Imperial College London

Department of Aeronautics

Second Year Laboratory

Aerodynamics II (AERO50001)

Profile Drag and Wake Momentum Deficit

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1 Introduction

For a wing of uniform section and infinite span, the total drag consists of two parts: the pressure (or form) drag and the skin friction drag. The former is the streamwise component of the resultant pressure force on the wing (the other component being the lift) and the latter is the force resulting from the action of the viscous shear stresses at the surface of the wing. The sum of these two is the Profile Drag.

The pressure drag may be obtained experimentally from the distribution of the pressure around the wing profile at any cross-section. The profile drag may be obtained from measurements of the momentum deficit in the wake behind the wing, taken sufficiently far downstream for the static pressure in the wake to have returned to the value far upstream.

2 Theory

2.1 The Pressure Drag

We take coordinates x and y respectively along the chord line of the wing section and perpendicular to it, with the origin at the leading edge, as shown in figure 1.

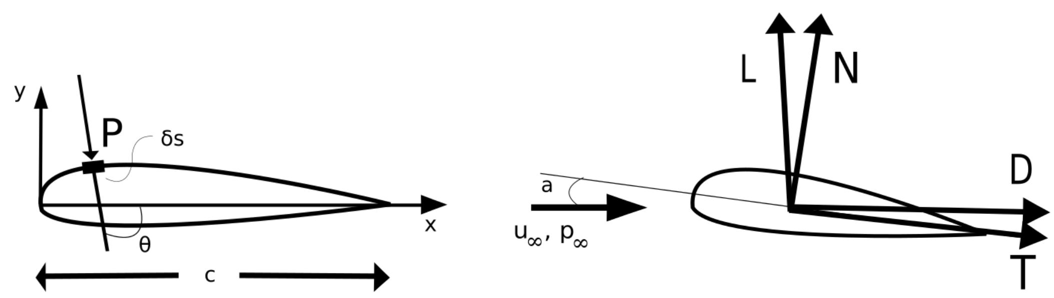

Figure 1: Pressure acting on an element δs (left) and Forces acting on an aerofoil (right)

At angle of incidence α, the resultant force experienced by the wing may be resolved into a normal force N in the y-direction and a tangential force T in the x-direction. The drag force on the wing will then be

$$D = Tcos\alpha + Nsin\alpha$$

If the pressure acting on the element δs of the surface is p and the normal to the surface locally makes an angle θ with the chord line, then the contributions to T and N from the pressure p are

$$T = p\ \delta s\ cos\theta$$

and

$$N = p\ \delta s\ sin\theta$$

For the complete section we can then write:

$$T = \oint p\ cos\theta\ ds$$

and

$$N = \oint p\ sin\theta\ ds$$

Putting $cos\theta\ ds = dy$ and $sin\theta\ ds = dx$, these become

$$T = \int (p_F - p_R)\ dy$$

and

$$N = \int (p_L - p_U)\ dx$$

where subscripts F and R refer to the front and rear of the section respectively. Similarly, subscripts L and U refer to the lower and upper surfaces respectively.

For a *wing of symmetrical section at zero incidence*, $p_U = p_L$, $N = 0$ and $T = D_p$, the pressure drag. In this case, the non-dimensional Drag Coefficient due to pressure drag is calculated as:

$$C_{D_p} = 2 \int_0^Y \left(C_{P,F} - C_{P,R}\right)\ d\left(\frac{y}{c}\right) \tag{1}$$

where $C_P = \frac{p - p_\infty}{\frac{1}{2}\rho U_\infty^2}$, $C_D = \frac{D}{\frac{1}{2}\rho U_\infty^2 c}$, c is the chord length, and Y the maximum thickness (normalised by c).

