Fluid Mechanics MTF053

Flow Around Immersed Bodies

Hands-on Lab

Division of Fluid Dynamics
Department of Mechanics and Maritime Sciences
Chalmers University of Technology

Lab Session Outline

laboration work	4 hours
assessment	1 hour

Objectives

1. Understand how shape and surface roughness affects the forces on a body immersed in a flow
2. Determine forces using model experiments
3. Understand the concept of separation and what causes it to appear
4. Study the pressure distribution around a cylinder and along a wing profile

Content

The laboration is divided into three parts:

Part I: Drag Measurements

Determine the drag for a number of axisymmetric bodies and cylinders. Investigate the effects of surface roughness and body shape on arising forces. Explain the differences.

Part II: Measurement of Forces on a Wing Profile

Investigate how the drag and lift of a wing profile is affected by the angle of attack.

Part III: Pressure Measurements

Investigate how the static pressure varies around a cylinder and along a wing profile. Determine the pressure drag of a cylinder using the pressure measurements.

Prerequisites

Read these parts of the textbook (Fluid Mechanics F. White) before the laboration:

A Successful Application	Section in chapter 5.4
Geometric Similarity	Section in chapter 5.5
Dynamic Similarity	Section in chapter 5.5
Pitot-Static Tube	Section in chapter 6.12
Experimental External Flows	Chapter 7.6 (excluding example 7.6)

Assessment

Each student should present his/her results in the form of a filled lab form. The assessment takes place at the end of the lab session (or later according to agreement with the lab assistant). The lab assistant will be available for consultation after the lab session.

Theory

Forces on an Immersed Body

A solid body immersed in a fluid flow is subjected to a force $\mathbf{F}$. The force $\mathbf{F}$ is the net force resulting from pressure and friction forces acting on the body, see Fig. 1.

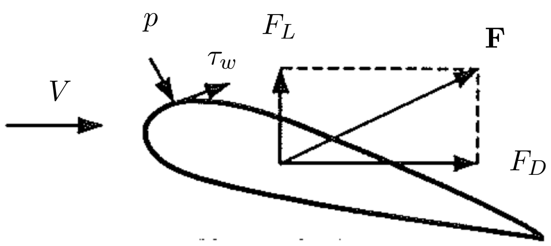

Figure 1: Forces on an a wing immersed in a fluid flow

The force $\mathbf{F}$ can be divided into two components: the drag force F_D (the force component in the flow direction) and the lift force F_L (the force component in the flow normal direction). The drag force can in turn be divided into pressure drag F_{D_p}, the drag generated by pressure forces, and friction drag F_{D_f}, the drag generated by friction/viscous forces.

The force magnitude $F = |\mathbf{F}|$ is usually expressed in using a non-dimensional property, C, defined as

$$F = C\frac{\rho V^2}{2}A \tag{1}$$

where V is the freestream velocity and A is a characteristic area.

Reynolds Similarity

Reynolds Similarity law says: the flow around geometrically similar bodies is similar if the Reynolds number is the same in both cases. In practice this means that one can use model-scale measurements to estimate the forces on a body in prototype scale as long as the model-scale test is done with the same Reynolds number, i.e., the size of the tested body does not have to be the same, nor does the fluid velocity, the fluid, pressure, temperature, etc.

The Reynolds number is defined as:

$$Re = \frac{VL}{\nu} \tag{2}$$

where V is the freestream velocity, L is a characteristic length, and ν is the kinematic viscosity.

Reynolds similarity implies that the non-dimensional property C in Eqn. 1 is a function of Reynolds number for a given geometry.

$$C = f(Re) \tag{3}$$

More detail about similarity can be found under *"Geometric Similarity"* and *"Dynamic Similarity"* in Fluid Mechanics, F. White, Chapter 5.5.

Characteristic Length and Area

The characteristic length, L, and the characteristic area, A, for a specific body may be defined arbitrarily. For symmetric bodies, such as for example cylinders, the diameter, D, is often used as the characteristic length. Usually, the projected area normal to the flow is selected as the characteristic area, for further reading see *"Experimental External flows"* in Fluid Mechanics, F. White, Chapter 7.6. If the cylinder length is b, the characteristic area is calculated as

$$A = bD$$

For asymmetric bodies, such as for example wing profiles, the wing chord, c, (Fig. 2) is used as the characteristic length and the planform area is used as the characteristic area. If the wingspan is b, the characteristic area is calculated as

