Chapter 7

Experiment 4: Pressure Distribution Over an Airfoil And Hot-Wire Anemometry

7.1 Objective

The objectives of this experiment are to:

1. Measure the pressure distribution over a Clark Y-14 airfoil at various angles of attack
2. Determine the lift and drag forces from the pressure measurements
3. Compute the corresponding lift and drag coefficients
4. Estimate the drag coefficient from the downstream velocity distribution
5. Compare the lift and drag coefficients computed from the pressure distribution and velocity distribution to those obtained using the sting balance and understand the reason for their difference

7.2 Overview

7.2.1 Lift and Drag Coefficients from Pressure Force Measurements

An airfoil develops lift due to the fact that the pressure on the upper surface is lower than the pressure on the lower surface. The overall pressure distribution can be measured using holes or pressure taps in the surface of the wing that are connected to small tubes embedded in the wings. These small tubes are, in turn, connected to a suitable differential pressure transducer. A model of the Clark Y-14 airfoil has been equipped with pressure taps. The taps are located on the upper and lower surfaces at 0, 7.5, 10, 20, 30, 40, 50, 60, and 70 percent of the chord. There is an additional pressure tap at a distance of 80% of the chord from the leading edge on the upper surface.

The first step in determining the lift and drag is to break the pressure force up into its components normal to the chord ($F_{p,N}$) and parallel to the chord ($F_{p,c}$). Then the following equations can be applied to obtain the lift and drag forces:

$$F_L = F_{p,N} \cos\alpha - F_{p,c} \sin\alpha \tag{7.1}$$

$$F_L = F_{p,c} \cos\alpha - F_{p,N} \sin\alpha \tag{7.2}$$

where α is the angle of attack. The lift and drag coefficients are then calculated in the usual manner.

The pressure distribution normal to the chord is determined by plotting the pressures perpendicular to the chord at a position corresponding to the image of the pressure tap on the chord when viewed from above. The projected area per unit span for each of the pressure taps must also be determined. The pressure force on the upper and lower surfaces can then be determined by using an appropriate numerical integration technique, e.g., trapezoidal rule, Simpson's rule, etc. (see Holman (2001), pg. 267-271). The net pressure force normal to the chord, $F_{n,p}$ can then be determined by subtracting the pressure force per unit span on the upper surface from the corresponding value for the lower surface. The drag is determined from the pressure distribution by plotting the pressure distribution perpendicular to a line that is perpendicular to the chord at the image point of the pressure taps on the normal line. The projected area per unit span for each of the pressure taps must also be determined. The pressure force acting in the downstream and upstream directions and the net pressure force parallel to the chord, Fc, can be determined using the same approach as was used to determine the normal pressure force. Barlow *et al.* (1999) in Section 4.5 present a good discussion of this approach and show sample figures that are similar to the figures that are requested in the Results section.

