

Measurement of Pressure Distribution and Forces Acting on an Airfoil

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1. Purpose

The experiment objectives are to measure the surface pressure distribution, lift and drag forces, and velocity distribution in the wake of a Clark-Y airfoil set at various angles of attack and to compare the results, including their uncertainties, with benchmark data. The experiment also introduces students to concepts related to digital acquisition systems: calibration, noise, settling time, and sampling time.

2. Experiment Design

The geometry and forces acting on a generic airfoil in a constant flow field (U_∞) are shown in Figures 1a and 1b. The experiments are conducted using a Clark-Y airfoil mounted in the test section of a closed circuit open test section vertical return wind tunnel (Figure 2). The tunnel enables measurements for turbulent flows up to $Re = 500,000$. ($Re = U_\infty c / \nu$, where U_∞ is the free-stream velocity in the tunnel, c is the airfoil cord length, and ν is the kinematic viscosity of air). It has four 90° corners equipped with vanes, two diffusers, a contraction section, test section and fan. The vanes, settling chamber and contraction section help in achieving a uniform flow in the test section.

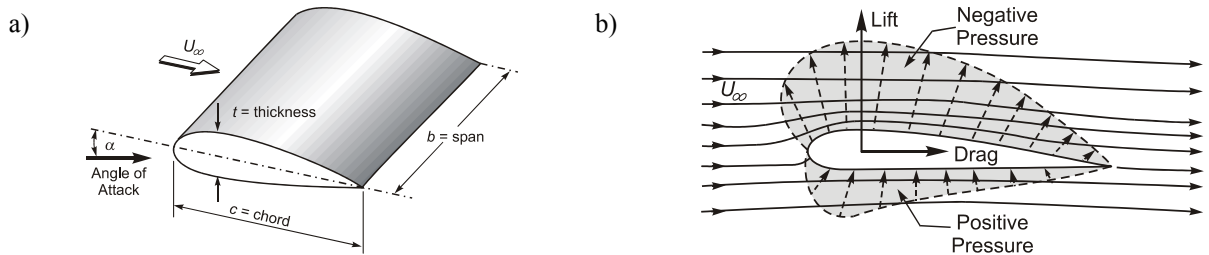


Figure 1. Airfoils characteristics: a) geometry; b) hydrodynamics

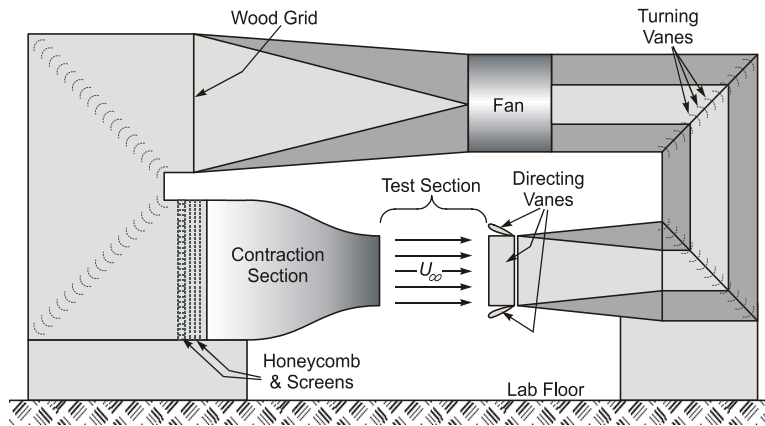


Figure 2a. Layout of the open test section wind tunnel

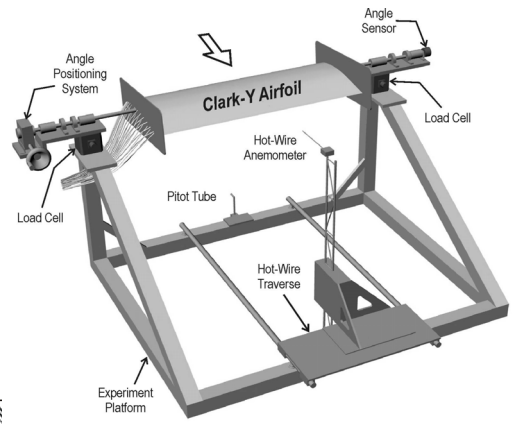


Figure 2b. Schematic of the airfoil showing different components of the measurement systems

The tunnel's closed circuit is approximately 18.3 m long. The test section is a 0.76 m by 0.76 m square, 1.52 m long. A resistance temperature detector and a Pitot tube are placed upstream in the upper half of the test section to control the temperature and free stream velocity, respectively. The pitot tube is connected to a pressure transducer along with a digital display for visualization of experimental conditions. Another pitot tube, placed at the bottom half of the test section, is connected to a Rouse manometer for demonstration purposes (see Figure 2.c). A hotwire is also placed

downstream of the airfoil for measuring velocities profile in the wake of the airfoil. A Clark-Y airfoil was selected for the experiment because it exhibits good aerodynamic performance over a wide range of Reynolds numbers and also since there is abundant benchmark data available for comparison. The geometry of the Clark-Y airfoil and the positioning of the pressure taps used in the experiment are illustrated in Figures 3.a and 3.b, respectively. Positioning of the airfoil at various angles of attack is made with a hand wheel connected to a digital display. The airfoil is set on a pair of load cells that measure the overall forces (lift and drag) acting on the airfoil (see Figure 3.a and 3.c). An overall view of the system is provided in Figure 3.a.