$$A = bc$$

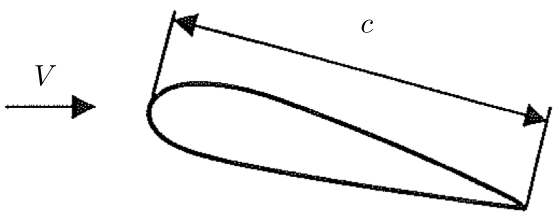

Figure 2: Characteristic length of a wing profile

Symmetric Bodies

A symmetric body is only affected by a force in the flow direction (the drag force F_D). According to Eqn. 1, F_D is associated with a constant C_D that follows Reynolds similarity. Fig 3 shows an empiric relation for C_D as a function of Re_D for a cylinder. For low Reynolds numbers the curve approaches a linear relation (a 45° line). For Reynolds numbers lower than 1.0, the drag force can be calculated using the Stoke formula

$$F_D = const \mu DV \tag{4}$$

Eqn. 4 in Eqn. 1 gives

$$C_D = \frac{const}{Re_D}$$

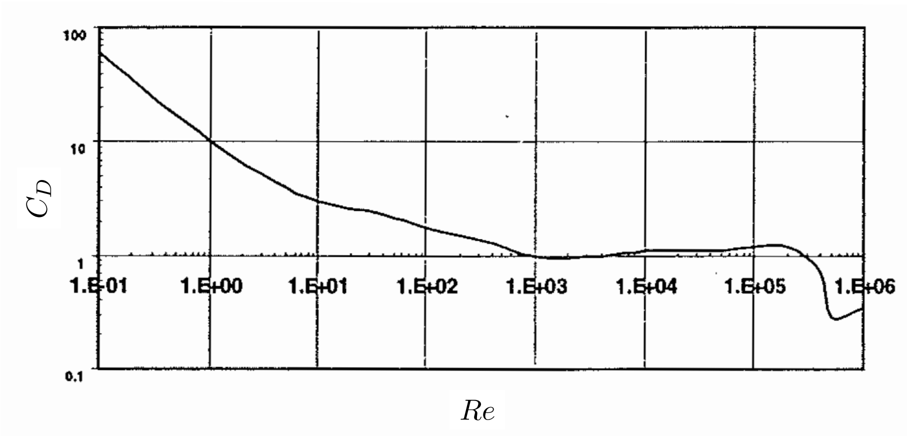

Figure 3: Drag coefficient for an long cylinder

which gives a straight line in a log-log diagram. As seen from the equations, the drag force, F_D, is directly proportional to the freesream velocity at low Reynolds numbers. In the Reynolds number range $3 \times 10^2 < Re < 3 \times 10^5$, C_D is approximately constant. This means that in this Reynolds number range, the drag force is proportional to the freestream velocity squared V^2.

As mentioned before, the drag force can be divided into pressure drag and friction drag. The Reynolds number is proportional to the ration of momentum forces and friction forces. At high Reynolds numbers, the flow is dominated by momentum forces and thus the friction drag is low in relation to the pressure drag and the drag force may be estimated by integration of pressure forces over the surface of the body. Fig. 4 shows the pressure distribution around a cylinder. The pressure difference, Δp, is obtained as

$$\Delta p = p - p_{atm}$$

where p_{atm} is the pressure in the undisturbed fluid (the atmospheric pressure). As can be seen in the figure, there is a pressure rise in front of the cylinder as the stagnation point is approached. There is also an increase in pressure behind the cylinder from the low pressure in the wake region to the atmospheric pressure of the surroundings. The pressure along the cylinder surface is representative of cylinder flows in general and will be studied in detail in Part III of the laboration.

