

Introduction

As engineers we are interested in determining the fluid dynamic forces acting on objects immersed in flows. The drag force is the force on an object that is parallel to the flow direction. It is produced by flow friction due to viscosity (viscous drag), and pressure variations around an object due to the formation of a wake (form drag). Other forces are the lift and side forces which are perpendicular to the flow. Moments may also be produced as shown in Figure 1.

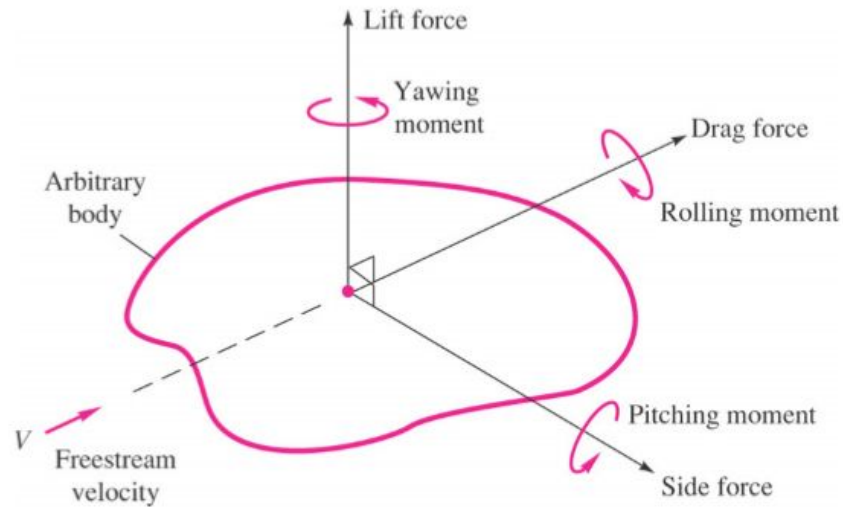


Figure 1: Forces and moments on an immersed object.

For practical reasons, experiments to measure the forces are conducted on a scale model in a windtunnel and the magnitudes of the flow velocity and the forces will be different to

those experienced by the prototype. Engineers have developed the method of dimensional analysis that quantifies the fluid dynamic forces through non-dimensional numbers such as the Reynolds number, Re , and the drag coefficient, C_D .

Various measurement methods may be applied to determine the flow parameters and the forces and moments acting on immersed objects. A combination of pitot and static tubes connected to a manometer may be used to determine velocity and transducers or spring balances can measure the forces and moments.

Aims

The aims of this experiment are:

1. to learn about flow measurement techniques;
2. to observe the velocity dependence of the drag forces on various shaped objects, and to quantify them non-dimensionally (Part A);
3. to measure the velocity distribution in the wake of an object and to apply the conservation of linear momentum to determine the drag coefficient around an object (Part B).
4. To think about what the flow may look like around these objects, and use a simulation app to aid in this exercise, hence learning about how the measured drag force relates to certain flow features.

Theory - Estimating Drag from Wake Measurements

By measuring the velocity profile in the wake of an immersed object and by applying the conservation of linear momentum to a control volume about that object we can calculate the drag force, F_D , and subsequently the drag coefficient, C_D .

The flow setup is shown Fig. 2. Here P is the static pressure, V is the velocity and $P_t = P + \frac{1}{2}\rho V^2$ is the total pressure. The control volume is selected to eliminate unbalanced normal and shear stresses. The outlet boundary is far enough downstream of the object that the static pressure, which drops in the wake, has been able returned to the equilibrium inlet boundary value, viz. $P_2 = P_1$. The top and bottom surfaces of the control volume follow streamlines in the flow at a point far enough removed from the object that $dV/dy = 0$. At the inlet the velocity is uniform across the section but downstream of the object the velocity is a function of the wall-normal coordinate, y . At both locations the height of the control volume is H . As it is not practical to make the wake measurements at location 2, which is far downstream, the measurements are instead obtained at an intermediate position, m , using a rake of pitot tubes (not shown). At that intermediate location the streamlines are deflected vertically and the control volume height is larger than H . For simplicity this small deflection is neglected in the present analysis.

