Wind Tunnel Lab

Aerofoil Surface Pressure and Profile Drag Measurement

1. Overview

This lab session is designed to provide you with an opportunity to gain knowledge of how the aerodynamic characteristics of an aerofoil can be obtained through wind tunnel experiments. Measurements of the surface pressure distribution and the wake profile of a **NACA-0012 2D aerofoil** will be conducted for a range of angles of attack at a fixed freestream velocity. The lift and drag characteristics of the aerofoil will then be calculated by post-processing of the experimental data. You will also be able to assess the factors which may affect the accuracy of measurements.

2. Background

Consider an aerofoil placed in a uniform air stream. The surface of the aerofoil is subjected to a static pressure distribution and a shear stress distribution. These distributions when integrated over the aerofoil surface leads to a resultant aerodynamic force, R, which can be decomposed into a normal component to the aerofoil chord, N, and an axial component, A, along the chord (see Figure 1). This resultant force can, also, be decomposed into a lift component, L, normal to the free stream direction, and a drag component, D, parallel to the free stream direction.

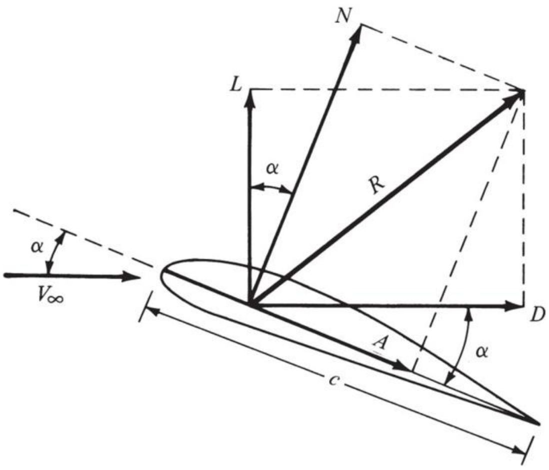

Figure 1: Resultant aerodynamic force and the components into which it splits.

The aerodynamic characteristics of an aerofoil are dependent on the Reynolds number, Re, the conditions of the free stream, the surface conditions, and the angle of attack, α. The Reynolds number based on the aerofoil's chord, c, is defined as

$$Re = \frac{\rho V_\infty c}{\mu} \quad (1)$$

where V_∞ is the freestream velocity, ρ and μ are the density and the dynamic viscosity of the air, respectively.

If the surface shear stress is ignored, the lift component on a 2D aerofoil can be deduced from the surface pressure distribution on the top and bottom surfaces. As for the drag component, it can be deduced from the velocity measurement of the aerofoil wake. Note that the profile drag of an aerofoil is due to a combination of skin friction and pressure drag contributions. At low to moderate angles of attack, the profile drag is mostly due to skin friction, which in turn is dependent on whether the flow is laminar or turbulent. At higher angles of attack, there is a large contribution from the pressure drag.

The integration of the momentum deficit across the wake at a given streamwise station can be used to calculate the drag of the aerofoil. The wake traversing technique [1] uses this idea to perform calculations that lead to the profile drag. The integration is carried out by traversing pitot pressure probes across the wake. Note that the wake thickness is not known, and it depends on the streamwise station behind the aerofoil's trailing edge.

3. Experimental Apparatus and Model

3.1 Experimental Apparatus

Our experiment will be performed in a low speed open-return facility with a test section measuring 0.457m x 0.457m. The length of the test section is 1.4m. More information on wind tunnel testing techniques can be found in [2].

A NACA 0012 aerofoil section is mounted across the entire width of the test section. The **chord length of the aerofoil is 0.152 m**. The aerofoil has **23 pressure taps** at its mid-span location; i.e. 12 taps on the upper surface and 11 taps on the lower surface. Table 1 in the Appendix 1 gives the chordwise positions of the taps. The pressure taps are connected to individual pressure ports, for the pressures to be measured.

