THE UNIVERSITY OF TEXAS AT ARLINGTON
DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

MAE 3182:

Measurement of Aerodynamic Forces on a NACA 0012 Airfoil

Version - Spring 2022

I. Learning Objectives

- Pressure measurements using a differential pressure scanner
- Pressure measurements using an analog barometer
- Use pressure taps on the airfoil to calculate the lift and drag on a body
- Computer-based pressure measurement
- Methods for data reduction
- Analog-to-digital conversion
- Practical applications of a data acquisition system (DAQ)

II. Equipment

- PC with external data acquisition system – Dell PC with Esterline DTCNet DAQ
- 32 ports pressure scanner – Pressure Systems ESP-32HD
- Pitot tube – Custom made
- Unislide – Velmex Inc. MA4039W1-S6
- Digital encoder read out – Velmex Inc. QC110-AR
- Stepper controller – Velmex Inc. VXM-1
- NACA 0012 airfoil equipped with 20 pressure taps – Model AF102, TecQuipment Ltd.
- DTCNetX interface and EXCEL software
- Low-speed wind tunnel, Model AF100, TecQuipment Ltd.

III. Introduction

Wind tunnels, in conjunction with the appropriate scaling laws, attempt to replicate the actual aerodynamic environment encountered in flight through subscale testing. Virtually every aircraft and component in operation is the result of an extensive development process based on wind tunnel testing. The Wright brothers' first successful flight was largely due to their efforts in conducting high-quality wind tunnel tests of their wing designs. Although aircraft design and performance can be developed to a certain extent using computational fluid dynamics (CFD) codes, wind tunnel confirmation of the numerical prediction is fundamental. Wind tunnel flow qualities such as uniformity and a low turbulence level are critical. The wind tunnel in WH221 is an open-circuit tunnel, where a downstream fan draws air in through a large bell-mouth inlet. The design of a wind tunnel is centered on maintaining flow uniformity and low free-stream turbulence levels. The methods and techniques adopted to achieve this goal are discussed and analyzed in the theoretical lectures provided as part of this course.

The focus of this lab is to measure and calculate lift, drag and pitching moment of a symmetric NACA 0012 airfoil by using pressure measurements along the airfoil surface.

IV. Theory

The capability of measuring/calculating the aerodynamic forces and moments acting on airfoils/wings in wind tunnel facilities is the starting point for the performance characterization of every flying vehicle. This lab experiment has the main objective of characterizing a wing built on a NACA 0012 airfoil in terms of Lift, and Drag for different angles of attack (AOA).

a. Drag and lift calculation by using measured pressure distribution

The calculation of lift and drag for an airfoil requires projecting the surface forces acting on the airfoil along the x-axis and y-axis (wind axis in Fig. 1), respectively.

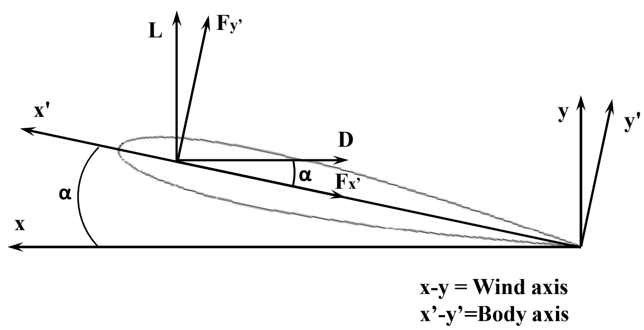
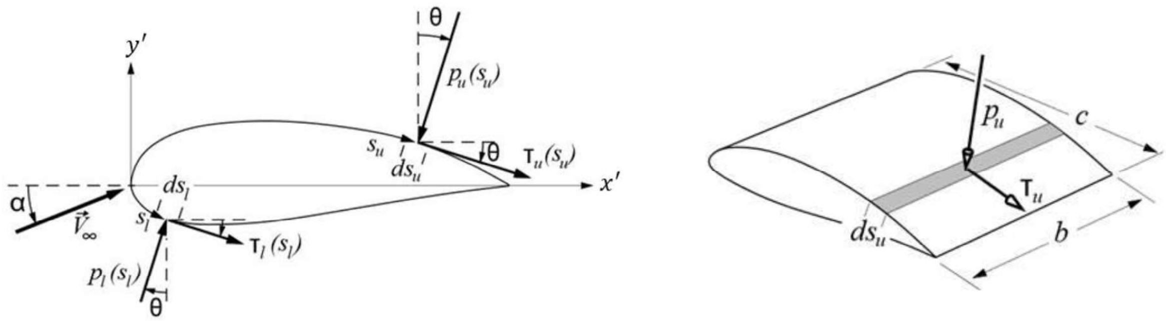


Figure 1. Nomenclature used for the reference systems.