2.2 The Profile Drag

We apply conservation of mass and momentum to a large control volume enclosing the wing section, with the boundary drawn sufficiently far from the wing in all directions so that the pressure is uniform on it. We also assume steady flow. The reaction to the profile drag, $-D$, will then be the only force acting on the fluid passing through the CV. So

$$-D + net\ momentum\ flux\ into\ the\ CV = 0 \Rightarrow D = net\ momentum\ flux\ into\ the\ CV$$

Hence $D = \rho \int U_W(U_\infty - U_W)\, dy_w$, or $C_D = \frac{2}{c}\int \frac{U_W}{U_\infty}\left(1 - \frac{U_W}{U_\infty}\right) dy_w$, where U_W is the velocity in the wake and y_w is the distance across the wake (refer to figure 2).

Since the pressure on the control volume boundary is p_∞, it follows that $U = U_\infty$ outside the wake and integrand is zero except where $U < U_\infty$. Writing the above expression in terms of total pressures, H_W and H_∞, we get:

$$C_D = \frac{2}{c}\int \left(\frac{H_W - p_\infty}{H_\infty - p_\infty}\right)^{\frac{1}{2}} \left(1 - \left(\frac{H_W - p_\infty}{H_\infty - p_\infty}\right)^{\frac{1}{2}}\right) dy_w \qquad (2)$$

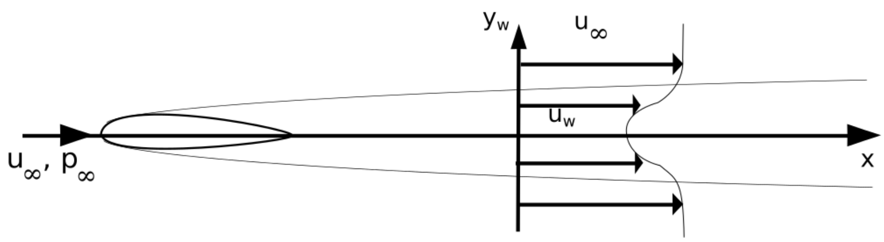

Figure 2: Wake velocity profile

3 The Experiment

3.1 Apparatus

A wing of 15.24cm (6") chord and NACA 0015 section is mounted in the working section of the wind tunnel located in Roderic Hill Building 206A. The working section has dimensions 18"x18"x 62". Around the centre section of the wing there are 16 surface pressure tappings, the locations of which are given in Table 1 below and are shown in Figure 3. Four chord lengths downstream of the trailing edge, an array of pitot tubes is mounted on the floor of the tunnel and the horizontal location of the array may be adjusted. The array consists of 24 tubes whose centres are spaced 0.254cm apart. In this experiment only 18 tubes are connected, as indicated in Table 2.

All 16 surface pressure tappings and the 18 wake pitot tubes are connected to multi-tube manometers. Also connected to both manometers is a pitot-static tube mounted upstream of the wing in the working section.

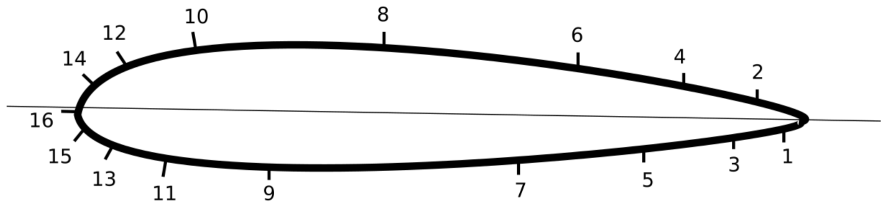

Figure 3: Location of pressure tappings

Hole No.	**1**	**3**	**5**	**7**	**9**	**11**	**13**	**15**
x/c	0.958	0.858	0.713	0.525	0.152	0.065	0.020	0.003
y/c	0.0094	0.02815	0.0469	0.06565	0.06565	0.0469	0.02815	0.0094
Hole No.	**16**	**14**	**12**	**10**	**8**	**6**	**4**	**2**
x/c	0	0.0087	0.028	0.090	0.303	0.593	0.742	0.888
y/c	0	0.01875	0.0375	0.05625	0.075	0.05625	0.0375	0.01875