Data acquisition is conducted with an Automated Data Acquisition System (DA), as shown in Figure 3.c. DA is controlled and interfaced by LabView software described in Appendix B. DA contains several measurement modules: tunnel controls, pressure measurements, force measurements. The pressure distribution around the airfoil is obtained by 28 pressure taps connected through tygon tubes to the ports of a scanning valve that sequentially senses the pressures at various airfoil locations. Pressures sensed by the scanning valve are measured by a differential pressure transducer that has one port connected at all times to the pressure measured in the free stream (p_∞), while the other port is connected to the scanning valve output port. The load cell is calibrated prior to the experiment to obtain the relationship between forces acting on the airfoil and voltage output from the load cells' strain gages.

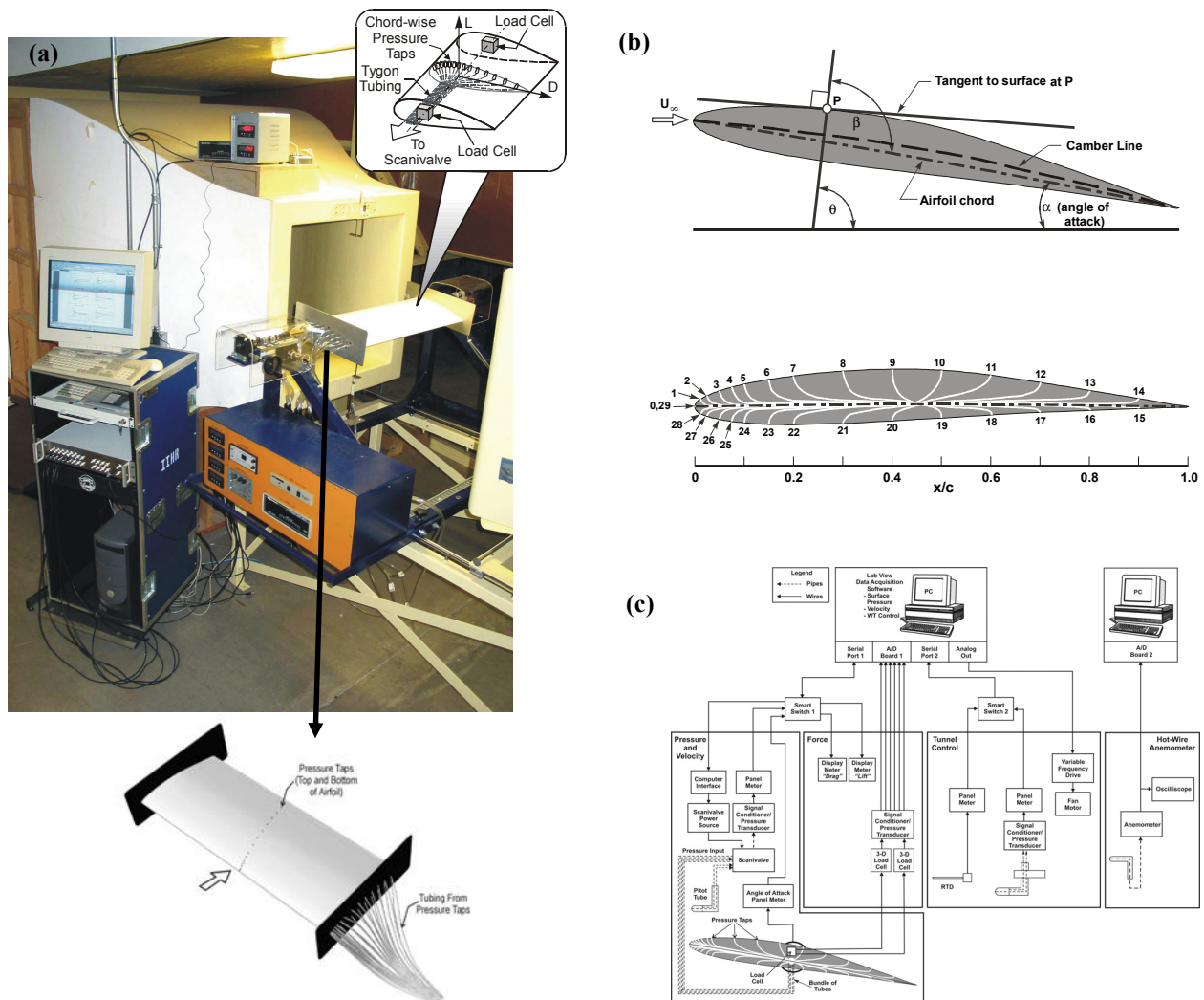


Figure 3. The experimental layout: a) photograph of the test section and instrumentation; b) the geometry of the Clark-Y airfoil; c) DA components