Starting with the general form of the integral equation for the conservation of linear moment

$$\sum \vec{F} = \frac{d}{dt} \left(\int_{CV} \vec{V} \rho dV \right) + \int_{CS} \vec{V} \rho \vec{V} \cdot dA \quad (1)$$

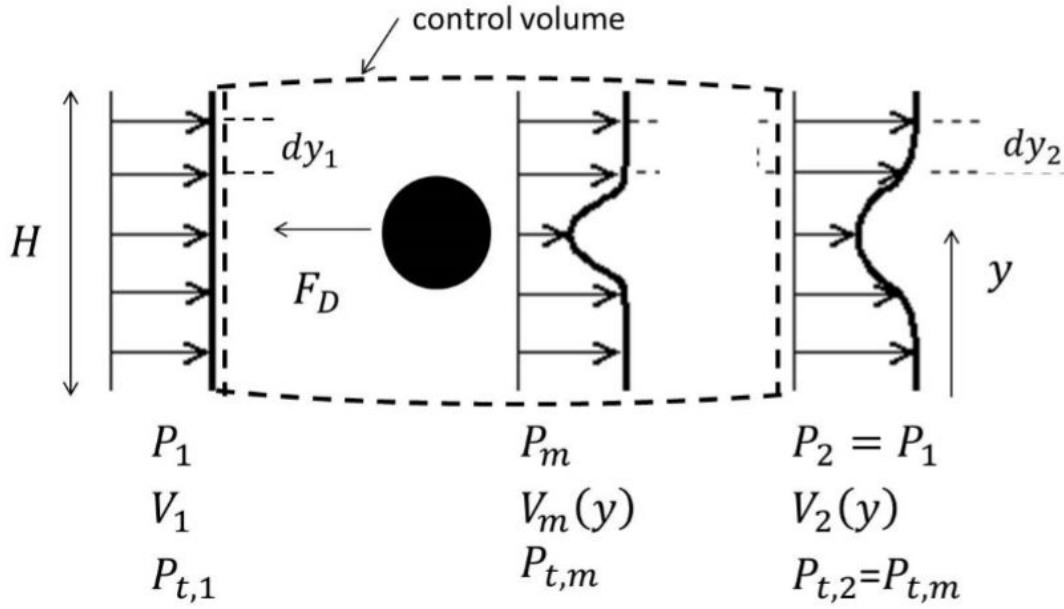


Figure 2: Schematic of the experimental setup.

and considering steady, two-dimensional flow conditions with constant density while assuming that wall friction losses are negligibly small compared to F_D we have

$$F_D = \rho W \left(\int_0^H V_1^2 dy_1 - \int_0^H V_2^2 dy_2 \right). \quad (2)$$

Here W is the width of the tunnel (into the page in Fig. 2). It is convenient to perform the integration along a coordinate y_2 at station 2, made possible because V_1 is uniform and both ends of the control volume are of height, H . Eq. (2) is manipulated by invoking continuity along a *stream tube* between stations 1 and 2, $\rho H V_1 dy_1 = \rho H V_2 dy_2$, to give

$$F_D = \rho W \int_0^H V_2 (V_1 - V_2) dy. \quad (3)$$

The drag force is non-dimensionalised by dividing through by the dynamic pressure force giving

$$C_D = \frac{F_D}{\frac{1}{2} \rho V_1^2 W L} = \frac{2}{L} \int_0^H \left[\frac{V_2}{V_1} - \left(\frac{V_2}{V_1} \right)^2 \right] dy \quad (4)$$

where L is the characteristic length of the immersed object in the y coordinate direction. (For a cylinder L is the diameter.)