Where, α is the AOA, $F_{y'}$ is the normal force and $F_{x'}$ is the axial force. The surface force is a contribution of both the pressure and shear distribution over the entire surface of the airfoil. Fig. 2 depicts these distributed aerodynamic loadings in the airfoil body reference frame and the resultant local forces over a differential strip of surface area spanning the wing.



(a) (b)

Figure 2. (a) Nomenclature used for the integration of forces in the body reference frame and (b) resultant force acting over elemental area of wing.

Lift (L) and Drag (D) is therefore calculated by integrating the elementary forces (both pressure and shear) along the entire wing surface. Of course, to carry out the integration and determine Lift and Drag, we must know the body shape and the distributions of wall shear-stress and pressure along the surface. The pressure distribution can be obtained experimentally by use of a series of static pressure taps along the body surface. On the other hand, it is usually very difficult to measure the wall shear stress distribution (How would you do it?). Hence, the contribution of shear stress along the surface will not be accounted for in the forgoing analysis or results. The total force that the pressure generates on the airfoil is reported in Eq. (1) after neglecting the shear forces on the surface.

$$\vec{F} = \oint -(P \cdot \hat{n})\, dS \tag{1}$$

In particular, let us consider the elementary pressure force acting on the airfoil for the body reference axis (Fig. 2). The local pressure, which is normal to the surface, is oriented at an angle relative to the perpendicular (ϑ in Fig. 2a) accordingly to the local slope of the profile. The sign convention for ϑ is usually positive when measured clockwise [5] from the y' axis to the direction of P. The angles in Fig. 2a are shown all positive. The body axis components of pressure force acting on the airfoil are shown in Eq. (2).

$$\begin{cases} dF_{y'} = \left(d\vec{F} \cdot \hat{\jmath}\right) = -P_U\, dScos\vartheta + P_L\, dScos\vartheta \\ dF_{x'} = \left(d\vec{F} \cdot \hat{\imath}\right) = -P_U\, dSsin\vartheta + P_L\, dSsin\vartheta \end{cases} \tag{2}$$

Where, $dS = bds$ being b the span of the semi-infinite wing as shown in Fig. 2b. The total normal and axial forces acting on the wing in the body reference frame are obtained by integrating Eq. (2) from the leading edge (LE) to the trailing edge (TE) as shown in Eq. (3).

$$\begin{cases} F_{y'} = -b \int_{LE}^{TE} P_U\, cos\vartheta\, ds + b \int_{TE}^{LE} P_L\, cos\vartheta\, ds \\ F_{x'} = -b \int_{LE}^{TE} P_U\, sin\vartheta\, ds + b \int_{TE}^{LE} P_L\, sin\vartheta\, ds \end{cases} \tag{3}$$

Equation 3 can be further simplified by using the geometric relation between the elementary surface (ds) and the body reference system (dx, dy) as showed in Eq. (4).

$$\begin{cases} F_{y'} = -b \int_{x'=0}^{x'=c} (P_U - P_L)\, dx \\ F_{x'} = b \int_{y'(x'=0)}^{y'(x'=c)} (P_U - P_L)\, dy \end{cases} \tag{4}$$

Where c is the chord of the airfoil. Now, the local pressure coefficient $C_{p,l}$ is introduced for practical purposes in order to take into account for different free stream flow conditions (Eq. 5).

$$C_{P,l} = \frac{P_l - P_\infty}{1/2\rho_\infty U_\infty^2} \tag{5}$$

The total pressure forces generated on the airfoil can be written in terms of pressure coefficients once divided Eq. (4) by the reference force (dynamic pressure multiplied by planform area) and knowing that the circular integral of $P_\infty/(0.5\rho_\infty U_\infty^2) = const.$ is identically null (Eq. 6).

$$\vec{F} = -\oint (P_\infty \cdot \hat{n}) dS = 0 \tag{6}$$

Equation 7 reports the final expression of the force coefficients expressed in the body reference frame (x'-y' in Fig. 1).

