- For a cylinder, the separation point is dependent on the Reynolds number (to be better discussed).

- A bluff body is characterized by the flow separation being observed in an important part of his surface (see Bearman (1984) and Meneghini (2002)). A cylinder is a classical example of bluff body;

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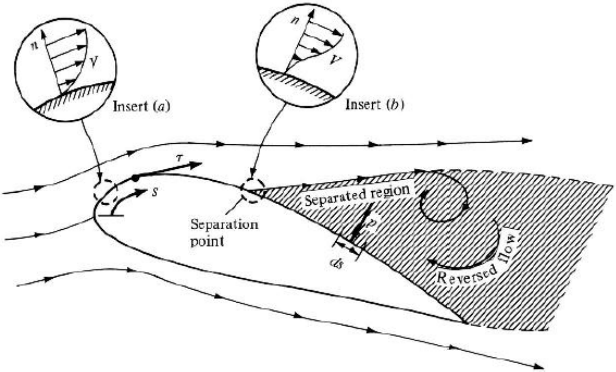
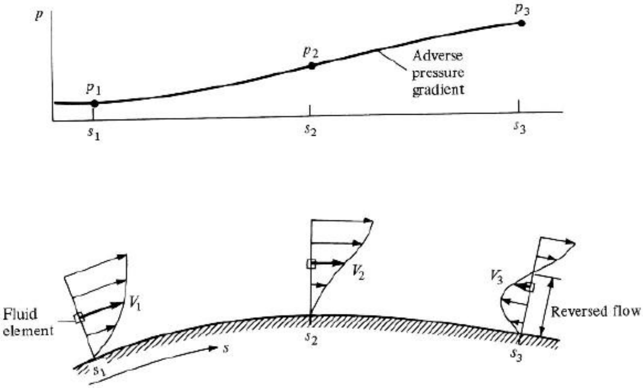
- Focus of the class: Circular cylinders.



Extracted from Anderson (2011).



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- As already mentioned, the flow separation in problems involving circular cylinders strongly depends on the Reynolds number $Re = U_\infty D/\nu$ (occurring around 80°, measured from the frontal stagnation point);

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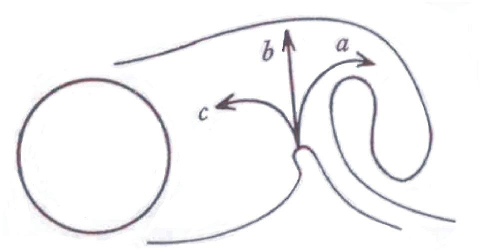
- The flow separation gives rise to two free shear layers of opposite circulation. The interaction of the free shear layers causes the formation of vortexes.



Extracted from Gerrard (1966).

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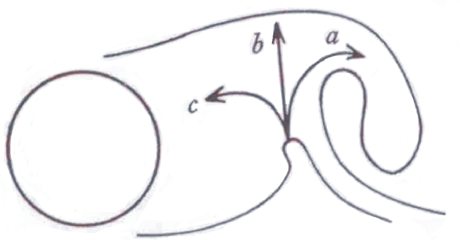

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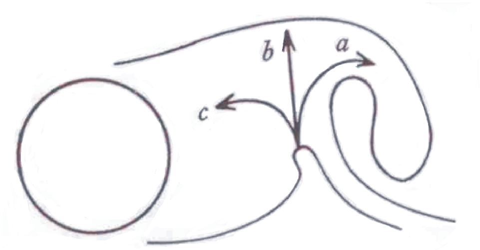

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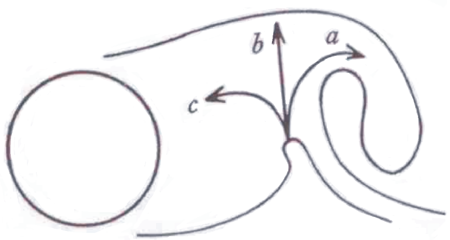

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- **Path a**: Decreases the strength of the vortex that is being formed
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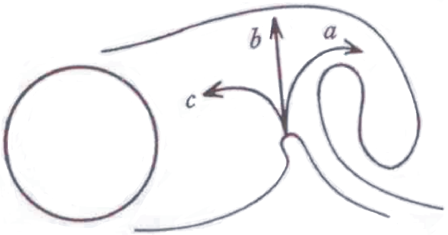

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- **Path a**: Decreases the strength of the vortex that is being formed
- **Path b**: Attracted by the vortex under formation, this path is responsible for interrupting the formation process and causes the vortex-shedding phenomenon.
- **Path c**: Associated with the new vortex, with opposite circulation.

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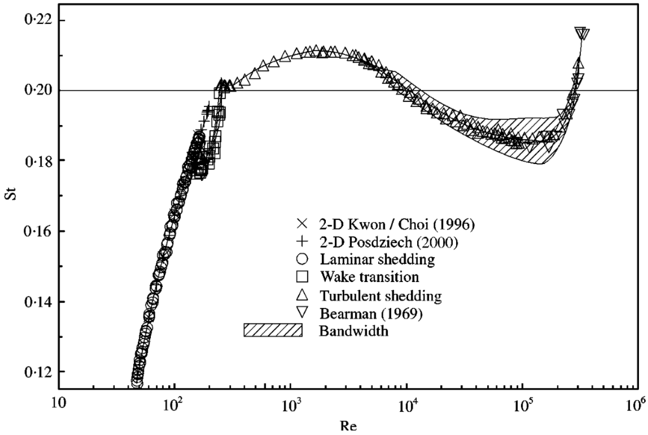
- Since the velocity field (not the incoming flow) is oscillatory, the pressure field also depends on time. This leads to oscillatory hydrodynamic forces acting on the cylinder.