A rake of 13 Pitot pressure probes is mounted on a traverse mechanism, allowing the rake to be moved vertically (traversed) across the wake within the aerofoil's mid-span. The 13 pressure probes have an external diameter of 1.65mm, with spacing between 5mm to 20mm between the centrelines of the adjacent probes. Table 2 in the Appendix 1 gives the relative spacing and the corresponding pressure transducer numbers. The spacing between the centrelines of the two outmost probes is 120mm which is sufficient to cover the total width of the wake. Nevertheless, the rake will need to be traversed by some distance in the appropriate direction in order to capture the whole wake at different angles of attack. All the pressure data is saved in Pascals and the pressure is relative to local atmospheric pressure. Angles in the data file are given in degrees.

3.2 NACA 0012 Aerofoil Section

This is a symmetrical aerofoil section, whose thickness distribution can be derived analytically from the equation below [3]:

$$\pm y_t = \frac{t}{20}\left[0.2969x^{1/2} - 0.126x - 0.3516x^2 + 0.2843x^3 - 0.1015x^4\right] \tag{2}$$

where t = 0.12 is the aerofoil's maximum thickness referred to a unit chord (c = 1), and x is measured from the leading edge ($0 < x < 1$).

4. Experimental Procedure

The surface pressure distribution and wake pressure profiles are to be measured at the following angles of attack: α=0°, 3°, 6°, 9°, 12° and 15°. The procedure of measurements is as follows:

a) First, make sure that the wing incidence angle is set to approximately zero. Ensure that the wake rake is locked in an upright position. Note that incidence angle in our case is the same as angle of attack.
b) Switch on the wind tunnel motor and set the free stream velocity at the outlet of the working section to about 20m/s.
c) Set the actual wing incidence angle to zero, by balancing the upper and lower surface pressures. By finely adjusting the wing incidence it is possible to get the pressures to lie over each other.
d) Set the aerofoil to zero incidence angle and then traverse the wake rake until the wake position is found.
e) Repeat the above procedure for α =3°, 6°, 9°, 12° and 15°. All the experiments are carried out under the assumption of two-dimensional planar flow.

At each setting it would be useful, for later analysis, to collect four sets of data. This will give an indication of the deviation of the measured data sets and allow minimizing random errors by data averaging.

5. Data Processing

In the experiments, the static pressure at each test point on the aerofoil, p_S, is measured. The pressure coefficient at each point, C_p, is defined as:

$$C_p = \frac{p_S - p_\infty}{\frac{1}{2}\rho V_\infty^2} = \frac{p_S - p_\infty}{p_T - p_\infty} \tag{3}$$

We can then calculate the normal force coefficient by integrating the pressure around the aerofoil:

$$C_n = \frac{1}{A}\oint_{Lower} C_p dA - \frac{1}{A}\oint_{Upper} C_p dA \tag{4}$$

where the integration is taken over the projected area on the wing-chord-plane dA. From the definition of a 2D aerofoil we define the coefficients for a unit span, therefore:

$$dA = 1dx \tag{5}$$

where dx is the differential wing-chord length. Substituting (5) into (4):

$$C_n = \frac{1}{\mathrm{c}} \oint_{Lower} C_p dx - \frac{1}{\mathrm{c}} \oint_{Upper} C_p dx \tag{6}$$

Since the incidence angle of the aerofoil is small, we can neglect the contribution from the axial force component and obtain the lift coefficient as:

$$C_l = C_n cos\alpha \tag{7}$$

Similarly, we can define the pitching moment by multiplying the normal force by its distance from a reference location (typically quarter chord), i.e.:

$$C_m = \frac{1}{\mathrm{c}^2} \oint_{Lower} C_p (x - x_{ref}) dx - \frac{1}{\mathrm{c}^2} \oint_{Upper} C_p (x - x_{ref}) dx \tag{8}$$

Based on the thin aerofoil theory, the theoretical value of the lift coefficient for 2D symmetric aerofoils is given by:

$$c_l = 2\pi\alpha \tag{9}$$

where α is the angle of attack / incidence expressed in **radians**.