$$\begin{cases} C_{F,y'} = -\frac{1}{c} \int_{x'=0}^{x'=c} (C_{P,U} - C_{P,L})\, dx \\ C_{F,x'} = \frac{1}{c} \int_{y'(x'=0)}^{y'(x'=c)} (C_{P,U} - C_{P,L})\, dy \end{cases} \tag{7}$$

Further details about the derivation of Eq. (7), along with the assumptions used, are reported in [5]. $C_{P,U}$ and $C_{P,L}$ are the pressure coefficient for the upper and lower side of the airfoil, respectively. The free stream velocity U_∞, is calculated by using the dynamic pressure measured by the Pitot probe. The static pressure upstream the airfoil, P_∞, can be calculated by using both the analog manometer $(P_{tot} - P_\infty)$

connected as shown in Fig. 3 and the total pressure reading from the manometer attached to the wall (P_{tot}) (Note: we are assuming the absence of pressure losses between the inlet entrance and the Pitot probe location).

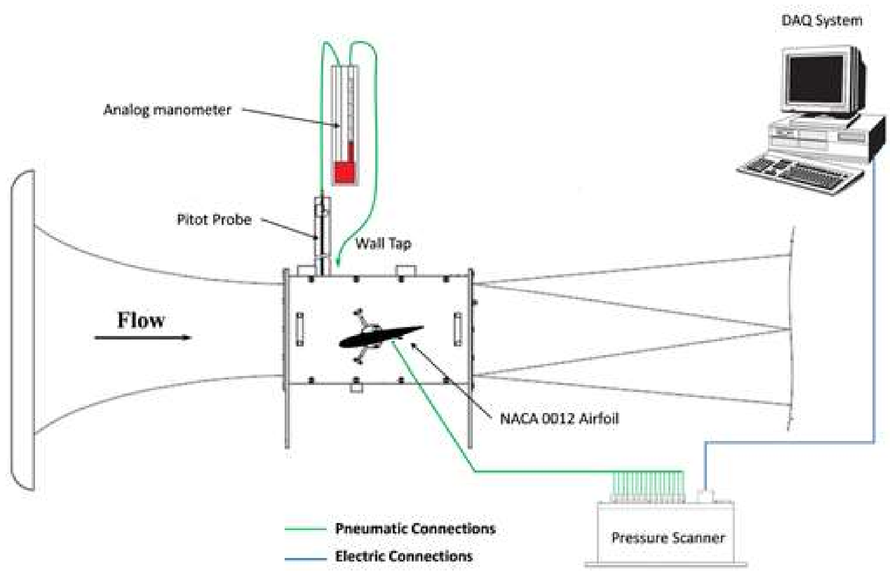


Figure 3. Schematic of wind tunnel test setup.

The resulting lift and drag coefficient are reported in Eq. (8) once the force coefficients $C_{F,x'}$ and $C_{F,y'}$ are projected back to the wind reference system (x-y in Fig. 1) [5-6].

$$\begin{cases} C_L = -C_{F,x'} \sin(\alpha) + C_{F,y'} \cos(\alpha) \\ C_D = C_{F,x'} \cos(\alpha) + C_{F,y'} \sin(\alpha) \end{cases} \tag{8}$$

The numerical integrations in Eq. (7) can be performed by using the trapezoidal formula in Eq. (9).

$$\int_{x_{i-1}}^{x_i} f(x)dx \approx \Delta x \cdot \frac{[f(x_{i-1}) + f(x_i)]}{2} \tag{9}$$

It is strongly suggested to integrate, first, the pressure coefficients along the top and bottom surfaces and, then, subtract them since the pressure taps on the upper and lower surfaces **are not aligned** with each other. The change in thickness along the chord of the NACA 0012 airfoil (Eq. 10 by [7]) is also needed for the calculation of $C_{F,x'}$ in Eq. (7).

$$\pm\frac{y}{c} = 0.60\left[0.2969\sqrt{\frac{x}{c}} - 0.126\frac{x}{c} - 0.3516\left(\frac{x}{c}\right)^2 + 0.2843\left(\frac{x}{c}\right)^3 - 0.1015\left(\frac{x}{c}\right)^4\right] \tag{10}$$

- **Based on the theoretical discussions presented in class, explain:**

1) What type of drag you are able to calculate by using the pressure taps: pressure drag, friction drag or both? Please explain clearly the rationale that supports your thoughts.