2.1 Data reduction (DR) equations

The measured variables are the test section air temperature, free stream velocity, pressure distribution around the airfoil, and the lift and drag forces acting on the airfoil. Using these measurements, the pressure coefficient, C_p , and the lift coefficient, C_L , for the airfoil are obtained. The data reduction equation for the pressure coefficient, C_p , is given by:

$$C_p[p_i, p_\infty, \rho, U_\infty] = \frac{2(p_i - p_\infty)}{\rho U_\infty^2} \quad (1)$$

where, p_i is the static pressure at any pressure tap on the airfoil surface, p_∞ is the free stream pressure (measured on the Pitot static port), ρ is air density, and U_∞ is the free-stream velocity given by

$$U_\infty = \sqrt{\frac{2(p_{stagn} - p_\infty)}{\rho}} \quad (2)$$

where, p_{stagn} is the stagnation pressure measured at the tip of the Pitot tube placed at the upper half of the test section. The data reduction equation for the lift coefficient, C_L , is given by

$$C_L[L, \rho, U_\infty, b, c] = \frac{2L}{\rho U_\infty^2 bc} \quad (3)$$

where, L is the lift force acting on the airfoil surface, b is the airfoil span, and c is the airfoil chord (as shown in Figure 1.a). The lift force can be obtained in two ways. By integrating the measured pressure distribution over the airfoil

$$L = \int_s (p_i - p_\infty) \sin(\theta_i) ds \quad (4)$$

where, θ_i is the angle of surface normal to free-stream flow at each of the pressure taps (Fig 3b), as specified in Appendix A. The data reduction equation for the drag coefficient C_D is given by

$$C_D[D, \rho, U_\infty, b, c] = \frac{2D}{\rho U_\infty^2 bc} \quad (5)$$

Alternatively, both the lift and drag forces can be directly measured with the load cell using the following calibration equation

$$L = 9.81(A_1 \cdot V + B_1) \quad (a); \quad D = 9.81(A_2 \cdot V + B_2) \quad (b) \quad (6)$$

where, A and B are calibration coefficients, V is the load cell voltage output, and M is the calibration load mass.

3. Experiment Process

3.1. Test Setup

The experiment measurement system comprises: the wind tunnel, the airfoil, and the DA (see Figure 3). The DA acquires measurements velocities and temperature in the test section, pressures on the surface of the airfoil, forces on the airfoil, velocity profile in the wake, and the angle of attack. Before taking the measurements there are several preparatory operations:

Load cell operation

- Install the model in the test section and set it to zero angle of attack.
- Calibrate the load cell. The load cell measures three force components, i.e., F_x (the drag force), F_y and F_z (the lift force). Calibrations are only conducted for lift and drag forces. For this purpose, a series of six loads (from 0 to 1.635 kg) are successively applied to a special calibration frame, as demonstrated by the TA. Open the calibration software and follow the instructions as specified in Step 1, Appendix B. Using the software, plot the measurements and calculate the calibration coefficients by applying a linear regression to the measured data. Obtain force measurements for two angles of attack: 1) 0° and 2) 6° , 13° , or 16° .

Pressure transducer operation

- Remove the airfoil from the test section and set the target flow conditions in the tunnel test section. $Re = 300,000$ (15 m/s free stream velocity) is recommended for the experiment to compare results with the available benchmark data. Open the software for pressure and force measurements and follow the steps indicated in Step 2, Appendix B.
- With the wind tunnel speed set at 15m/s, place the airfoil back on its mount and set the angle of attack to 0° .
- Additional software is used, as demonstrated by the TA, to demonstrate the effect of the noise of DA (a residual signal in the DA recordings, that collectively represents the electronic noise, digitization effects, and other uncontrolled environmental parameters and the effect of the digitization levels (the resolution with which the DA converts the analog to digital signal).

- Two important data acquisition parameters are established using another set of software interfaces. Specifically, the settling time (needed for the DA to recover after changing its setting from a pressure tap to the next one is determined.) and the sampling time (the length of time needed for a measurement to capture the actual mean value of a turbulent – fluctuating – quantity) are explained as indicated by the TA.
- Repeat pressure measurements for an angle of attack of 6° , 13° , or 16° .