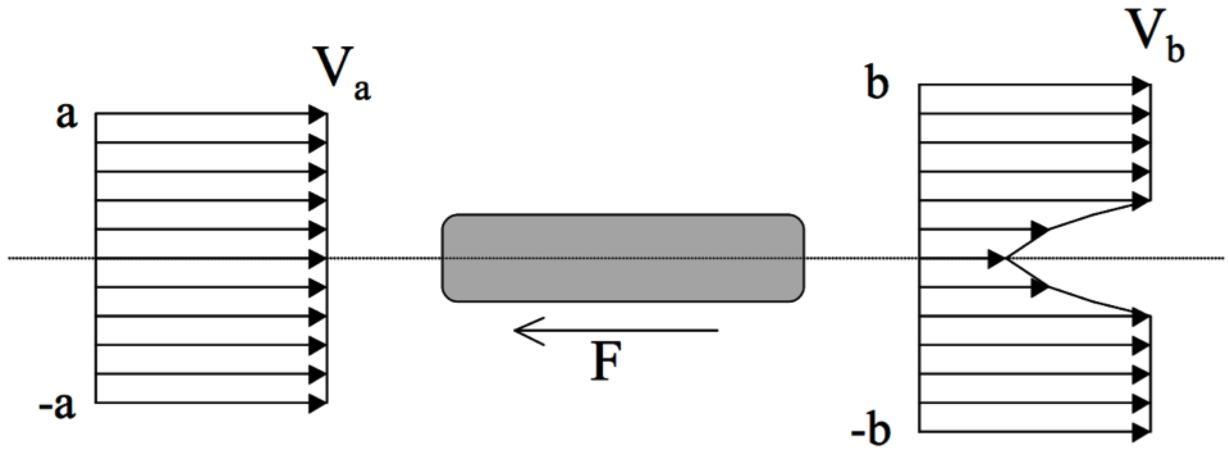

Figure 7.1: Momentum Deficit Method of Drag Measurement. Velocity versus position plotted upstream and downstream of the object. Drag force of object against the flow results in "momentum deficit" in flow stream downstream of the object. Note displacement of bounding streamlines.

7.2.2 Drag Coefficient from Velocity Distribution in the Wake

The drag on an object such as an airfoil can also be determined by measuring the velocity profile in the wake of the airfoil and then determining the momentum deficit. If the static pressure along the control volume is everywhere equal, it can be shown that, using the momentum equation

$$D = \int_{-a}^{a} s\rho U_\circ^2 dy - \int_{-b}^{b} s\rho U^2 dy \tag{7.3}$$

and thus that

$$C_d = \frac{D}{\frac{1}{2}\rho U_\circ^2 c} \tag{7.4}$$

The limits of integration (b) for the second integral in the momentum equation can be found in terms of the limits of the first integral (a) by applying the integral form of the steady state equation for conservation of mass, i.e.,

$$U_\circ a = \int_0^b U(y)dy \tag{7.5}$$

7.2.3 Anemometer Background- Principles of Operation

Heat Transfer

The principle of the hot-wire system is governed by the conservation of energy equation in that the velocity of the surrounding fluid is a measure of the electrical energy supplied to the wire balanced with the thermal energy transferred by forced convection. In general the heat losses from the wire due to radiation and conduction to the probe leads are neglected. Considering these simplifications, the conservation of energy is a function of the internal heat generated within the wire, power supplied to the wire, and the aerodynamic heat transfer by forced convection from the surface of the wire

$$\frac{d(\rho_w c_w T_w)}{dt} = I^2 R_w - \pi L d_w h(T_w - T_e) \tag{7.6}$$

which at steady state becomes

$$I^2 R_w = \pi L d_w h(T_w - T_e) \tag{7.7}$$

Through experimental correlation King found that his derived equation for heat transfer from a heated wire verified Boussinesq?s theory with the addition of a constant. It is important to notice that at high Reynolds number Boussinesq?s and King?s equations are identical.

$$q_{conv} = \overline{h}\pi d_w L(T_w - T_e) = L\left(k + 2\sqrt{\pi k c_p \rho u r_w}\right)(T_w - T_e) \tag{7.8}$$

$$Nu = \frac{\overline{h}d_w}{k} = \frac{1}{\pi} + \sqrt{\frac{2\ Re\ Pr}{\pi}} \tag{7.9}$$

King's Law was further developed by stating that all of the properties of the fluid, except the velocity and wire resistance, are a function of the stagnation temperature ($T_\circ$) such that the constants can be grouped together as follows:

$$E^2 = (IR_w)^2 = A + Bu^n \tag{7.10}$$

where n theoretically equals 0.5 but 0.45 better fits experimental data.

Control Circuit

For complacency of the heat transfer equations and the steady state approximation to hold true, it is required that the hot-wire anemometer system have a high frequency response from several hundred kHz to 1 MHz.