The velocity profiles are estimated from pitot and static pressure measurements. Pitot tubes measure the total pressure, P_t , while static pressure taps measure the static (i.e. thermodynamic) pressure. From the Bernoulli Equation applied to a streamline that stagnates at the tip of a pitot tube, it can be shown that the difference between the two pressure measurements leads to an estimate of the velocity:

$$V = \sqrt{\frac{2}{\rho} (P_t - P)}. \quad (5)$$

So called pitot-static tubes can measure P_t and P at the same location. However, in this experiment P_t is measured only at location m , while the static pressure is measured only

at location 1. To get around this limitation on measurement locations, we must improvise. Firstly, the total pressure at location 1 is the same as the total pressure at location m when the immersed object is removed from the test section. This is expressed at $P_{t,1} = P_{t,m}^*$ where the asterisk denotes that the measurement is made without the immersed object present. Secondly, we can assume that viscous losses between locations m and 2 are negligibly small to that $P_{t,2} = P_{t,m}$. Noting that $P_2 = P_1$, it then follows that

$$V_1 = \sqrt{\frac{2}{\rho} (P_{t,m}^* - P_1)} \quad (6)$$

$$V_2 = \sqrt{\frac{2}{\rho} (P_{t,m} - P_1)}. \quad (7)$$

Substituting Eq. (6) and (7) into Eq. (4) and approximating the integral numerically by a summation of the dynamic pressure over discrete points on the pitot rake gives

$$C_D = \frac{2}{L} \sum_{i=1}^n \left[\left(\sqrt{\frac{P_{t,m,i} - P_1}{P_{t,m,i}^* - P_1}} - \frac{P_{t,m,i} - P_1}{P_{t,m,i}^* - P_1} \right) \Delta y_i \right] \quad (8)$$

where Δy_i is the distance between the i th and $(i + 1)$ th pitot tubes.

In the present setup $P_t - P = \rho_w g \Delta h_i$ is measured by the hydrostatic pressure difference in water-filled manometer columns. The manometer contains 16 columns, of which the first 15 are connected by plastic tubes to the 15 pitot tubes on the rake positioned in the wake of the immersed object. The 16th manometer column is connected by another plastic tube to the upstream static pressure wall tap. The height difference is $\Delta h_i = h_{16} - h_i$. The drag coefficient is therefore given by

$$C_D = \frac{2}{L} \sum_{i=1}^{15} \left[\left(\sqrt{\frac{\Delta h_i}{\Delta h_i^*}} - \frac{\Delta h_i}{\Delta h_i^*} \right) \Delta y_i \right] \quad (9)$$

Pre-work

It will be logistically difficult for us to monitor if you are doing this before your zoom lab session, however the ‘pre-work’ component is intended to be done before the lab. This year, please complete pre-work questions 1-3 (see below) in your groups, and include it at the start of your lab reports. The pre-work component should not be longer than 2 pages. For pre-work item 4 (wind-tunnel App), there is no submission requirement. The pre-work is worth 20% of the grade for this piece of assessment.

Answer the following questions. Some wider reading may be necessary to answer the questions.

1. Write down the mathematical definitions of the Reynolds number and the drag coefficient.
2. Print out the figure in Appendix A showing the drag coefficient of a sphere versus the Reynolds number. Clearly mark the points on the graph corresponding to flows

of air at 25 °C and 101.3 kPa over an 80 mm diameter sphere with velocities of $V = 5, 10, 15, 20, 25$ and 28 m/s.

3. A pitot tube and a static pressure tap are placed in a flow of air and connected to adjacent columns of a manometer containing fresh water as shown in the figure below. The columns are connected to a common reservoir such that the water pressure at the base of the columns is the same. Calculate the air velocity, V , when the manometer height difference is 53 mm. You may use the same air density as used in Question 1.
4. Download and Install the Wind Tunnel App on your mobile devices and play around with it. The paid version of the wind tunnel app is strongly recommended as it allows you to sketch different shapes, however this is not strictly required. In parallel to this, read about streamlines, streaklines, and pathlines. If you do not have a mobile device, then collaborate with a friend over zoom or otherwise using the share-screen function.