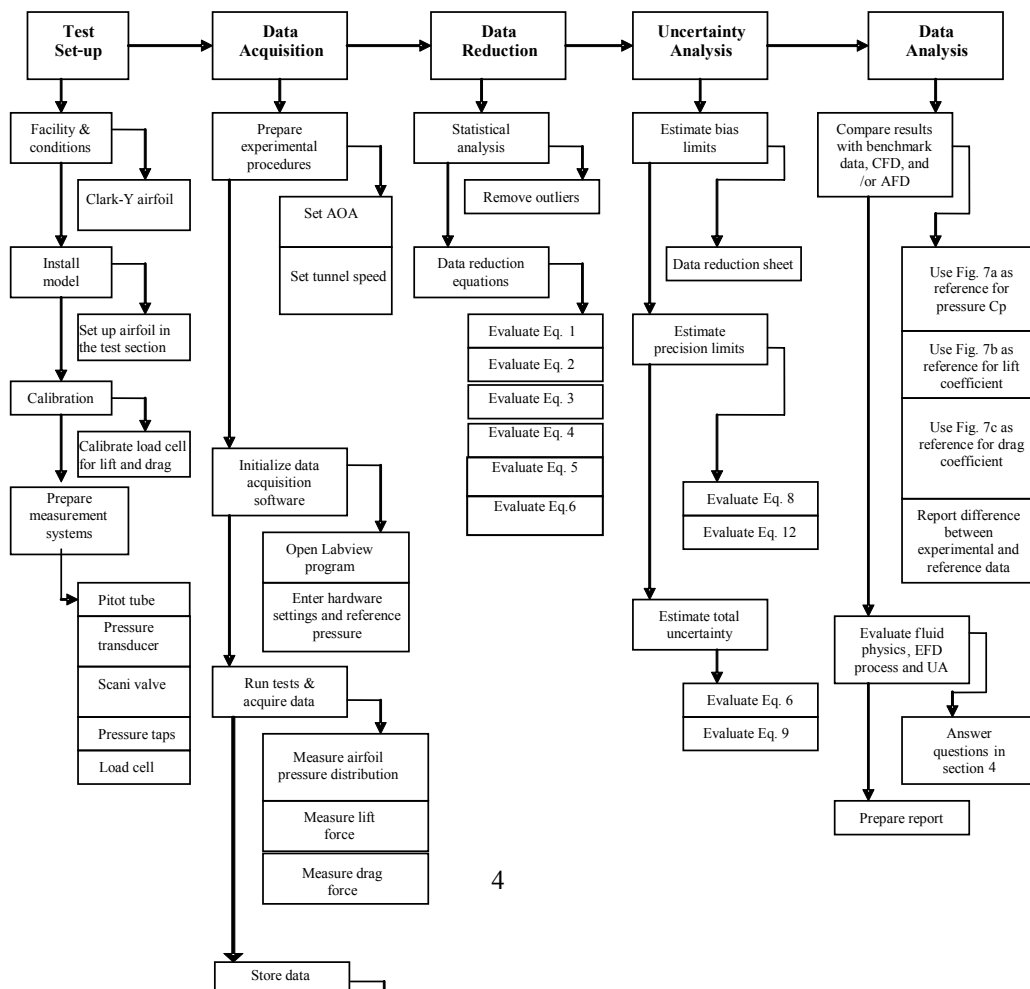
Hot-wire operation

- Make sure the output of hot-wire probe is connected to the correct DA channel and open the DA software. Record the velocity in the wake of the airfoil starting with the velocity in the center of the wake. Continue taking velocity measurements above and below the center of the wake, in increments of 1, 2, 3, 4, 5, 10, 15, and 20 cm. See Step 5 in Appendix B for additional details. Obtain velocity profile for two angles of attack: 1) 0° and 2) 6° , 13° , or 16° .

3.2. Data Acquisition

The data acquisition steps are listed below:

1. Install the airfoil, and calibrate the load cell for both lift and drag forces.
2. With the flow and angle of attack set to the desired values open Labview and follow the procedure in Step 3 of Appendix B. Enter the values of the settling and sampling determined above in the software interface. Measure the pressure distribution around the airfoil and the free-stream velocity. The DA software outputs the averaged measured pressure and graphically displays the measurements as they are collected. Note that the input connections to the scanning valve are as follows:
 - a. Ports 0 to 28 are connected to the corresponding pressure taps located on the airfoil (see Figure 3.b).
 - b. Port 40 is connected to the Pitot-static tube to measure the stagnation pressure.
3. Measure the lift and drag forces using the load cell. Maintaining the same flow conditions as above, open Labview program for load cell data acquisition and follow the guidelines specified in Step 4 of Appendix B. The software records the voltage output from the load cells. These voltage values are converted to forces using the calibration equation (Equation 6) and the established calibration coefficients.
4. Measure the velocity profile in the wake of the airfoil with the hot-wire anemometer. Establish a datum for which to reference elevation of hot-wire probe. Record velocity in intervals of 0, 1, 2, 3, 4, 5, 10, 15, and 20cm above and below datum.



3.3 Data Reduction

A spreadsheet will be provided for the data reduction. Data reduction includes calculation of the following quantities:

1. Calculate C_p for all 28 pressure taps.
2. Calculate Lift force and corresponding C_L value on the airfoil obtained by integrating the measured pressure over the airfoil surface.
3. Calculate Lift force and corresponding C_L value on the airfoil obtained from load cell.
4. Calculate the Drag force and corresponding C_D value on the airfoil obtained from load cell.
5. Calculate the Drag force and corresponding C_D value on the airfoil obtained from hot-wire velocity.
6. Perform Steps 1. through 5. again for an angle of attack of 6° , 13° , or 16° .

3.4. Uncertainty Assessment

Uncertainties for the experimentally measured pressure and lift coefficients will be evaluated. The methodology for estimating uncertainties follows the AIAA S-071 Standard (AIAA, 1995) as summarized in Stern et al. (1999) for multiple tests (sections 6.1 and 6.3). The block diagram for error propagation to the final results are provided in Figure 4. Based on previous experiments, it was found that bias and precision limits for the ρ , U_∞ , θ , s , and c are negligible, hence for the present analysis only include the bias limit for $p_i - p_\infty$. The spreadsheet provided for calculating the experimental uncertainties contains bias and precision limit estimates for the individual measured variables based on experiments.