2) Do you think that the measured lift is very affected (i.e. unacceptably inaccurate value) by neglecting the contribution of shear stresses? Why?

V. Experiment Description

A. Apparatus

The tunnel used for this experiment is reported in Fig. 4. The AF100 wind tunnel is open return suction type having a closed test section. It is supported by a steel tubular structure for improved mobility/easiness of installation. Air enters the tunnel through a bell-mouth diffuser that accelerates the flow through a honeycomb flow straightener which has the main purpose of reducing the lateral velocity components coming from the swirling motion of the air in the room. The air stream enters, then, the test section and exits by passing through a protective grid before moving through the variable speed axial fan. Downstream the axial fan is located a silencer. The speed of the axial fan and, thus, the nominal velocity in the test section is controlled by an electric drive control in the Control and Instrumentation Unit (white front panel in Fig. 4). The test cell has a square cross section characterized by side dimension of ≈300mm and is composed of acrylic transparent panels. Each lateral panel is equipped with supports for the various models and force balance available. Four holes are located on the top panel of the test section to locate the two Pitot devices and the two static-pressure ports upstream and downstream the center of the working section.

Figure 4. AF100 locate in WH221.

Specifically for this experiment, a Pitot tube is mounted on the slide which has a vertical travel of 4cm to span part of the tunnel core (Fig. 5) and, thus to measure the average free stream velocity (U_∞ in Eq. 4). The slide is driven by a stepper motor that has its dedicated controller but which can also be computer controlled via a LabVIEW™ interface (Fig. 6). The slide will move a specified distance with a specified speed. More information about the traversing system can be found in the lab manual for the boundary layer survey.

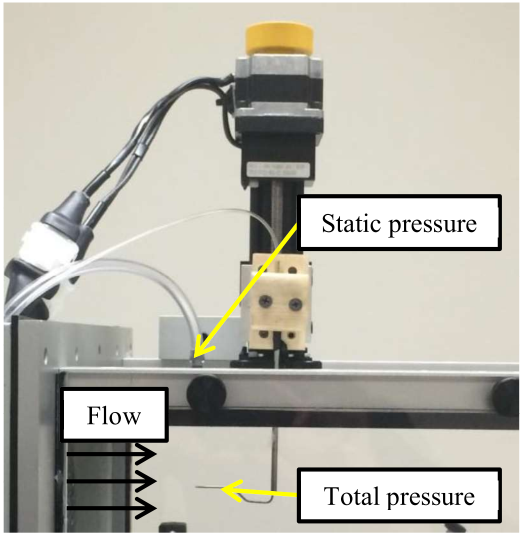


Figure 5. Pitot tube mounted in the tunnel.

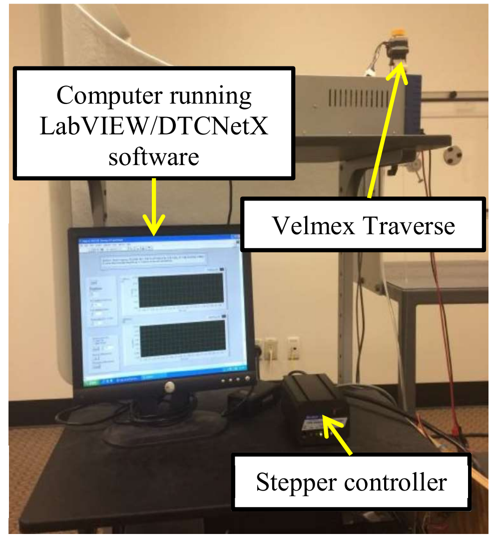


Figure 6. Computer and other electronics.

For this experiment, only the analog manometer connected to the AF100 control board is used to measure the differential pressure.

A 32-channels pressure scanner (Fig. 7) is used, in addition to the analog manometers, in order to collect the surface pressure on selected regions of the airfoil. The data stream from the pressure scanner are collected by the DTCNetX software from the Ethernet port **and converted directly to psig**.