The profile drag is related to the deficit of momentum in the aerofoil wake. Please refer to the derivation in Topic 5 slides. The total momentum deficit in the wake is equivalent to the total drag, as given by the following expression:

$$D = \int_{wake} \rho u(y) \left(V_\infty - u(y)\right) dy \tag{10}$$

where $u(y)$ is the measured velocity profile for the wake. The drag coefficient can be obtained by:

$$c_d = \frac{D}{\frac{1}{2}\rho V_\infty^2 c} = \frac{2}{c} \int_{wake} \frac{u(y)}{V_\infty} \left(1 - \frac{u(y)}{V_\infty}\right) dy \tag{11}$$

In the experiments, the following pressures should be considered:

p_T = freestream total pressure
p_∞ = freestream static pressure
p_{Tw} = total pressure at a station in the wake
p_{sw} = static pressure at a station in the wake

From the Bernoulli equation:

$$p_T = \frac{1}{2}\rho V_\infty^2 + p_\infty \tag{12}$$

where ρ is the air density which is 1.225 kg/m^3 at standard sea-level conditions. This can be rearranged to give:

$$p_T - p_\infty = \frac{1}{2}\rho V_\infty^2 \tag{13}$$

At a generic point in the wake, we can write:

$$p_{Tw}(y) - p_{sw}(y) = \frac{1}{2}\rho(u(y))^2 \tag{14}$$

Dividing Equation (14) by (13), we get:

$$\frac{u(y)}{V_\infty} = \sqrt{\frac{p_{Tw}(y) - p_{sw}(y)}{p_T - p_\infty}} \tag{15}$$

Substituting Equation (15) into Equation (11) and integrating yields the drag coefficient, c_d. Integration of Equation (11) can be performed numerically using a computer program or within an Excel spreadsheet. For convenience, we can assume that the static pressure in the wake is equal to the static pressure of the freestream, i.e. $p_{sw}(y) = p_{s\infty}$ (this is approximately true!).

6. Sources of Experimental Uncertainties

Error analyses are part of any experimental investigation. In principle, the experiment should be assessed to give the level and type of uncertainty of the data recorded which are then combined to provide an estimate of the level of uncertainty of the final results. Although error analyses are not required during this lab session, the possible sources of measurement uncertainties and feasible solutions for minimising the measurement errors are considered.

In wind tunnel tests, the common errors are caused by insufficient sensitivity of the sensors and by human errors involved in reading mean values of slightly fluctuating quantities. Other errors may include those due to slight surface imperfections in the model, the deflection of the model and supports under aerodynamic loads as well as the interference of the model supports to the flow field.

7. Other Factors Affecting Measurements

It is worth emphasising that the effect of freestream turbulence and wind tunnel blockage should be considered when the results from different wind tunnels are compared. The freestream turbulence level can affect the aerodynamic characteristics of an aerofoil by changing the location of onset of turbulent flow along the aerofoil surface such that the results obtained on the same model in different wind tunnels may not be identical. On the other hand, the tunnel blockage effect is due to the presence of tunnel walls, which imposes a constraint to the flow motion around the model and causes the measurements to be different from those obtained in free air, see Figure 2.

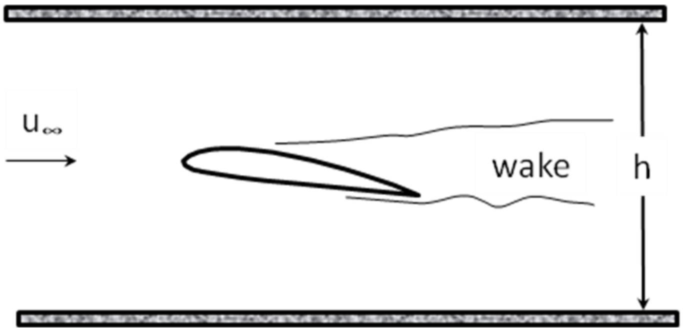

Figure 2: Schematic of an aerofoil inside a wind tunnel test section illustrating the reduction of the flow passage height due to the presence of the model and its wake