The data reduction equation for the pressure coefficients (Equation 1) is of the form, $C_p = f(p_i - p_\infty, \rho, U_\infty)$. We will however, only consider bias and precision limits for $p_i - p_\infty$ (see uncertainty analysis spreadsheet). Note that the uncertainty assessment does not include error sources such as pressure lag exceeding the data acquisition delay time, undetected leaks in the pressure tubing, model orifice effects, vibration effects on the probes, unsteady flow effects, undetected leaks in the scanning valve, and positioning of the traverse at the location of the measurements.

The total uncertainty for the pressure coefficient measured at each pressure tap is given by equation (24) in Stern et al. (1999)

$$U_{C_p}^2 = B_{C_p}^2 + P_{C_p}^2 \quad (7)$$

The bias limit in Equation (7) is the same for taps and is given by equation (14) in Stern et al. (1999). Neglecting the correlated bias limits and discarding the terms with negligible bias limit

$$B_{C_p}^2 = \sum_{i=1}^j \theta_i^2 B_i^2 = \theta_{(p_i - p_\infty)}^2 B_{(p_i - p_\infty)}^2 \quad (8)$$

where, B_i is the bias limit for the individual variable and $\theta_i = \partial C_p / \partial X_i$ is sensitivity coefficient. The sensitivity coefficient $\theta_{(p_i - p_\infty)}$, is evaluated using the average values for the individual variables, is given by

$$\theta_{(p_i - p_\infty)} = \frac{\partial C_p}{\partial (p_i - p_\infty)} = \frac{2}{\rho U_\infty^2}$$

The precision limit for each pressure tap in Equation (7) was estimated using equation (23) in Stern et al. (1999)

$$P_{C_p} = 2S_{C_p} / \sqrt{M} \quad (9)$$

where S_{C_p} is the standard deviation of the pressure coefficients at each pressure tap evaluated using equation (22) in Stern et al. (1999) for the $M = 10$ repeated tests. Precision limits will have different values for each of the 28 taps.

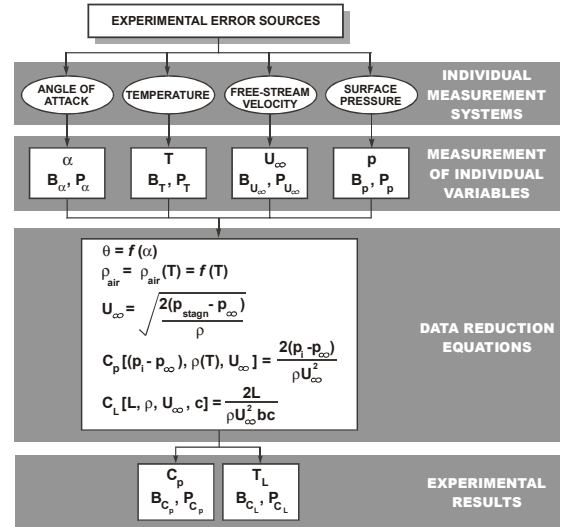


Figure 4. Block diagram showing propagation of error through data reduction equations

However, for this experiment, the precision limit will be calculated only at tap 0. Pressure measurements at tap 0 will be repeated 10 times.

The data reduction equation for the lift coefficient (Equation 3) is of the form $C_p = f(p_i - p_\infty, \theta, s, \rho, U_\infty, c)$. We will only consider bias limits for $p_i - p_\infty$ (see data reduction spreadsheet). The total uncertainty for the measurement of the lift coefficient is given by (equation 24 in Stern et al., 1999)

$$U_{CL}^2 = B_{CL}^2 + P_{CL}^2 \quad (10)$$

The bias limit in equation (10) is given by equation (14) in Stern et al. (1999). Neglecting the correlated bias limits and the terms assumed with negligible bias limits

$$B_{CL}^2 = \sum_{i=1}^j \theta_i^2 B_i^2 = \theta_{(p_i-p_\infty)}^2 B_{(p_i-p_\infty)}^2 \quad (11)$$

Given the above assumptions and using the lift force determined by integration (Equation 4), the expression for the bias limit of the lift coefficient is

$$B_{CL}^2 = B_{(p_i-p_\infty)}^2 \sum_{i=1}^k \left[\frac{\partial C_L}{\partial (p_i - p_\infty)} \right]^2 = \left[\frac{B_{(p_i-p_\infty)}}{0.5 \rho U_\infty^2 c} \right]^2 \sum_{i=1}^k [\sin(\theta_i) ds_i]^2 \quad (12)$$

Notations used in equation (12) are defined in Table 1 and Appendix A ($k = 29$).

The precision limit in Equation (10) was estimated using equation (23) in Stern et al. (1999)

$$P_{CL} = 2S_{CL} / \sqrt{M} \quad (13)$$

where, S_{CL} is the standard deviation of the lift coefficients evaluated using equation (22) in Stern et al. (1999) for the $M = 10$ repeated tests. Based on previous measurements, an average value for the precision limit will be provided in the uncertainty analysis spreadsheet.