Extracted from Norberg (2001).

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- Forces associated with pressure, of great importance for bluff bodies;
- Forces associated with friction: Associated with the shear stress (important on bluff bodies).
- Forces associated with waves: Highly important in flows with the presence of free-surfaces (ships, for example).

We decompose the hydrodynamic forces into two terms:

- Drag force (F_D): Component of the force into the direction of the relative velocity. Drag coefficient $C_D = \frac{F_D}{1/2 \rho U_\infty^2 DL}$

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- In the flow around a bidimensional cylinder, the force coefficients can be well approximated by

$$C_L(t) = \hat{C}_L \sin(\omega_s t)$$
$$C_D(t) = \bar{C}_D + \hat{C}_D \sin(2\omega_s t + \phi)$$

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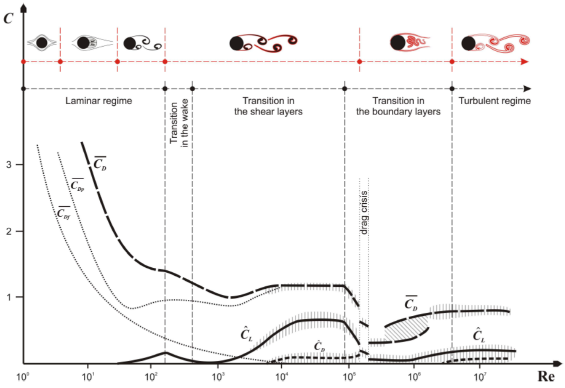
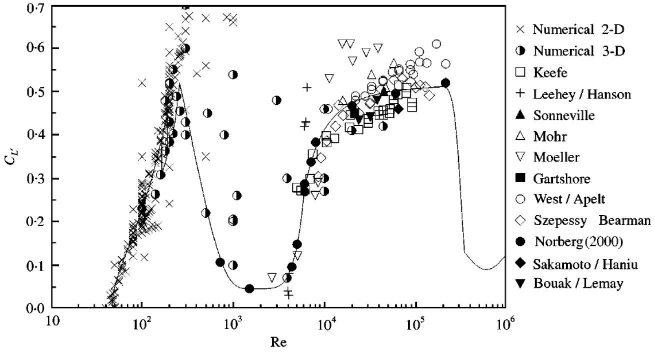
Reynolds number range	Name of the regime	Characteristic feature	General properties
$Re < 1$		Creeping flow	**Laminar regime**
$3–5 < Re < 30–40$	L	Steady separation (recirculation bubble)	
$30–40 < Re < 150–300$	L	Periodic laminar shedding	
$150–300 < Re < 1 \times 10^5–2 \times 10^5$	TrW and TrSL		**Subcritical regime:** laminar separation transition in shear layer turbulent wake
$150–200 < Re < 200–250$	TrW1	Transition of laminar vortices in wake,	
$200–250 < Re < 350–500$	TrW2	Transition of irregular vortex during its formation	
$350–500 < Re < 1 \times 10^3–2 \times 10^3$	TrSL1	Development of transition waves in free shear layer	
$1 \times 10^3–2 \times 10^3 < Re < 2 \times 10^4–4 \times 10^4$	TrSL2	Formation of transition vortices in free shear layer	
$2 \times 10^4–4 \times 10^4 < Re < 1 \times 10^5–2 \times 10^5$	TrSL3	Fully turbulent shear layer	
$1 \times 10^5–2 \times 10^5 < Re < 3.5 \times 10^5–6 \times 10^6$	TrBL		**Critical regime:** laminar separation turbulent reattachment turbulent separation Turbulent wake
$1 \times 10^5–2 \times 10^5 < Re < 3 \times 10^5–3.1 \times 10^5$	TrS0/TrBL0	Onset of transition at separation point	
$3 \times 10^5–3.1 \times 10^5 < Re < 3.3 \times 10^5–3.4 \times 10^5$	TrS1/TrBL1	Single separation bubble regime	
$3.3 \times 10^5–3.4 \times 10^5 < Re < 3.6 \times 10^5–3.8 \times 10^5$		Unstable regime	
$3.6 \times 10^5–3.8 \times 10^5 < Re < 5 \times 10^5–1 \times 10^6$	TrS2/TrBL2	Two-bubble regime	
$5 \times 10^5–1 \times 10^6 < Re < 3.5 \times 10^6–6 \times 10^6$	TrS3/TrBL3	Supercritical regime—fragmented separation bubble.	
$3.5 \times 10^6–6 \times 10^6 < Re < 6 \times 10^6–8 \times 10^6$	TrBL4	Transcritical regime—partial transition	
$Re > 8 \times 10^6$	T	Postcritical regime—complete transition	

Extracted from Raghavan & Bernitsas (2011).



Extracted from Assi (2009).



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- Consider a riser of external diameter equal to 8 in. Consider also a typical ocean current of intensity $U_\infty = 1$ m/s. Assuming $\nu = 10^{-6}$ m^{2}s, the Reynolds number is $Re = 1.01 \times 10^5$;
- For some floating units of cylindrical geometry, Reynolds number easily exceeds 10^7 (Fujarra et al. (2012));
- Proper characterization of the flow around cylinder at high Reynolds numbers is an open research topic of great relevance.