Tunnel blockage effect is an important factor to be considered when the experimental data are deduced. For a 2D aerofoil mounted across the full width of a wind tunnel test section, it is attributed to three main sources.

a) The so-called "solid blockage" due to a lateral constraint to the flow pattern about the aerofoil. This effect is a function of model thickness and size, and it results in an equivalent increase in dynamic pressure and hence an increase in forces and moments measured at a given angle of attack.
b) The so-called "wake blockage" due to a lateral constraint to the flow pattern about the wake. This effect increases with the size of the aerofoil wake and leads to a drag increase of the model.
c) An alteration to the streamline curvature of the flow around the aerofoil due to the constraint from the tunnel ceiling and floor. This results in an increase in the aerofoil lift and moment coefficient.

The systematic error caused by tunnel blockage effect can be accounted for by using tunnel wall corrections. The following equations can be used to correct the lift and drag coefficients due to this effect:

$$c_l = c_{lu}(1 - \sigma - 2\varepsilon) \tag{16.a}$$

$$c_d = c_{du}(1 - 3\varepsilon_{sb} - 2\varepsilon_{wb}) \tag{16.b}$$

where c_{lu} and c_{du} is the uncorrected lift and drag coefficients, respectively.

ε_{sb} and ε_{wb} are the solid and wake blockage ratios, respectively. They can be calculated as:

$$\varepsilon_{sb} = \frac{K_1 V}{A^{3/2}} \tag{17.a}$$

$$\varepsilon_{wb} = \frac{c}{2h} c_{du} \tag{17.b}$$

where A and h are the cross-sectional area and height of the wind tunnel test section, respectively; K_1 is a constant (for an aerofoil mounted across the entire width of a wind tunnel test section, K_1=0.76), V is the volume of the aerofoil model (for an aerofoil with a chord length of c, a maximum thickness of t and a span of b, $V = 0.7tcb$).

σ accounts for the curvature effect and it can be calculated using:

$$\sigma = \frac{\pi^2}{48}\left(\frac{c}{h}\right)^2 \tag{18}$$

Finally, the total blockage ratio, ε, is given by:

$$\varepsilon = \varepsilon_{sb} + \varepsilon_{wb} \tag{19}$$

By a rule of thumb, the wind tunnel blockage effect can be neglected when the total blockage ratio of a given model is less than 5%.

8. Computational Methods

Several methods of computing the performance of aerofoils exist with varying levels of accuracy and computational expense. You may be familiar with using Reynolds Averaged Navier Stokes (RANS) simulations (often referred to as CFD) to find the aerofoil performance. Recent progress in computational power have made high fidelity methods like RANS massively accessible, and in many cases massively misused.

Before high fidelity CFD simulation was available, low order modelling methods were required to estimate the performance of aerofoils. An example of one of these methods is xFoil. This program uses a combination of a potential flow panel method[1] and an analytical boundary layer model[2] to calculate the performance metrics for an arbitrary aerofoil shape. Potential flow methods were touched upon in Topic 6. The boundary layer solver uses the pressure gradient solution at the surface of the aerofoil from the potential flow model to compute the state of the boundary layer. The boundary layer solution is then fed back into the panel method until the solution converges. However, because the solution in this case is so sensitive to the transition location and flow separation location (if present), small errors in the boundary layer model can have a large impact on the solution.

You are not required to understand the workings of programs like xFoil for this lab. An xFoil solution for NACA 0012 has been included in the report template for comparison with your experimental results. If you would like to generate a solution from xFoil for yourselves then it can be downloaded within a graphical interface called XFLR5 at xflr5.tech.

9. References

The following references will help you through the experiment and the interpretation of the laboratory data:

[1] Katz, Joseph; Plotkin, A., Low speed aerodynamics. From wing theory to panel methods, 2005.
[2] Drela, M., "Two-dimensional transonic aerodynamic design and analysis using the Euler equations," MIT, 1985.

