LMECA 2323: Aerodynamics of External Flows

Laboratory: Low Reynolds Number Flow around a Cylinder in a Wind Tunnel

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Guidelines

Evaluation format: You will produce a written report presenting and analyzing your results. The report must be concise and should not exceed **7 pages** (a rewrite on the theory is **not required**, please focus instead on your observations and interpretation). Reports exceeding the page limit will incur a penalty. Emphasis will be placed on clarity and readability, in particular on the quality of the plots. Figures must **at least** be vectorized (.pdf), include a grid, proper labels with units, and relevant x- and y-axis limits.

Groups : This homework must be completed in groups of three. Group registration must be completed via Moodle.

Submission: Submit both your **Report** (PDF) and your **Python code** via Moodle. Files must be named following the convention *"FIRSTNAME_LAB1REPORT.pdf"* and *"FIRSTNAME_LAB1CODE.py"*. If multiple code files are submitted, please compress them into a single `.zip` archive.

Questions: Questions may be posted on the dedicated Moodle forum.

Recall of Theory

The *Reynolds* number of an aerodynamic flow characterizes the ratio between inertia and viscous effects. This single parameter determines the regime of any incompressible flow in a unique way. It is defined as

$$Re_D \triangleq \frac{U_\infty D}{\nu},$$

where U_∞ is a characteristic velocity of the flow (upstream velocity), D is a characteristic length (cylinder diameter), and ν is the kinematic viscosity of the fluid.

Friction and pressure forces apply on any body placed in a flow. Given a reference frame aligned with the upstream velocity direction U_∞, the projection on the streamwise direction of those forces is called the *drag force* (F_D), while the projection on the transverse direction is called the *lift force* (F_L). For a symmetrical bluff body, there is no lift on average, so this force will not be measured during the experiment. For an infinite span body, the drag consists of two contributions: the pressure drag (also known as shape drag) due to the body wake, and the friction drag due to wall friction.

The drag coefficient is the dimensionless quantity determined by normalizing the drag force with the dynamic pressure of the inflow and a reference area S (here $S = D\,b$, where b is the span of the cylinder):

$$C_D = \frac{F_D}{\frac{1}{2}\rho U_\infty^2 S}.$$

Instruments

- *Low velocity aerodynamic wind tunnel.*
- *Pitot-static tube.* A Pitot-static tube is used to measure both the *static pressure* p_∞ and the *total (stagnation) pressure* p_t of a flow. It consists of two pressure-sensing ports: the *Pitot port*, which directly faces the flow, measures the stagnation pressure p_t, while the *static port*, flush with the side of the tube, measures the static pressure p_∞. The difference between the total and static pressures corresponds to the dynamic pressure of the flow, from which the flow velocity U_{infty} can be determined.
- *Precision manometer:* Furness Controls FCO560 2 [kPa]. This instrument measures differential pressures at a frequency of 10 [Hz]. Its resolution is 0.01 [Pa], and the systematic error (associated with the measurement device) is
$$\delta\Delta p_{\text{device}} = 0.001 \times \text{reading} + 0.03 \text{ [Pa]}.$$
- *Strain gauges.* The electrical resistance of one gauge changes depending on the deformation applied to it. Several gauges measure the deformations (which correspond to an output voltage variation) that are related to mechanical strain induced by aerodynamic forces. As this instrument is quite sensitive, a calibration must be done prior to any new experiment. For this laboratory, calibration is already done by the assistant before the experiment. The calibration data can be found on Moodle.
- *Rotating cylinder.* A cylinder held by metallic arms is placed in front of the outlet of wind tunnel. Dimensions of the cylinder are a diameter of 50 [mm] and a length of 425 [mm].
- *Tufts on a rod.* For flow visualization.

Required measurements

1. **The dynamic pressure of the inflow** (upstream of the cylinder), in order to deduce the corresponding upstream velocity and the Reynolds number of the experiment.
2. **The pressure difference** $p(\theta) - p_\infty$ **around the stagnation point** (from -10° to 10° by steps of 5°). In order to find the actual position of the stagnation point.
3. **The drag of the cylinder** using the strain gauges, in order to deduce the drag coefficient C_D.
4. **The pressure all around the cylinder** (by steps of 5° up to 90° and by steps of 10° afterward), in order to deduce the pressure coefficient $C_p(\theta) = \frac{p(\theta)-p_\infty}{1/2\rho U_\infty^2}$ and find the corresponding drag coefficient (due to pressure drag only) and compare it to the C_D obtained with the strain gauge. Finally, compare $C_p(\theta)$ to the theoretical case of potential flow. Comment.

