Course of “Fluid Labs” A.A. 2024-2025

EXP Test case 3
Analysis of the hydrodynamic forces acting on a cylinder in steady free surface flow

Case description and objectives

Goal of this test case is to investigate the drag and lift forces acting on a cylinder submerged in a steady-state free-surface water flow. The experiments have been performed in the water channel facility of the Hydraulics Laboratory, and the two force components (horizontal and vertical) have been measured through a balance. In the case study proposed, the Reynolds number of the cylinder $Re=DU_{\infty}/\upsilon$ is within the range of the "sub-critical regime"[*]; therefore, it will be not surprising to notice that the flow separates at a certain distance from the front stagnation point, causing a recirculation zone behind it, and that an oscillating wake is created by the shedding of two counter-rotating vortexes. As a result, also drag and lift will show an oscillating behavior.
The scheme of the experiment is reported in Figure 1 here below. The balance is fixed to the ground and connected to the cylinder through the endplates. The hydrodynamically shaped endplates allow to hold the cylinder and ensure some sort of "two-dimensional flow" around it by suppressing the three-dimensional effects at the cylinder ends. Two load cells are installed inside the balance, and they provide an output voltage linearly proportional to the applied force.

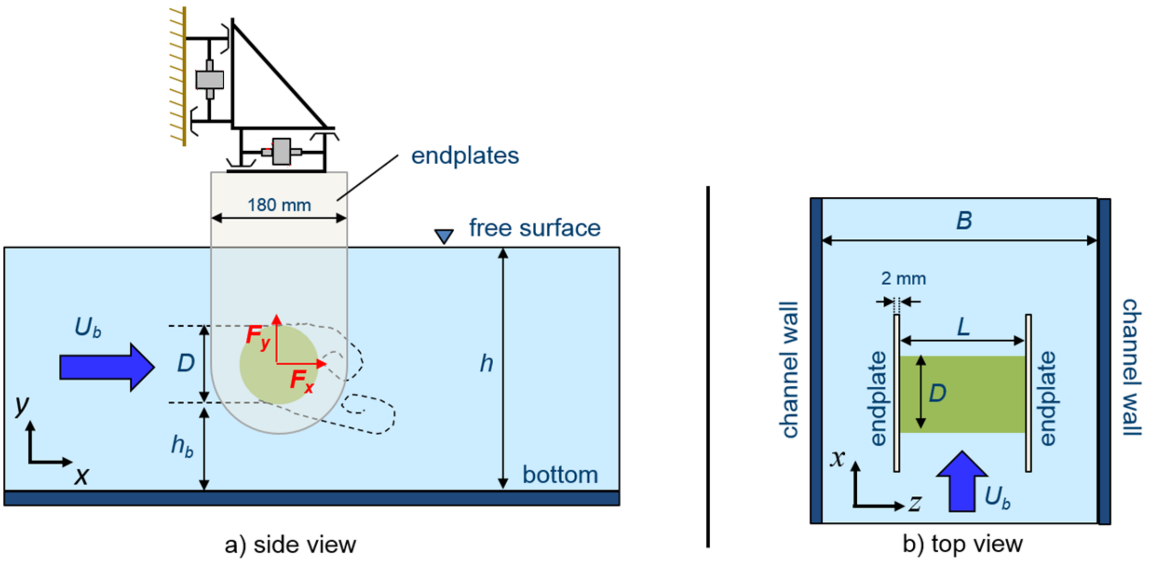


Figure 1. Sketch of the experimental setup.

The calibration of the balance has been performed after the installation of the endplates and the cylinder on the balance, by applying weight standards to the cylinder without water in the channel. When developing the calibration function, it was taken into account that the real forces experienced by the cells are not only those produced by the applied load, but they also include the weight of the structure, and other small contributions related with the deformability of the structure. The calibration function has been determined in such a way that the condition F_x=0, F_y=0 corresponds to the absence of applied (external) forces, net of the weight and the small deformability-related contributions.
When water flows in the channel, assuming that the dynamic forces on the endplates is negligible since they are hydrodynamically shaped, the horizontal external force F_x is equal to the drag force acting on the cylinder, F_D. Conversely, the vertical external force F_y is equal to the sum of the lift force acting on the cylinder F_L and the buoyancy force acting on the cylinder and the endplates, F_B. Thus, whereas F_D is simply taken as the calibration output F_x, F_L will be given as F_y - F_B. The buoyancy force, F_B, could be theoretically calculated by multiplying the volume of the immersed parts (cylinder and part of the endplates) by the specific weight of water. However, since knowing all the geometrical details with high accuracy is not trivial, directly measuring

[*] Note that the classification of flow regimes discussed in the class lecture refers to unconfined flows. This is not the case of this experiment, in which the cylinder is located in a water channel with finite size cross section. However, it is reasonable to expect some similar behavior to the unconfined case.

F_B with the balance appears a preferred option. This is achieved by making a test in still water with the same level of the flowing-water test. Since no drag and lift forces play a role in the static test, in this case the horizontal external force F_x will be zero and the vertical external force F_y will be equal to F_B.

Input data

The input data of the problem are summarized in the table here below.