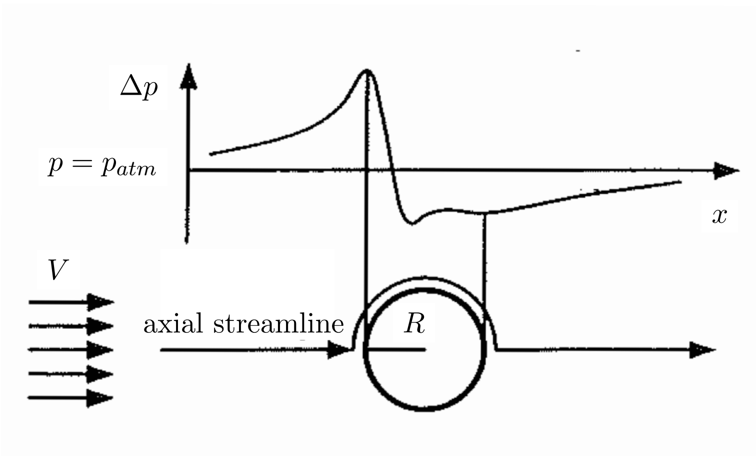

Figure 4: Pressure distribution over a cylinder in a fluid flow

Asymmetric Bodies

The net force on an asymmetric body, as for example a wing profile, is not aligned with the freestream flow direction. As mentioned before, the net force can be divided into two components, the drag force F_D and the lift force F_L. The two components are each associated with a non-dimensional constant: the drag coefficient, C_D, and the lift coefficient, C_L. If the Reynolds number is kept constant, both C_D and C_L will vary with the angle of attack, α. Both coefficients increase with increased angle of attack initially. The lift coefficient, C_L, reaches a maximum value for a critical angle of attack value, α_c. If the angle of attack is increased further, the lift coefficient will decrease.

Explanation: At low angles of attack the flow is attached to the wing almost to the trailing edge. For angles greater than the critical angle of attack, the flow over the wing separates almost from the leading edge of the wing, which means that the wing is stalled and not capable of turning the flow and thus not producing any lift. This phenomenon is of great importance when for instance landing an airplane. It is important to generate as much lift as possible at low speed without stalling the wing.

The angle of attack for which the lift-to-drag ratio has its maximum is called the best glide angle. This angle is important for gliders and for long range flights as this is the conditions at which the longest range can be flown at the lowest cost (lowest drag force).

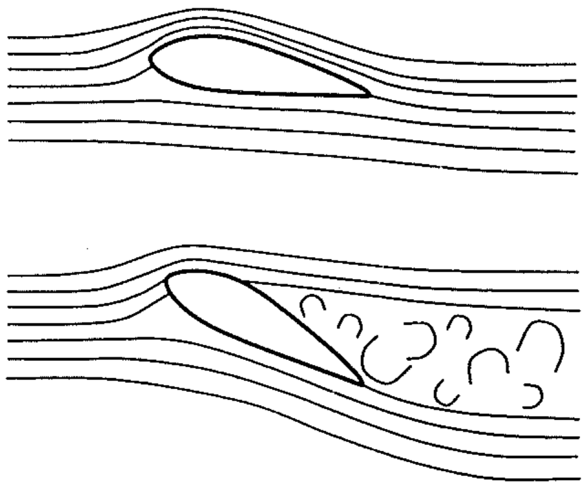

Figure 5: Wing stall

End Effects

The discussion above is valid for two-dimensional flow, i.e., if the body is assumed to have infinite length. In reality, the flow is affected by the ends of the body and close to the ends the flow is significantly altered. If the length of the body is long in comparison to the characteristic length, end effects may be neglected. If that is not the case, end effects can be lowered using end plates (thin plates mounted at the ends of the body).

Equipment

Wind Tunnel

When doing measurements, we need to a have an air stream with a constant and uniform velocity. In order to be able to achieve the best possible conditions, one would need a big and expensive closed wind tunnel. It is, however, possible to achieve conditions good enough for this laboration using an open simple "wind tunnel" - an axial fan attached to a duct with circular cross section. Inside of the duct, guide vanes have been installed that breaks down vortical flow structures generated by the fan. At the end of the duct the area is reduced by adding a convergent nozzle. The nozzle increases the flow velocity and makes the velocity profile more uniform.

The rotational speed of the fan is controlled by a transformer. Note! do not increase the rotational velocity of the fan too fast as that may lead to breakage of the transformer fuse.

Prandtl Tube

The flow velocity, V, is measured using a Prandtl tube. This measuring device is described under *"Pitot-Static Tube"* in Fluid Mechanics, F. White, Chapter 6.12.

The Bernoulli equation is valid for steady-state, inviscid flow, which can be assumed to be fulfilled in the freestream. If the gravity is neglected, the Bernoulli equation along a streamline reduces to

$$p + \frac{\rho V^2}{2} = const \tag{5}$$

where p is the static pressure, ρ is the fluid density, and V is the freestream velocity.