Required results/plots

1. Compute the flow velocity U_∞ and diameter-based *Reynolds* number Re_D
2. Compute and plot the pressure coefficient $C_p(\theta)$ around the cylinder (from 0° to 180°). Interpolate C_p for small angles (-10° to 10°) to identify the exact position of the stagnation point, and shift your data accordingly.
3. Compare (and plot together) your measured $C_p(\theta)$ to the theoretical case of potential flow. Comment on the similarities and differences.
4. Compute the pressure drag coefficient and compare it to the value obtained from the strain gauges. Discuss any discrepancies and compare both results with other available measurements in the literature.
5. Finally, experimental results **are worthless** without an estimation of the uncertainty inherently linked to the latter. Estimate the uncertainty of each $C_p(\theta)$ value as well as there statistical distribution ($\pm 2\sigma$) and display them as confidence intervals (ex. `plt.errorbar()`) on your first pressure coefficient plot.

Velocity deficit estimated Drag

As a complementary approach, the drag can also be estimated using a momentum balance applied to a to a two-dimensional control volume surrounding the cylinder, see Fig. 1. This method relies on the following assumptions:

- Sections AC and BD must be sufficiently far apart so they lie in an irrotational region, and so that the mean streamwise velocity equals U_∞. Consequently, the mean pressure equals p_∞.
- The turbulence is assumed homogeneous on sections AC and BD, implying that $\overline{u'v'} = 0$ on these boundaries.

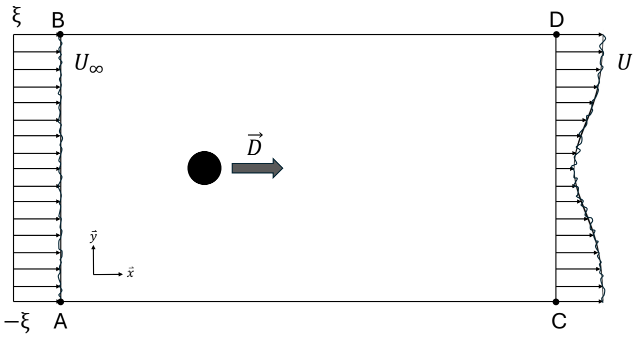

Figure 1: Control volume representation

By establishing the momentum balance using this control volume, one can obtain the expression of the drag of the cylinder (per unit length):

$$\mathcal{D} = \rho \overline{U}_\infty^2 D \left[\int_{-\xi}^{\xi} \frac{\overline{U}}{\overline{U}_\infty}\left(1-\frac{\overline{U}}{\overline{U}_\infty}\right) \mathrm{d}\left(\frac{y}{D}\right) + \underbrace{\int_{-\xi}^{\xi} \frac{\overline{U'^2_\infty}}{\overline{U}^2_\infty}\,\mathrm{d}\left(\frac{y}{D}\right)}_{\text{Negligible}} - \int_{-\xi}^{\xi}\frac{\overline{u'u'}}{\overline{U}^2_\infty}\,\mathrm{d}\left(\frac{y}{D}\right) + \int_{-\xi}^{\xi}\frac{(\overline{p}_\infty-\overline{p})}{\rho\overline{U}^2_\infty}\,\mathrm{d}\left(\frac{y}{D}\right)\right] \tag{1}$$

Additional required analysis

Beside the measures from the balance and the manometer, you are asked to:

1. Compute the drag coefficient of the cylinder based on the velocity deficit the latter generates.
2. Comment on the discrepancies and similitude.
3. [BONUS] (not counted in the page limit) Detail the derivation of the expression (1). (*Hint :* Do not forget to take the momentum flux on the top and the bottom sides of the control volume).

The velocity profile has already been measured by the assistant five diameters downstream of the cylinder center as well as a point-wise measurement of the inflow (considered uniform) using a pitot-static tube. The data of the experiment can be found on the moodle website under the form of `.npy` files. The latter are raw data, you may have to crop the edge of the profile to properly compute the integrals. Length are given in [mm], velocities in [m/s], pressures in [Pa] and temperatures in [K].

Note on uncertainty

Uncertainty on dynamic pressure

The uncertainty on the dynamic pressure measurement can be computed as,

$$\delta\Delta p = \sqrt{\delta\Delta p_{device}^2 + \delta\Delta p_{reading}^2 + \delta\Delta p_{random}^2}. \tag{2}$$

As mentionned earlier, the instrument used to measure the pressure differential is a Furness Controls FCO560 2 [kPa]. The latter have a systematic error (inherently linked to its internal architecture):

$$\delta\Delta p_{device} = 0.001 \cdot \overline{\text{reading}} + 0.03 \text{ [Pa]} \qquad \text{(Where the reading is the value returned by the sensor).} \tag{3}$$