Symbol	Parameter	Value	Units
B	Width of the channel	0.5	m
D	Diameter of the cylinder	0.06	m
L	Width of the cylinder	0.185	m
t	Thickness of the endplates	0.002	m
b	Length of the endplates	0.180	m
h	Water level in the channel upstream of the cylinder	0.45	m
h_b	Distance of the cilinder wall from the channel bottom	0.18	m
f_s	Sampling frequency	200	Hz
Q	Volumetric flow rate of water	75	l/s
ρ	Density of water	998	kg/m^3
μ	Dynamic viscosity of water	0.001	Pa·s

The complete set of acquisition data is provided in the following MATLAB workspaces. In each workspace, the values of F_x and F_y are provided in the form of vectors. These values have already been converted from the voltage output of the cells through the calibration functions, as explained previously.

Filename	Condition
FORCEdata_stillwater.mat	Cylinder and endplates, still water in the channel
FORCEdata_flow.mat	Cylinder and endplates, flowing water in the channel
FORCEdata_NatOsc.mat	Cylinder and endplates, still water in the channel, cylinder hit once manually

Questions

1. Calculate the channel bulk velocity U_b based on the measured quantities upstream of the cylinder Q, B, h. Assume that this velocity is the free stream one approaching the cylinder, U_∞, and then calculate the Reynolds number $Re=DU_\infty/\upsilon$.

2. Calculate the buoyancy force F_B acting on the immersed parts (cylinder and part of the endplates).

3. Calculate the Reynolds-averaged drag and lift forces acting on the cylinder, $\langle F_D \rangle$ and $\langle F_L \rangle$, and the Reynolds averaged drag and lift coefficients, $\langle C_D \rangle$ and $\langle C_L \rangle$. Note that the drag and lift forces acting on the endplates are considered negligible.

4. Calculate the uncertainties of C_D and C_L starting from the definition of these quantities and applying the error propagation law

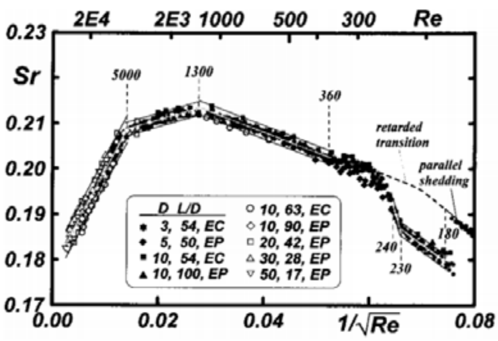
$$\boldsymbol{y = y(x_1, x_2, \dots, x_n)} \quad \rightarrow \quad \boldsymbol{u(y)} = \sqrt{\left(\frac{\partial y}{\partial x_1}u(x_1)\right)^2 + \left(\frac{\partial y}{\partial x_2}u(x_2)\right)^2 + \cdots + \left(\frac{\partial y}{\partial x_n}u(x_n)\right)^2}$$

Make reference to the values of uncertainty in the following table, and try to estimate the missing values

Variable	Instrument	Uncertainty	Units
B	Ruler	???	mm
D	Vernier caliber with scale value 0.05	???	mm
L	Ruler	???	mm
h	Piezometer	1	mm
Q	Proline Promag 50L installed in a 200 mm pipe (DN200)	???	of reading
ρ	-	≈0	
F_x	From calibration of frame	0.045	N
F_y	From calibration of frame	0.025	N

Note that these formulas might be applied at the instantaneous level, that is, obtaining the uncertainty for every single value $C_D(t)$ and $C_L(t)$; in this case, the uncertainties of the two coefficients will vary over time. However, it appears more practical to calculate directly the uncertainties of the Reynolds-averaged coefficient, $\langle C_D \rangle$ and $\langle C_L \rangle$, starting from $\langle F_D \rangle$ and $\langle F_L \rangle$. The uncertainties for F_x and F_y do reasonably hold also for their Reynolds-averaged values, $\langle F_x \rangle$ and $\langle F_y \rangle$.

5. Use the MATLAB function “fft_of_force” provided to compute the FFT (Fast Fourier Transfom) of the F_L signal and find out the frequency spectrum. Identify the vortex shedding frequency, f, as the main peak of the frequency spectrum, and calculate the Strouhal number Sr=f· D/Ub. Compare it with the reference value from the literature at the same Reynolds number for the unbounded case. As a reference solution, the plot provided in the paper by Fei et al. (1998) might be used, as reported here below in Figure 2.



6.

Figure 2. Strouhal number versus Reynolds number for unbounded flow over a circular cylinder, from Fey et al. [Physics of Fluids 10, 1547 (1998); doi.org/10.1063/1.869675].

7. It is necessary to ensure that the vortex shedding frequency is significantly different from the natural frequencies of the system. Otherwise, the structure could vibrate under the fluid loading, making the assumption of fixed body fail. In order to measure the natural frequencies of the structure in water, the cylinder is hit along the *x*-direction once using a stick, and left free to vibrate in still water. Based on the results of this test (FORCEdata_NatOsc), and using the MATLAB function “fft_of_force”, calculate the natural frequencies of the balance structure in still water and verify that no risk of resonance-induced vibration occurs.

Optional question

8. Setting the same water level in static and dynamic tests is important for the accurate measurement of the dynamic force. Provide an estimate of the errors in the force coefficients $\langle C_D \rangle$ and $\langle C_L \rangle$ due to a

different water level in the static and dynamic tests (assume Δh=2 mm, for example). Consider that the water-section area of each of the two endplates, as observed from the top, is a rectangle with size 180 mm × 2 mm (see Figure 1).