The ESP-32HD is a miniature differential pressure scanner module that allows for multiple measurements of dry, non-corrosive gases to be taken. **The scanner integrates 32 silicon piezoresistive pressure sensors ranging from ± 1 psid**. Each pressure sensor incorporates a temperature sensor and EEPROM for storage of calibration data as well as sensor identification information such as pressure range, factory calibration date, and user-managed last or next calibration date. The microprocessor uses the data from the EEPROM to correct for sensor zero, span, linearity and thermal errors. The scanner also provides digital temperature compensation capability of the sensors to reduce thermal errors. Proper and periodic on-line calibration maintains system accuracy of up to ±0.03% FS (Full Scale) after re-zero. The output of the sensors is electronically multiplexed through a single onboard instrumentation amplifier at rates up to 50,000 Hz using binary addressing. This binary pressure data is then relayed through an auto-negotiating 10 or 100 Mbit Ethernet interface. The binary pressure data is scaled to engineering units of psig (differential) within the host DCTNetX interface software and written into a storage Excel data file on the PC.

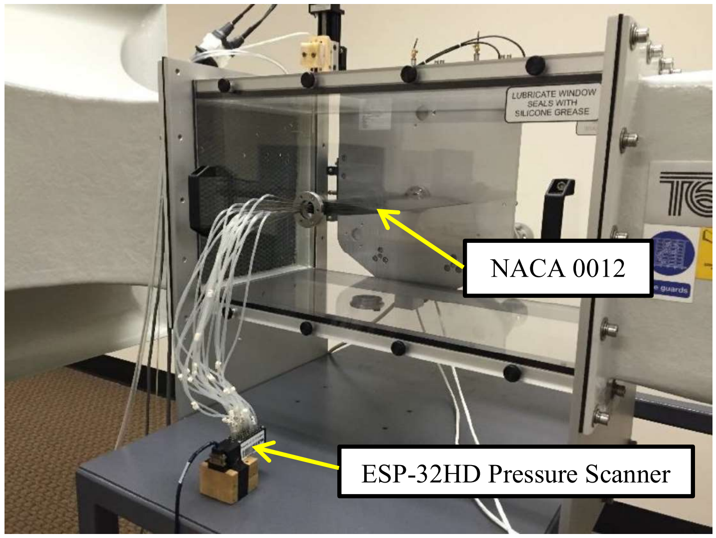


Figure 7. Test setup used for pressure measurements on airfoil surface.

The TecQuipment NACA 0012 airfoil showed in Fig. 7 allows monitoring the local pressure for maximum 20 points on the center section of the wing. A schematic of the airfoil along with the location of the pressure taps is shown in Fig. 8.

Upper Surface Tapping	Distance From Leading Edge
1	0.76
3	3.81
5	11.43
7	19.05
9	38.00
11	62.0
13	80.77
15	101.35
17	121.92
19	137.16

Lower Surface Tapping	Distance From Leading Edge
2	1.52
4	7.62
6	15.24
8	22.86
10	41.15
12	59.44
14	77.73
16	96.02
18	114.30
20	129.54

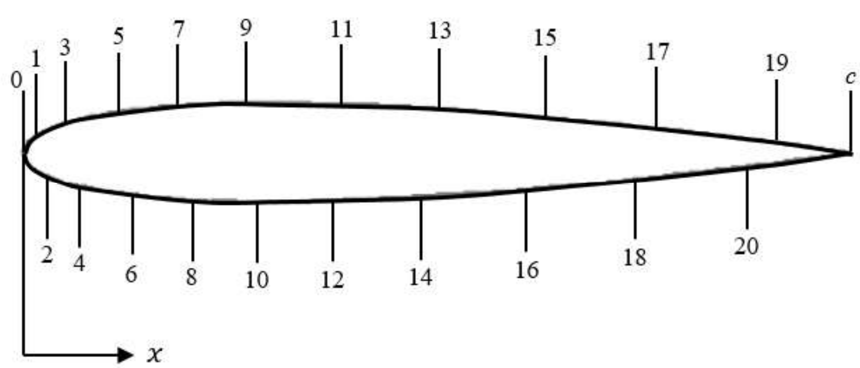


Figure 8. Pressure tap axial locations in <u>millimeters</u> (*c = 150 mm*).

The wing has a span of $\boldsymbol{b} = \mathbf{300}\boldsymbol{mm}$ and is characterized by a chord $\boldsymbol{c} = \mathbf{150}\boldsymbol{mm}$ (Fig. 8). A goniometric wheel (Fig. 9) is used to change the AOA of the axisymmetric airfoil. Figure 9 shows the other side of the test section where the 3-components force balance is installed.