Table 1: Surface Pressure Tappings

Tube No.	**1**	**3**	**5**	**7**	**8**	**9**	**10**	**11**	**12**
Distance from Tube 1 [cm]	0	0.508	1.016	1.524	1.778	2.032	2.286	2.54	2.794
Tube No.	**13**	**14**	**15**	**16**	**17**	**18**	**20**	**22**	**24**
Distance from Tube 1 [cm]	3.048	3.302	3.556	3.81	4.064	4.318	4.826	5.334	5.842

Table 2: Wake Pitot Tube Array

3.2 Measurements and calculations

With the wing set at zero incidence and the manometer vertical, start the tunnel and increase the speed to until the micromanometer reads $\sim$ 55mmWC (meaning mm of H_2O). Incline the manometer to a suitable angle, taking care that fluid is not displaced beyond the end of the tubes. Adjust the position of the wake pitot tube array if necessary.

Record the levels of the liquids in all the tubes, as well as the readings of the micromanometer (mmWC).

It may not be sufficient to assume that a zero incidence on the scale is a true aerodynamic incidence. You MUST therefore plot your manometer readings DURING the experiment, ensuring that overlaid values from top and bottom of the aerofoil provide a smooth distribution. To some extent, this can also be checked visually from the manometer. If necessary, adjust the model incidence to give the most symmetrical pressure distribution between the top and the bottom of the model.

Convert the readings from the surface pressure tappings to pressure coefficients. Plot C_p against x/c and y/c using the readings from alternate surfaces to obtain more detailed curves. Calculate the area under the C_p vs y/c curve and hence evaluate the pressure drag coefficient, as given by equation (1). From the readings of the wake pitot tubes, calculate values of the integrand in equation (2) and plot against distance from the wake centre line, y_w. Calculate the area under the curve and hence evaluate the profile drag coefficient, as given by equation (2).

Appendix 1- Lab Oral assessment

The lab is assessed both orally and through a written report. The oral assessment will take place the day following the lab. Each group must prepare a short presentation with slides that include

- Plot of C_p versus x/c (include graph with best-fit curve and error bars)
- Plot of C_p versus y/c (include graph with best-fit curve and error bars).
- Plot of integrand of equation (2) versus y_w (include graph with best-fit curve and error bars).
- Values of total profile drag C_D and the components due to pressure and skin friction.
- Sources of uncertainty and an error estimate of the total C_D.

Details about the report are provided in the next section.

Appendix 2- Lab report

For this laboratory a short individual report must be produced (max 6 pages). The essence of a good report is that it is complete, concise and informative. You therefore do not need to reproduce any of the material that is given in the lab handout, but you can refer to it as a reference if you wish. The report should contain the following:

Title page: as per handbook instructions (include date of experiment, group number, group members)

Objective: [5%] Describe the overall objective of the experiment (max 3 lines)

Experimental results: [30%]
Plot of C_p versus x/c (include graph with best-fit curve and error bars). Given the results of this plot (and error estimates), comment on the actual angle of incidence of the wing section.

Plot of C_p versus y/c (include graph with best-fit curve and error bars).

Briefly describe how the pressure drag coefficient can be obtained from this plot, and give the value found (with error estimate).

Plot of integrand of equation (2) versus y_w (include graph with best-fit curve and error bars).

What is the value of the total profile drag coefficient (and error estimate)?

Calculate the skin friction coefficient.

Error analysis [10%]
What is the accuracy of the manometer readings?

Briefly describe how the error in the pressure drag coefficient was estimated and comment on the factors that could affect the accuracy of the calculated pressure drag coefficient.

Discussion [25%]
In your own words, explain how pressure drag and skin friction arise? How are these two components of drag different from each other?

For this experiment, which component of drag is expected to be dominant – pressure drag or skin friction? Provide a brief explanation and discuss whether your experimental results agree with your expectations.

Discuss any anomalies/scatter in the experimental results you have obtained.

Numerical results [20%]
Perform a numerical simulation of the flow for the same Reynolds number and angle of attack using a commercial software. Make sure that the results are grid independent. Compare the numerical results with your measurements of C_p and C_D, and discuss similarities and differences.

Conclusions [10%]
Provide a list of the main conclusions from the experiment.

Appendix
Include a table of data here.