4. Data Analysis

Data analysis includes the following steps as shown below. Use **Data reduction sheet** for all calculations and **attach** it along with your lab reports. The data analysis section of the lab report **must** include the answers to all 6 questions given below.

1. If the lift L is a function of the free-stream velocity U_∞ , density ρ , chord c , angle of attack α , and viscosity μ , what are the dimensionless groups (π parameters) that characterize this problem?
2. How do the experimental measurements of the pressure distribution apply to a full-scale aircraft having a similar airfoil section?
3. Include the **calibration plots for both lift and drag** along with your lab report. The plots should have Voltage on the x-axis and Mass on the y-axis, and should include the calibration equation. The following figure shows an example plot for lift calibration. The drag calibration should be made the same way.

Mass [kg]	Lift [V]
0	-0.0181
0.295	-0.0901
0.415	-0.1197
0.765	-0.2059
1.31	-0.3371
1.635	-0.415

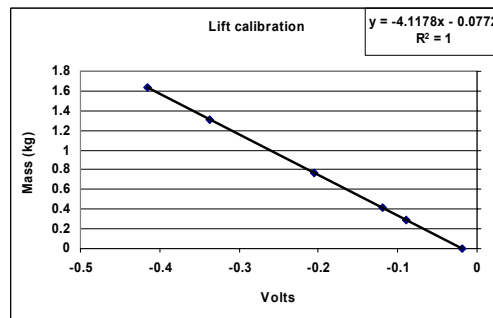


Figure 5. Load cell calibration curve

4. Plot **Cp versus x/c** for the angle of attack that you have chosen for your experiment. Plot the benchmark data (figure 6a) corresponding to the same angle of attack on the same graph. Show the calculated uncertainty for C_p at the tap number where precision limits were performed, using an **uncertainty band**. Indicate the **percentage of uncertainty** on the graph. Example plots are given in the **data reduction spreadsheet**.

- Compare the results for C_L obtained from **both pressure distribution and load cell** with the benchmark data. **Figure 6b** shows the benchmark data for C_L , and the coordinates are given in **data reduction sheet**.
- Compare the results for C_D obtained from **load cell and hot-wire probe** with the benchmark data. **Figure 6c** shows the benchmark data for C_D , and the coordinates are given in **data reduction sheet**.
- Discuss the relationship between the output voltage of the hot-wire anemometer and velocity based on the equation provided below.