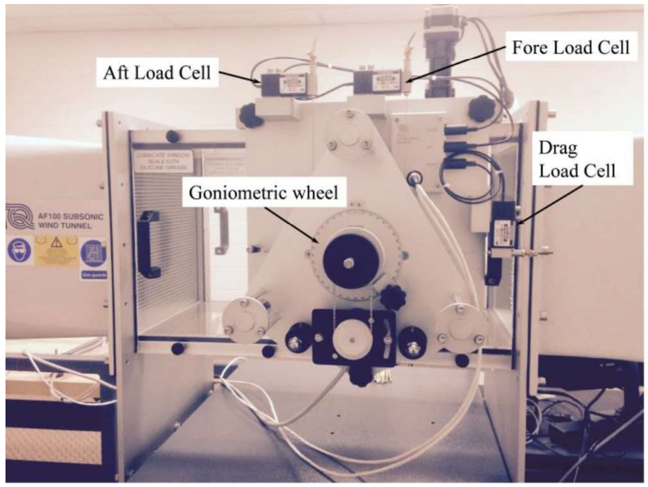


Figure 9. Force balance mounted on test section assembly and goniometric AOA wheel.

B. Experimental Procedure

Using the instructions below, the Pitot tube will be used to measure the dynamic pressure and, thus, to calculate the freestream velocity. The wind tunnel motor contains a drive unit which changes the input electrical power accordingly to the position of the speed knob on the control panel. Below are listed all the steps to be performed in order to complete the experimental campaign in the subsonic wind tunnel:

1. Record the room temperature and the atmospheric pressure (P_{tot}) by using the thermometer and the barometer on the wall.
2. Open the DTCNetX pressure scanner interface and connect the DTCNet DAQ using the "TCP" connection under the "Comms." tab.
3. Set the name of the data file as "C:\Program Files\DTCNetX\pressure_data.csv" using the "Logging File" textbox under the "Setup" tab. Note, this will be the path and filename for data storage. In this case the .csv filename is "pressure_data".
4. Set the data acquisition parameters under the "Data Buffer" tab to the following:
    - Stop the data collection "After a single cycle".
    - Set the number of cycles to $n = 1$.
    - Ensure the "Log to Disk at Every Event" option is checked.
    - Start the data collection "On Demand".
    - Set the "Samples per Cycle" to 20.
5. Manually zero the pressure scanner to eliminate any potential offset by clicking the "0.000" tab.
6. Set the airfoil AOA to zero degrees.
7. Start the wind tunnel to the test speed and wait for the flow to become steady. You can see this by monitoring the analog manometer connected to the pitot tube and static port. Record the dynamic pressure from the analog manometer in mmH_2O. This will be used to calculate the freestream velocity.

8. Under the "Data Buffer" tab press the start button on the left hand side of the DTCNetX panel. A red light indicator should appear in the first white box in the upper right of the panel. The data collection procedure should take approximately 20-30 seconds. After the data acquisition is complete a green light indicator should momentarily appear in place of the second white box before all three boxes return to the nominal white color. After recording the first set of measurements check and ensure the data is writing to the correct file under the specified path.
9. Collect pressure measurements at AOA of 0°, 2°, 4°, 6°, 8°, 10°, 12°, 14°, 16°, 18°, and 20°. You will have a total of 1 data file containing the average differential pressure measurements ($P_l - P_{tot}$) in psig for the 20 individual pressure tap locations at the 11 different AOA.

C. Data Reduction

The data from the spreadsheets created from the DTCNetX software must be reduced using the procedure outlined in this subsection.

1. Convert the unit of pressure data from the manometer attached to the wall (P_{tot}), from mmHg to psf by using the conversion factor, 1 mmHg=133.3224 Pa.
2. Calculate the density of the air by the ideal gas law from the room temperature and pressure measurements.
3. Convert the unit of the pressure data from the analog manometers to Pa by using the conversion factor, 1mm H_2O = 9.8065 Pa;
4. Calculate the flow velocity by using Bernoulli's equation and the manometer readings for the dynamic pressure (please refer to previous lab manual).
5. Calculate the local pressure coefficients by using both the Pitot probe reading ($P_{tot} - P_\infty$) and the pressure scanner reading ($P_l - P_{tot}$). (Hint: $C_{p,l}$ = pressure-scanner reading + Pitot-probe reading divided by the dynamic pressure and use coherent units of measure)
6. Integrate the pressure coefficient along the airfoil profile and project along the wind reference frame (Eq. 7-8) in order to obtain the drag and lift coefficients by using pressure taps measurements. The limit of integration of $C_{F,x'}$ in Eq. (7) can be calculated by using the profile of the airfoil reported in Eq. (10) and by knowing the location of the pressure taps with respect to the chord of the airfoil (Fig. 8).