1) Anderson J D, Fundamentals of Aerodynamics, 6th edition, McGraw-Hill.
2) Pope A and Rae WH. Low-Speed Wind Tunnel Testing, John Wiley, New York, 1984.
3) Abbott IH and Von Doenhoif A. Theory of Wing Sections, Dover Publishing Inc., 1959.

10. Appendix 1

Table 1: Chordwise position of pressure tappings on upper and lower surface

Upper Tapping	x/c	Lower Tapping	x/c
1	0.0043	2	0.0098
3	0.0231	4	0.0431
5	0.0702	6	0.0976
7	0.1165	8	0.1487
9	0.1901	10	0.2430
11	0.2983	12	0.3427
13	0.3846	14	0.4393
15	0.4874	16	0.5383
17	0.5861	18	0.6349
19	0.6881	20	0.7363
21	0.7866	22	0.8392
23	0.8886		

Table 2: Vertical position of rake Pitot tubes

Rake Tapping	Y(mm)
24	-60
25	-40
26	-27.5
27	-17.5
28	-10.0
29	-5.0
30	0
31	5.0
32	10.0
33	17.5
34	27.5
35	40
36	60

11. Appendix 2: Methods of Assessment

You need to process the measured data to obtain the pressure distributions on the aerofoil as well as the wake profile. The outcomes you should obtain includes:

- Aerofoil pressure distributions
- Lift curve
- Drag Polar
- Pitching moment curve

You will present these outcomes in a report which will be submitted **within 2 weeks of the laboratory session**. A template for the report is provided on Classroom.

12. Appendix 3: Marking Scheme

Aerofoil Surface Pressure and Profile Drag Measurement Wind Tunnel Lab Report *Assessment Criteria*

Selection/ Grade ranges	Less than 20%	20-40%	40-60%	60-80%	80-100%
Abstract (10%)	Does not summarize key points.	Adequate summary but lacking clarity.	Clear summary but lacking key information. Within word limitation.	Good clear summary lacking minor details. Within word limitation.	Excellent summary of key elements, findings, and conclusions Within word limitation.
Introduction (10%)	Not enough information to understand the aim and rationale for the report. No background theory included.	Adequate description of the aims and objectives and rationale of the report but lacking clarity. Introduced background theory.	Clear description of the aims, objectives and rationale for the report. Define background theory with several key points missing. Lacking connection between theory and objectives.	Good description of aims and rationale with clearly defined objectives. Clear concise description of background theory with very few key points missing. Coherent and comprehensive.	Excellent description of aims and rationale with very clearly defined objectives and background theory. Original and flowing.
Methodology (20%)	Experiment procedure is not correctly described. Procedure is not included.	Correctly present overall experiment procedure with several mistakes. Fail to present several key steps in calculation.	Successfully present experiment procedure but have serval key aspects missing. Present the whole calculation process with few steps missing.	Clear procedure with few key points missing. Present the whole calculation process.	Clear presentation of experiment setup and comprehensive description of procedure. Comprehensively present the whole calculation process.
Results and Discussion (40%)	Only present the results without any description of calculation processes. Does not provide any plot. No relative analyses of results presented.	Fail to present most of the required plots. Fail to discuss requirements listed in the template.	Present most of required plots. Discuss most of requirements listed in the template.	Have all results in main body and appendix. Present all plots as required. Discussed every requirement listed in the template.	Have all results in main body and appendix. All required plots are well presented. Excellently discussed every requirement listed in the template with citations that perfectly support the analysis**.**
Conclusions (10%)	No clearly defined conclusions section.	Poorly defined conclusions section.	Conclusions somewhat limited and make reference to new material.	Clear concise conclusions with supporting evidence.	Excellent well supported conclusions.
Presentation (10%)	Poor English. No captions and citations. Does not follow the template. Exceed page limitation.	Standard English with few major mistakes. Limited captions and citations. Attempt to follow the template.	Standard English with few minor mistakes. Has captions and citations with few minor mistakes. Follow the template.	Good English. Good use of captions to describe plots and tables. Properly located citations. Follow the template.	Excellent English. Very clear captions. Insightful references that could help readers. Strict follow of the template.