$(\rho V^2)/2$ is the dynamic pressure and is the difference between the fluid pressure in the flowing fluid and the pressure at standing still conditions (stagnation). Applying the Bernoulli equation on the form given by Eqn. 5 for the streamline going through the tip of the Prandtl tube (index 0) gives

$$p_0 + \frac{\rho V_0^2}{2} = p + \frac{\rho V^2}{2} \tag{6}$$

The right-hand side of Eqn. 6 represents the conditions at the tip of the Prandtl tube while the right-hand side represents the conditions at the wholes located at the side of the tube. At the stagnation point, the velocity is zero ($V_0 = 0$), which gives

$$p_0 = p + \frac{\rho V^2}{2}$$

where p_0 is the stagnation pressure

The freestream velocity can now be calculated as

$$V = \sqrt{\frac{2(p_0 - p)}{\rho}} \tag{7}$$

Note that ρ in Eqn. 7 is the air density. The pressure difference $(p_0 - p)$ is measured using an alcohol manometer.

Alcohol Manometer

An alcohol manometer (see Fig. 6) is used to measure the pressure difference over the Prandtl tube. In order to increase the accuracy when measuring low pressure differences, the scaled tube is inclined. If the inclination angle is α, the relation between the manometer reading, h, and the measured pressure difference is the following

$$p_0 - p = \rho_{alcohol} g h \sin\alpha = kgh \tag{8}$$

where $k = \rho_{alcohol} \sin \alpha$

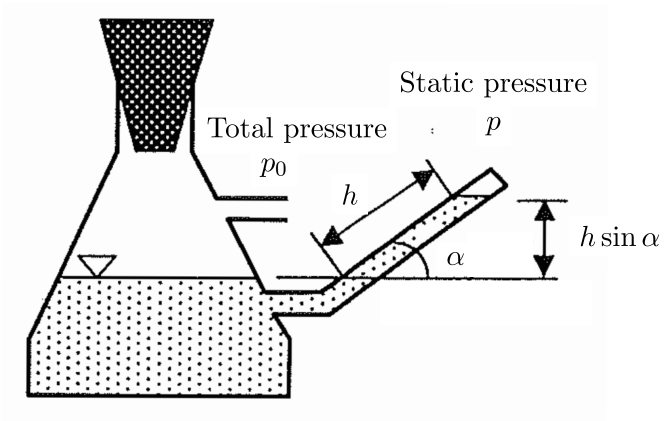

Figure 6: Schematic representation of a alcohol manometer

Due to the difference in surface area (see Fig. 6), the change in height of the alcohol surface in the container is negligible, i.e., only consider the deviation from the zero level on the scale. Note: the zero level does not have to be zero on the scale.

Do not make any adjustments of the manometers.
Ask the assistants for help if you think there is a need for adjustments.

Force Measurements

In Part I and II of the laboration, forces are measured with scales. The assistant will guide you in how to use those.

Estimation of Drag using Pressure Measurements

This section concerns Part III of the laboration.

The pressure difference Δp_n around the cylinder surface is expressed in relation to the pressure difference at the stagnation point, $p_0 - p$. Δp_n is measured using an alcohol manometer. If the angle of the inclined tube is held constant

$$\frac{\Delta p_\phi}{p_0 - p} = \frac{kgh_\phi}{kgh_{\phi=0}} = \frac{h_\phi}{h_{\phi=0}} \tag{9}$$

where h_ϕ is the manometer reading at the angle ϕ and $h_{\phi=0}$ is the manometer reading at $\phi = 0$, i.e., the manometer reading at the stagnation point. This means that it is sufficient to measure

h at the different angles ϕ. It is only the component in the flow direction ($\Delta p_n \cos\phi$) that contributes to the drag force. Using Eqn. 9 we get

$$\frac{\Delta p_\phi \cos\phi}{p_0 - p} = \frac{kgh_\phi \cos\phi}{kgh_{\phi=0}} = \frac{h_\phi \cos\phi}{h_{\phi=0}} \tag{10}$$

which gives

$$\Delta p_\phi \cos\phi = (p_0 - p)\frac{h_\phi \cos\phi}{h_{\phi=0}} = \frac{\rho V^2}{2}\frac{h_\phi \cos\phi}{h_{\phi=0}} \tag{11}$$

The pressure drag is now calculated as

$$F_{D_p} = \int_0^{2\pi} \Delta p_\phi \cos\phi R d\phi = \frac{\rho V^2}{4} D \int_0^{2\pi} \frac{h_\phi \cos\phi}{h_{\phi=0}} d\phi \tag{12}$$

Due to the symmetry, it is sufficient to integrate over one half of the cylinder and multiply by two.

$$F_{D_p} = \frac{\rho V^2 D}{2} \int_0^{\pi} \frac{h_\phi \cos\phi}{h_{\phi=0}} d\phi \tag{13}$$