As fluid flows over the wire, convection occurs so that the wire is continuously being cooled and in response changes the resistance of the wire. To compensate for the convective cooling, the voltage supplied to keep the wire temperature constant increases. A bridge circuit is constructed internally such that the measured resistance of the probe and cable is

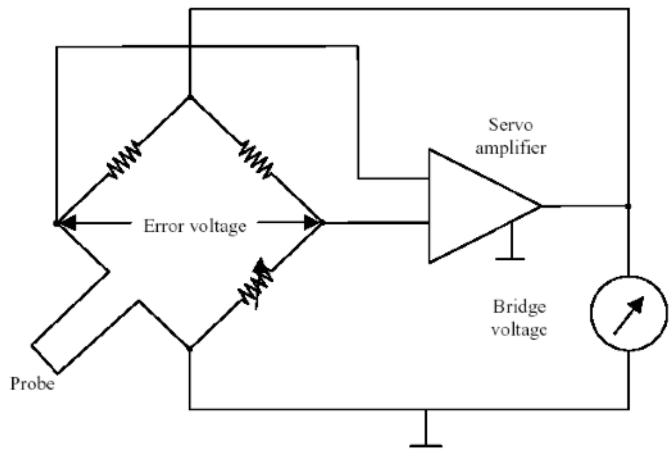

Figure 7.2: CTA Feedback System

set as the adjustable resistance value. A servo amplifier will compensate the bridge voltage so that the resistance of the lower two legs match. The change of resistance in the wire is stated to be proportional to the change in temperature. The change in voltage output across a hot-wire probe is interpreted as having a nonlinear relationship with the fluid velocity.

Incorporating the use of an oscilloscope, the voltage signal is conditioned by adjusting dampening trim-pots on the anemometer to filter out any noise associated with electrical circuitry or wire connections. Upon reduction of the data using King's Law, a measured velocity accuracy of 0.005% or greater may be obtained. Appendix A details the procedure for setting these conditions for a different CTA than the one used in the lab.

7.3 Procedure

7.3.1 Hot-wire calibration

1. The wind tunnel test section should be empty at the beginning of lab and ready for a hot wire calibration.

2. Install Pitot tube and connect to the Setra Pressure Transducer to measure dynamic pressure.

3. Open "NewMAE108Software.vi" Window

   (a) Turn wind tunnel on to 5 m/s

4. Load LabView Data Acquisition Program

(a) "Hotwire_experiment.vi"

(b) Turn on the CTA by plugging in the power cable

(c) Change the number of Samples to 2000 and the Sample Rate to 500 Hz to collect 5 seconds of data

5. The Sample Time is About 4 Seconds to Results Panel Display

   (a) Record output data to excel spreadsheet

      i. Dynamic pressure measurement (Run "NewMAE108Software.vi")

      ii. Channel 2 Voltage (anemometer) (Run "Hotwire_experiment.vi")

      iii. Note: Run one program at a time.

6. Repeat Steps 3-5 for Velocities 7,9,12,15, 20, 25, 30, and 35 m/s

   (a) NEVER TURN OFF THE WINDTUNNEL IF THE CTA IS ON

7. After all data is taken, turn the CTA off

8. Apply "King's Law" to Quantify the Relationship Between Voltage and Velocity using excel spreadsheet.

   (a) $E^2 = A + Bu^n$

   (b) $n = 0.45$

   (c) $E =$Voltage, $u =$Velocity

      i. Determine the velocity from the dynamic pressure

9. Plot the Square of the Anemometer Voltage Versus the Fluid Velocity to the Power of 0.45 in excel

10. Extrapolate the Calibration Coefficients A & B by Adding a Linear Best Fit Trend Line and Displaying the Associated Equation Using Excel

11. Use these coefficients to set up a table that will give you velocity from the voltage measured by the anemometer. (manipulation of King's Law).

12. The anemometer has been calibrated.

7.3.2 Pressure Force Measurements

1. Ask the TA to install the vertical airfoil

2. The wing model with the static pressure taps should be installed vertically in the wind tunnel. Make sure that the static pressure of the test section, p_∞, (the pressure at the upstream orifice ring at the exit of the contraction section, i.e., the wind tunnel taps) is connected to the reference or low-pressure side of the pressure transducer. Measurements are taken by connecting the numbered pressure taps to the high-pressure side of the transducer one at a time. The pressure output from LabView when one of the surface taps is connected on the high side of the pressure transducer is the difference between the static pressure upstream and the static pressure on the surface of the wing at that tap location, $p - p_\infty$. The pressure coefficient, C_p, is then computed as

$$C_p = \frac{p - p_\infty}{q} \tag{7.11}$$

   where $q = 1/2\rho V^2$ is the dynamic pressure (the dynamic pressure should not change throughout the experiment).