$$\text{Velocity[m/s]} = 6.568 \times \text{Volts} - 12.86$$

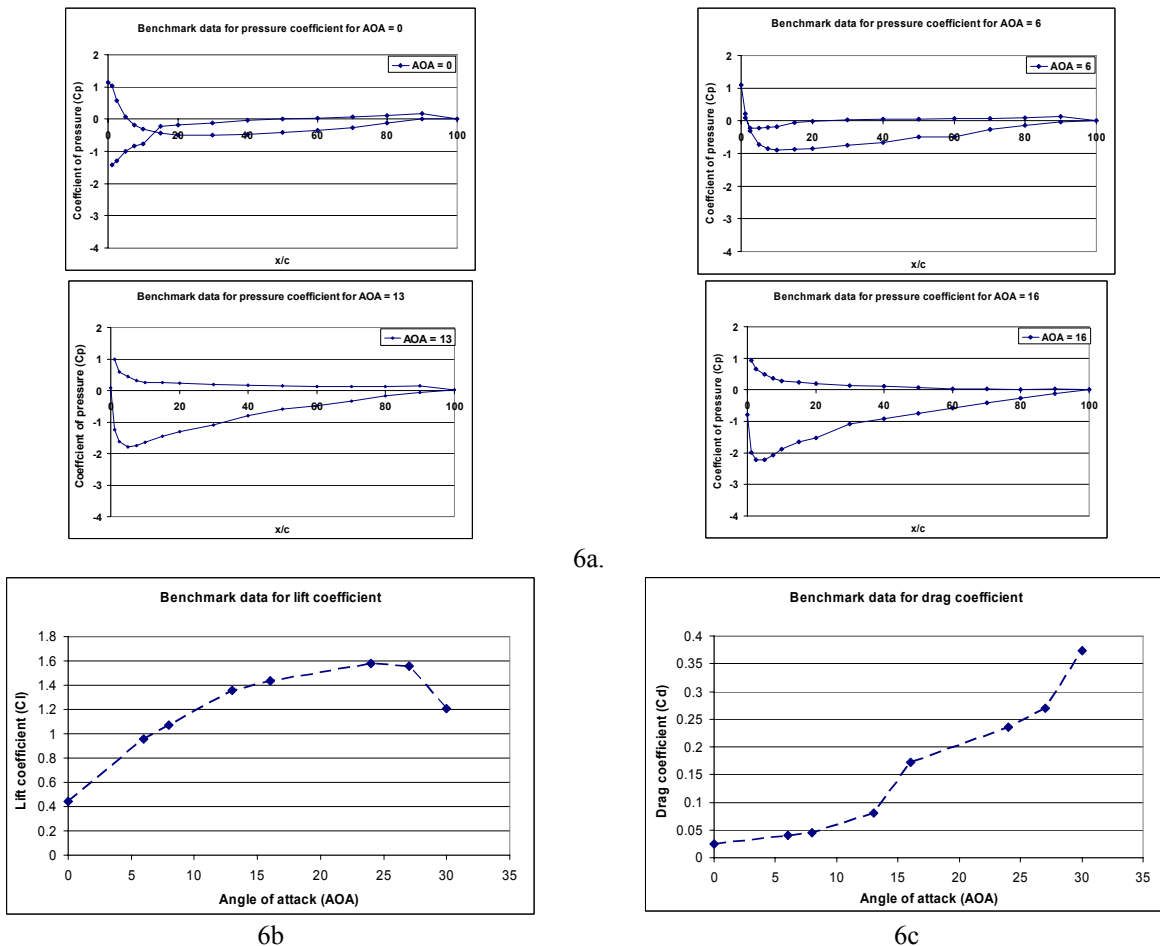


Figure 6. Reference data at Reynolds number 300,000; a) Distribution of the pressure coefficients for $\alpha = 0^\circ, 6^\circ, 13^\circ,$ and 16° b) Variation of the C_L with the angle of attack c) Variation of C_D with angle of attack

5. References

- AIAA (1995). *AIAA-071 Standard*, American Institute of Aeronautics and Astronautics, Washington, DC.
- Granger, R.A. (1988). *Experiments in Fluid Mechanics*, Holt, Rinehart and Winston, Inc. New York, N.Y.
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- Stern, F., Muste, M., Beninati, L-M., Eichinger, B. (1999). Summary of Experimental Uncertainty Assessment Methodology with Example, IIHR Report, Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City, IA.
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APPENDIX A
SPECIFICATIONS FOR THE EXPERIMENTAL FACILITY COMPONENTS

The relevant geometrical notations are provided in Figure 3.b. The positioning of the pressure taps on the airfoil surface is also specified in Figure 3.b.

Airfoil Geometry:

- maximum thickness, $t = 0.0254$ m;
- airfoil wing span, $b = 0.762$ m;
- chord length, $c = 0.3048$ m

Angle notations:

- surface to chord line angle, β ;
- angle of surface normal to free- stream flow, θ ;
- angle of attack, α .

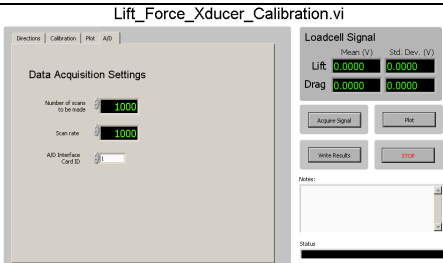
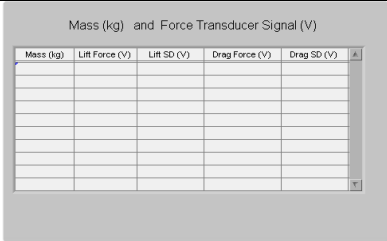
The numerical values for the airfoil relevant geometrical characteristics are provided in the table to the right. These values are also provided in the **data reduction sheet**. Lift force can be computed using the trapezoidal scheme for the numerical integration

$$L = \int_s (p_i - p_\infty) \sin(\theta_i) ds$$

$$\approx \sum_i \frac{1}{2} [(p_i - p_\infty) + (p_{i-1} - p_\infty)] \sin(\theta_{i-1,i}) \Delta s_{i-1,i}$$

N Tap Number (i)	x/C	Δs Surface Element Length (mm)	β Surface (i-1) - (i) to Chord Line Angle (degrees)
0	0.00	8.0	209.0
1	1.25	6.0	160.7
2	2.50	6.0	136.2
3	5.00	9.0	115.8
4	7.50	9.0	107.3
5	10.00	8.0	102.6
6	15.00	15.5	100.1
7	20.00	15.5	97.1
8	30.00	30.0	93.2
9	40.00	30.0	89.8
10	50.00	30.0	86.7
11	60.00	31.5	83.9
12	70.00	31.5	81.9
13	80.00	31.5	81.1
14	90.00	31.5	79.7
Trailing Edge	100.00	30.0	78.6
15	90.00	29.0	272.4
16	80.00	31.0	272.4
17	70.00	31.0	272.4
18	60.00	31.0	272.4
19	50.00	31.0	272.4
20	40.00	30.0	272.4
21	30.00	30.0	272.4
22	20.00	30.0	272.4
23	15.00	15.5	272.4
24	10.00	15.5	272.4
25	7.50	7.5	272.4
26	5.00	9.0	265.5
27	2.50	6.0	253.4
28	1.25	4.5	241.0

APPENDIX B
THE AUTOMATED DATA ACQUISITION SYSTEM (ADAS)

Step 1: Calibration of Load Cell	
<p>a. Getting started with the calibration of load cell. Double click on the program Lift_Force_Xducer_Calibration.vi from the ADAS shortcut and open the calibration program.</p>	 <p style="text-align: center;">Figure B.1</p>
<p>b. From the main menu select Calibration. A table shown in the right cell will pop up showing the mass (kg) versus lift and drag forces (Volts). Hit Run to start the program and click on Acquire Signal. Keep increasing the weights on the Load cell as directed by the TA and keep acquiring data to obtain the linear regression. The data recorded can be seen on the table.</p>	 <p style="text-align: center;">Figure B.2</p>

c. Select and click on the **Plot** tab from the main menu. The linear calibration curve between the loading mass and the output voltage can be observed once you hit the **Plot** button on the **Load cell Signal** as shown in Figure 1.