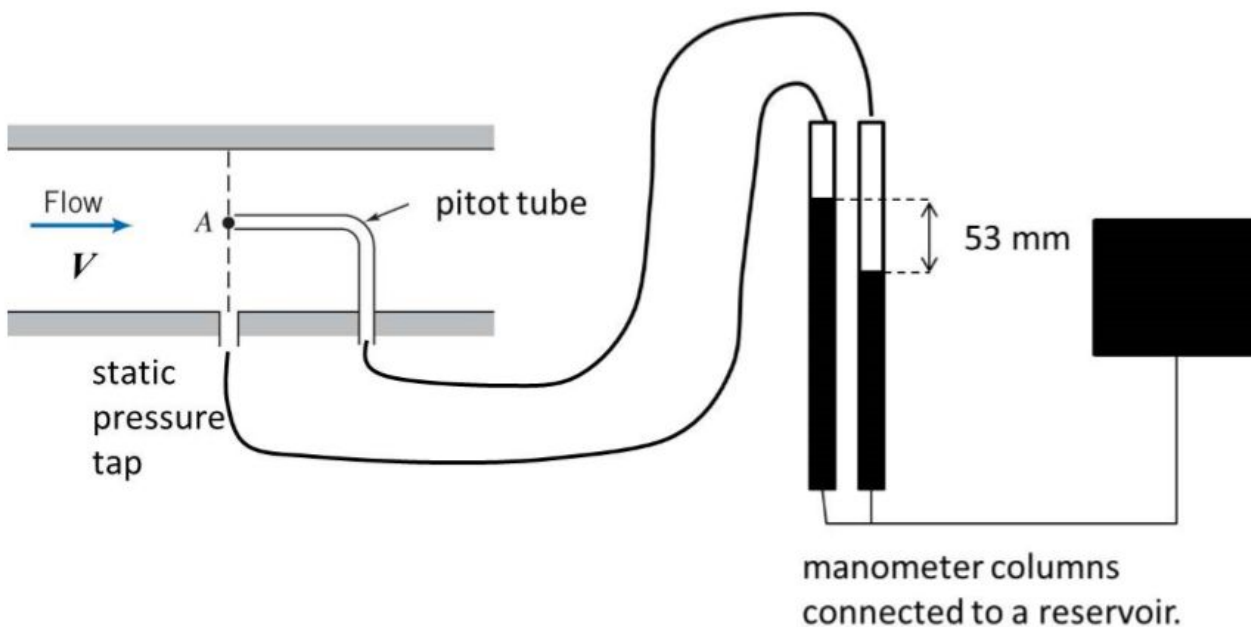


Figure 3: Pitot and static pressure measurements using a multitube manometer.

Experimental Procedure

This is the procedure you would have followed in person. This year you will watch the demonstrator go through a typical set of experiments which essentially go through these steps (roughly). Please watch the videos carefully. You will also be provided with some experimental data collected through these and previous similar experiments to use in your reports.

The procedure has three parts. Set-up deals with making careful observations of the wind-tunnel and components. Part A deals with using the force transducer to measure the drag force on various objects for a range of flow speeds and the non-dimensionalisation of those. Part B deals with measuring the pressure profile in the wake of an object and using the conservation of linear momentum (above theory) to calculate the drag coefficient.

Set-up

1. Examine all parts of the wind tunnel, including the intake and exhaust sections, the two-component force transducer, static pressure taps, inclined manometer calibrated for velocity, wake pitot tube unit and the multitube manometer. Make an annotated diagram of the equipment.
2. Examine a selection of models (sphere, hemisphere, streamlined shape, cylinder and the symmetric wing) as well as the pitot wake unit (i.e. the pitot rake). Use the calipers to measure and record the key dimensions of each shape. Don't forget to also measure the dimensions of the supporting rod.
3. The post-lab analysis requires an estimate of the air density. It may be related to temperature and pressure through the ideal gas equation. Temperature and pressure data are available from the Bureau of Meteorology's (BOM) Sydney Observatory Hill weather station (<http://www.bom.gov.au>) which is relatively close to the university. Note the date and precise time of your experiment so that the BOM data may be accessed at a later time.