The latter has a resolution of 0.01 [Pa]. The uncertainty from the rounding of the reading is then

$$\delta\Delta p_{reading} = \frac{0.01}{2} = 0.005 \text{ [Pa]}. \tag{4}$$

Finally, another source of uncertainty must be considered. Unlike the instrumental uncertainty, this contribution is associated with the intrinsic variability of the measured signal (*i.e.*, the flow itself), and corresponds to a *random error*. For a given spatial location, the pressure differential is recorded as a time series. Assuming that the measurements follow a Gaussian distribution, a confidence interval can be defined such that the computed mean value lies within this interval with a given confidence level. The random error is estimated as

$$\delta\Delta p_{\text{random}} = z_\alpha \frac{\sigma_{\Delta p}}{\sqrt{N}}, \tag{5}$$

where z_α is the critical value of the standard normal distribution corresponding to the chosen confidence level ($z_\alpha = 1.96$ to ensure a 95% confidence level), $\sigma_{\Delta p}$ is the standard deviation of the measured pressure time series and N, the number of samples. Note that this component of the uncertainty can be reduced as one wants simply by recording a longer signal.

Under the assumption of independent uncertainty contributions and normally distributed random errors, the combined uncertainty $\delta\Delta p$ defines a two-sided confidence interval at the 95% confidence level. Accordingly, the true value of the mean dynamic pressure is estimated to lie within

$$\Delta p_{\text{true}} \in \left[\Delta p_{\text{measured}} - \delta\Delta p,\ \Delta p_{\text{measured}} + \delta\Delta p\right], \tag{6}$$

with a confidence level of 95%. In other words, we are 95 % sure that the **time-average value** of the signal lies in this interval.

Besides estimating the uncertainty on the mean value, we can directly examine the distribution of the samples. Redefining

$$\delta\Delta p_{\text{random}} = z_\alpha\, \sigma_{\Delta p}, \tag{7}$$

we obtain an interval within which a single measurement is expected to lie with 95% confidence.

Uncertainty on air density

The air density is estimated assuming ideal gas behavior,

$$\rho = \frac{p_{amb}}{RT_{amb}}, \tag{8}$$

where p_{amb} and T_{amb} denote the ambient pressure and temperature measured in the laboratory during the experiment, and R is the specific gas constant for dry air (= 287.05 [J/(kg K)]).

Based on Eq. 8, the uncertainty associated with the derived quantity ρ is evaluated by propagating the uncertainties of the independent variables using first-order Taylor series expansion method:

$$\delta\rho = \sqrt{\left(\frac{\partial\rho}{\partial p_{amb}}\delta p_{amb}\right)^2 + \left(\frac{\partial\rho}{\partial T_{amb}}\delta T_{amb}\right)^2}. \tag{9}$$

Applying the partial derivatives, Eq. 9 leads to

$$\frac{\delta\rho}{\rho} = \sqrt{\left(\frac{\delta p_{amb}}{p_{amb}}\right)^2 + \left(\frac{\delta T_{amb}}{T_{amb}}\right)^2} \tag{10}$$

The uncertainties on ambient pressure and temperature are determined following the same methodology as for the pressure differential (Eq. 2). However, it is assumed that both quantities remain constant over the duration of the experiment. Consequently, no random contribution is considered.

Ambient pressure is measured using a Druck DPI142 sensor. According to the manufacturer specifications, the associated systematic uncertainty is $\delta p_{amb,device} = 0.0001 \cdot (1150 - 750)$ [mbar] = 4 [Pa]. The instrument resolution is 0.01 [mbar].

Ambient temperature is measured using an electronic thermometer. As no calibration data are available, the systematic uncertainty is (erroneously) neglected. The resolution of the device is 1 [°C].

Uncertainty on wind speed from Pitot-static tube

The freestream velocity is obtained from the measured dynamic pressure using

$$U_\infty = \sqrt{\frac{2\Delta p}{\rho}} \tag{11}$$

Again, the uncertainty on U_∞ is determined by propagating the uncertainties in Δp and ρ via first-order Taylor expansion method:

$$\delta U_\infty = \sqrt{\left(\frac{\partial U_\infty}{\partial \Delta p}\delta\Delta p\right)^2 + \left(\frac{\partial U_\infty}{\partial \rho}\delta\rho\right)^2} \tag{12}$$

$$\frac{\delta U_\infty}{U_\infty} = \sqrt{\left(\frac{\delta\Delta p}{2\Delta p}\right)^2 + \left(\frac{\delta\rho}{2\rho}\right)^2} \tag{13}$$

The pressure uncertainty $\delta\Delta p$ is obtained from Eq. 2, while the density uncertainty $\delta\rho$ is given by Eq. 10.