VI. Report Requirements

The report should include an appropriate introduction and procedure. It should be written from the standpoint that you are measuring the drag and lift of the selected airfoil by using the pressure taps while showing an understanding of the data.

a. Drag and lift measurement by using the pressure taps on the airfoil

1. Determine the drag and lift coefficients and, thus, lift and drag by using the pressure measurements from the sensors installed on the airfoil's surface. C_L and C_D can be calculated by dividing, respectively, the lift and drag by the dynamic pressure multiplied by the planform area of the wing [5].
2. Tabulate the numerical values of C_D, C_L, D and L for all AOA used for the experiment.
3. Plot the C_D vs. α and C_L vs. α.
4. Plot the drag polar of the wing (C_D vs. C_L).
5. Plot $C_{P,U}$ and $C_{P,L}$ for AOA of 0°, 14°, and 20° (on the same plot with legend).

b. Discussion of measurements and results

1. Calculate and comment on the $C_{L,max}$ and α at $C_{L,max}$. Explain what is happening to the flow over the airfoil for AOA higher than that at $C_{L,max}$.

2. Comment on the C_p distribution over the airfoil at the AOA plotted in 5a from above. Explain how these distributions reflect the C_L vs. α relationship (i.e. $C_{L,max}$ and α at $C_{L,max}$).
3. Determine the slope, $C_{L\alpha}$, of the linear region of the C_L vs. α relationship. How does the value compare with the thin airfoil theory? Calculate the Reynolds number over the airfoil given the conditions of the experiment and comment on possible deviations in the measured $C_{L\alpha}$ (consider the assumptions of the theory). Use the provided technical report R&M No. 3726 on Blackboard to discuss the influence of Reynolds number on the C_L vs. α relationship.
4. Explain the type of drag (i.e. pressure drag, friction drag or both) you are able to calculate with the pressure tap measurements.
5. If the experiment was repeated with the force balance how do you think the drag measurements would compare with the pressure tap drag measurements? Explain your reasoning.
6. Comment on any systematic errors as a result of the experimental setup that could influence the measurements (i.e. would the open instrumentation port on the side of the test section influence the measurements?).
7. A well established experimental technique for determining the drag of a body requires conducting a pitot-static survey of the wake downstream of the body and then performing a linear momentum balance using control volume analysis. Explain how such a method could be used to experimentally measure drag. <u>List all your assumptions and provide necessary equations to support your reasoning</u>. What type of drag (i.e. pressure drag, friction drag or both) would be measured when implementing this particular method?

References

[1] Dos Santos, L.A. et al., "Drag Estimation by Wake Survey Performed Measuring Velocities and Measuring Total and Static Pressures", ABCM Paper 06-0246, 11th Brazilian Congress of Thermal Sciences and Engineering.

[2] Schlichting, H., 1966, "*Boundary-Layer Theory*", 6th. Edition translated from German by J. Kestin, McGraw-Hill International Book Company, New York, USA.

[3] Bairstow, L., "*Applied Aerodynamics*", Longmans Green (1946).

[4] Schneider, S.P, "Hot Wires, Wakes, and Drag Measurement", Fluid Mechanics Lab course notes, Purdue University, 2004.

[5] Anderson, J.D., Jr., "Fundamentals of Aerodynamics", 2nd Edition, McGraw-Hill, Inc., New York, USA.

[6] Haritonidis, J. H., "Lift, Drag and Moment of a NACA 0015 Airfoil". Aerospace Engineering, The Ohio State University, Columbus, 2008.

[7] Gregory, N., and O'Reilly, C.L., "Low-Speed Aerodynamic Characteristics of NACA 0012 Aerofoil Section, including the Effects of Upper-Surface Roughness Simulating Hoar Frost", Reports and Memoranda No. 3726, London, January 1970.