Part A

1. Place the sphere into the force transducer.
2. Without flow, use the calibration knobs to zero the forces on the transducer digital display.
3. Start with a flow speed of 5 m/s up to a maximum of 15m/s. Do not exceed 50% on the power dial (ask the demonstrator, this is due to noise restrictions). Record the drag force as you go. Try and take at least 4 measurement points.
4. To reduce measurement uncertainty, repeat steps 2 and 3 a few times so that average values may be used in the final analysis.
5. Repeat the above steps for one other object shape. If you chose to experiment on the wing you may also like to measure the lift force.
6. (To be done after the lab session.) Plot the results for each shape in non-dimensional form as the drag coefficient versus the Reynolds number. Don't forget to subtract the drag on the holding rod; this can be estimated from its dimensions. Compare the results for each of the shapes you have investigated and explain the reasons for the different values. Additionally, compare the results for the sphere to the those found in Appendix A.

Part B

1. Place the cylinder into the force transducer and fit the wake pitot unit (also known as a rake) a short distance downstream of the cylinder (this should already be installed). Ensure that the pitot tubes are aligned with the flow direction. Check that the plastic pressure tubes are connected to the rake and multitube manometer at each end and that the tubes are not kinked. Make a note of which pitot tubes are connected to which manometer columns. The upstream static pressure tap should be connected to column 16 on the manometer.
2. Without flow, use the calibration knobs to zero the forces on the transducer digital display.

3. Increase the flow speed to 15m/s and record the transducer drag force (again, do not exceed 50% on the power dial).
4. Keeping the flow speed steady, record the liquid heights in each of the manometer columns. You may need to rotate the manometer assembly to get an accurate reading. The demonstrator will help you with this. If for example you choose an inclination of 5 to 1, when processing your results you will need to divide your height difference by a factor of 5.
5. Remove the cylinder, return the flow speed to the same value used in the above steps and record the liquid heights in each of the manometer columns.
6. (To be done after the lab session.) Estimate the drag coefficient using the information provided in the section titled "Theory - Estimating Drag from Wake Measurements" above. Compare and contrast this with values found in the text book or other literature and with the transducer drag readings you have made.

Report

The maximum length of the report is 10 pages (12pt Times New Roman Font, 1.5cm margins, single space) excluding appendices. This excludes the pre-work which is an additional 2 pages. Parts of the report beyond the 10 + 2 page limit will not be marked. We look for quality, not quantity. It is for instance completely possible to have a 6 page report that is of HD standard.

As a group, you are to prepare a professional standard laboratory report. The report should include a detailed description of the apparatus, a succinct summary of the experimental procedure and of the analysis method that is used. Raw data will be shared with you via Canvas. Sketches and other figures should be of a high standard and have a caption. All figures should be discussed in the body of the text including qualitative and quantitative explanations for what is shown.

In addition to discussing your analysed data, your lab report should also include either hand sketches or snapshots (from the wind tunnel App or other source) of what you expect the flow to look like around the objects tested (e.g. approximate streamlines and high or low pressure regions). If you use another source, you must provide a reference. You must explain the sketches you have provided noting specific areas of interest such as 'stagnation points' or where you believe streamlines are likely to move closer together or move further apart.

Higher marks will be awarded for reports which are creative in what is presented and which make reference to theory to explain what has been observed.

You will not be penalized for having results/graphs that perhaps don't 'look right' so long as all of the reasons for your trends are clearly explained, and backed with physical evidence (such as limitations of the experiment or other research which you have found which explains the potential reasons for the errors you have observed).

Appendix A: C_D vs Re for a sphere