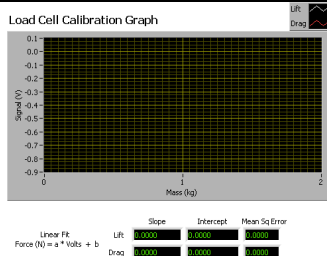


Figure B.3

d. Click on **Write Results** from the **Load cell Signal** box and the recorded data will be written to an output text file that will be used later to convert the signal from Volts to Newtons.




Figure B.4

Step 2: Setting up Wind Tunnel Conditions

a. Once the calibration is complete, the next step is to switch on the wind tunnel. The wind tunnel desired speed is controlled using the program shown in Figure 5. Open the program **VWT_Set_Motor_Speed.vi** from the ADAS. Click **Run** button on the program.

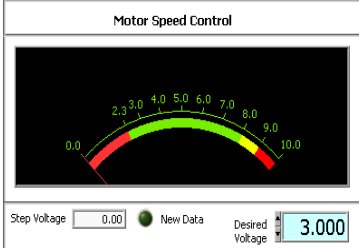


Figure B.5

b. Open program **VWT_Tunnel_Velocity.vi** and hit **Run** after inputting the atmospheric pressure in mm of Hg in the **Ambient Pressure** box. The wind tunnel velocity is displayed on the lower left hand corner of the main page. Adjust the speed on the tunnel by adjusting the **Desired Voltage** as shown in Figure 5. Once the wind tunnel velocity is set at the desired level proceed to step 3.

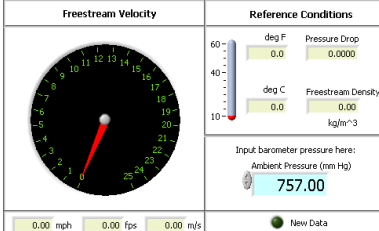


Figure B.6

Step 3: Measurement of pressure distribution

a. Open program **VWT_Scanivalve_Data_Acquisition.vi**. Select the **Ref Cond** tab from the main menu. Enter the values of manometer fluid density and the ambient absolute pressure in the two boxes as shown in Figure 8.

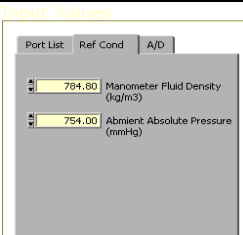


Figure B.7

b. After entering the density and pressure values, select **Port List** tab from the main menu. Enter the pressure tap numbers in the order they are required to be scanned as shown in Figure 9. Click on the **Run** button to start scanning the pressure taps.

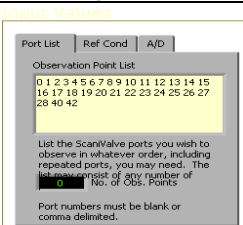


Figure B.8

Step 4: Lift force measurement

c. Open program **ATMI_Load_Cell_Test.vi** and click **Run**. The instantaneous lift force will be displayed on the **Lift** graph. The display shows the force in terms of volts, which can be converted to Newtons using the calibration curve. Once the force is noted click on the **STOP** button.

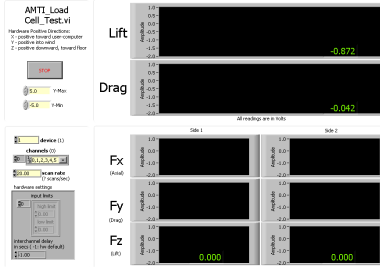


Figure B.9

Step 5: Hot-wire measurement

c. Open **hot_wire_daq.vi**. Verify that both channel fields depict the value of cable input. Set **number of scans** to 15,000 and **scan rate** to 1000. Press **run** to acquire mean velocity and standard deviation.

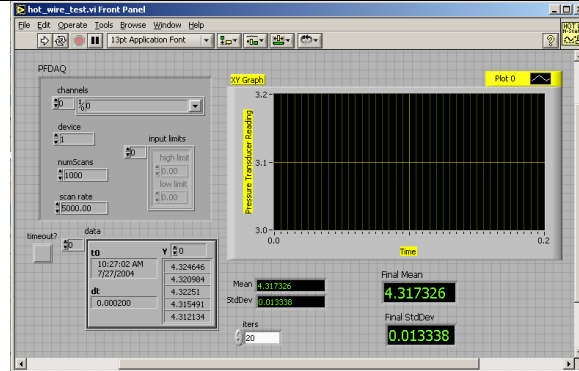


Figure B.10

d. For an angle of attack of 0° , establish a datum in the vertical direction by placing the hot-wire probe directly behind the airfoil and align the tail of the airfoil and the probe on the same horizontal plain. Survey the velocity in the wake by taking velocity measurements at elevations of 0, 1, 2, 3, 4, 5, 10, 15, and 20 cm above and below datum