3. For these measurements, the tunnel should be operated at an air speed of 25 m/s in order to directly contrast to the results found in Experiment 3. Pressure measurements should be made at angles of attack of 0, 4, 8, and 20 degrees.

7.3.3 Wake Measurements

1. Dummy sensor is available to facilitate spatial measurements

2. Set the free stream wind tunnel velocity to the desired value using Pitot tube (25 m/s).

3. Traverse the Pitot tube across the front of the airfoil taking approximately 3-4 measurements of dynamic pressure. (This is your inlet velocity profile)

4. Remove the Pitot tube and do not change the tunnel velocity for the rest of the experiment.

5. Position the anemometer at a known location behind the airfoil and record the location indicated by the traverse's ruler (a good location would be on the chord line).

6. Measure the distance from the chord line of the airfoil to the hotwire.

7. You now have enough information to know where the anemometer is with respect to the chord line using the traverse's ruler.

8. Switch Over to the “New Read Force” Window.

9. Change the number of Samples to 5000 and the Sample Rate to 1000 Hz for 5 seconds of data

10. Move the anemometer probe to your desired first position

11. Set the CTA toggle switch to the Operate mode

12. Start taking data

13. Record the position measured by the transverse and the anemometer voltage reading (channel ?

14. Move the probe to a new location and retake data

15. When in the wake, be sure to take enough points to accurately survey the wake. Typically this would require at least 10 points, but more points will give better results. Outside the wake, points can have larger spacing (typically 1-2 cm)

16. After you finish profiling the wake change angel of attack and repeat steps 2-15 for angles 4, 8, and 20 degrees.

17. When finished with experiment turn CTA off **BEFORE** you turn off the wind tunnel

7.4 Results

7.4.1 Specific Plots

1. Plot the pressure coefficient to a suitable scale at the pressure tap locations on an outline of the Clark Y-14 airfoil. (The airfoil can be drawn using the spreadsheet program and entering corresponding values for the $x-y$ locations of the airfoil surface.) Label two of the pressure values on the upper surface near the leading edge and one near the maximum thickness point.

2. On a separate graph, plot the pressure coefficient normal to the chord, $C_{p,N}$, for both the upper and lower surface, where $C_{p,N} = \frac{F_{p,N}}{qc}$. Label the pressure values of the coefficient of pressure for the upper surface and a dashed line for the values on the lower surface. Use the NACA report for the Clark Y-14 airfoil to obtain the requisite geometric information.

3. On a third graph, plot the pressure coefficient parallel to the chord, $C_{p,c}$, where $C_{p,c} = \frac{F_{p,N}}{qc}$. Label the pressure values you labeled on the first plot and use a solid line to connect the values of the pressure coefficient for the upper surface and a dashed line for the values on the lower surface.

4. Perform steps 1-3 for 0, 4, 8, and 20 degrees. **IMPORTANT: See Figure 4.23 of Barlow *et al.* (1999) for examples of how these plots should be presented.**

5. Next, apply the numerical integration techniques and equations discussed herein to compute the section lift and drag coefficients for angle of attack of 0, 4, 8, and 20. Compare and plot these values with the corresponding data that you generated in Experiment 3 and to the NACA Clark Y-14 data (Report No. 628).

6. On the plot from step 5 above, show the drag coefficient points determined from the downstream wake measurements.

7.4.2 Specific Questions

1. What is the uncertainty in your computed lift and drag coefficients for as computed from the pressure force measurements?

2. What is the uncertainty in your computed drag coefficient for as computed from the wake velocity profile measurements?

3. What happened to the wake velocity profiles as you changed the angel of attack of the airfoil? Why?

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