Lab #1 Pressure Measurements Laboratory

Objectives:

1. To get “hands-on” experiences on how to make pressure (surface pressure, static pressure and total pressure inside flow) measurements using conventional pressure-measuring instrumentations.

2. To learn how to determine the aerodynamic characteristics of an airfoil based on the airfoil surface pressure distribution measurements.

3. To know how to do raw data acquisition, experimental data reduction and processing, measurement error estimation, and final result analysis and discussion of an experimental study.

Technical Background:

1. The pressure-measuring instrumentations:
   a. Mechanical pressure gauge: to measure the atmosphere pressure to calculate the air density.
   b. Pitot-static pressure probe: to measure the static pressure and total pressure inside wind tunnel to determine the dynamic pressure and flow velocity.
   c. Electrical pressure transducer: DSA3217 pressure acquisition system
      i. The DSA3217 digital sensor arrays incorporate temperature compensated piezoresistive pressure sensors with a pneumatic calibration valve, RAM, 16 bit A/D converter, and a microprocessor in a compact self-contained module.
      ii. The precision of the pressure acquisition system is ±0.2% of the full scale (± 10 inch H₂O).
      iii. See manual for further detailed information.

2. The test airfoil:
   The airfoil used in the present experiment is a GA(W)-1 airfoil (also labeled as NASA LS(1)-0417). The GA (W)-1 has the maximum thickness of 17% of the chord length. Compared with standard NACA airfoils, the GA (W)-1 airfoil was specially designed for low-speed general aviation applications with a large leading-edge radius in
order to flatten the peak in pressure coefficient near the airfoil nose to discourage flow separation.

The airfoil is quipped with 43 pressure taps at its median span, and the locations of the pressure taps are indicated in Fig.1.

![Figure 1. GA(W)-1 airfoil and pressure tap locations.](image)

**Table 1: The coordinate of the pressure taps on the GA(W)-1 airfoil.**

<table>
<thead>
<tr>
<th>Lower Surface</th>
<th>Upper Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>tap</td>
<td>x/c</td>
</tr>
<tr>
<td>1</td>
<td>0.0000</td>
</tr>
<tr>
<td>2</td>
<td>0.0036</td>
</tr>
<tr>
<td>3</td>
<td>0.0306</td>
</tr>
<tr>
<td>4</td>
<td>0.0494</td>
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<tr>
<td>5</td>
<td>0.0735</td>
</tr>
<tr>
<td>6</td>
<td>0.0962</td>
</tr>
<tr>
<td>7</td>
<td>0.1201</td>
</tr>
<tr>
<td>8</td>
<td>0.1452</td>
</tr>
<tr>
<td>9</td>
<td>0.1921</td>
</tr>
<tr>
<td>10</td>
<td>0.2944</td>
</tr>
<tr>
<td>11</td>
<td>0.3746</td>
</tr>
<tr>
<td>12</td>
<td>0.4365</td>
</tr>
<tr>
<td>13</td>
<td>0.5023</td>
</tr>
<tr>
<td>14</td>
<td>0.6130</td>
</tr>
<tr>
<td>15</td>
<td>0.6569</td>
</tr>
<tr>
<td>16</td>
<td>0.7093</td>
</tr>
<tr>
<td>17</td>
<td>0.8004</td>
</tr>
<tr>
<td>18</td>
<td>0.8348</td>
</tr>
<tr>
<td>19</td>
<td>0.8759</td>
</tr>
<tr>
<td>20</td>
<td>0.9367</td>
</tr>
<tr>
<td>21</td>
<td>1.0000</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TAP 1 is at the airfoil leading edge (LE) and TAP21 is at the airfoil trailing edge (TE).
TAP 2-20 are along the lower surface, TAP 22-43 are along the upper surface.
The chord length of the airfoil is 101mm, i.e., \( C = 101\text{mm} \).

3. Calculating airfoil lift coefficient \( (C_l) \), drag coefficient \( (C_d) \), and moment (coefficient) \( (C_{m,LE}) \) by numerically integrating the surface pressure distribution around the airfoil:

![Figure 2. Pressure tap numbering convention](image)

First, recall that the surface pressure taps are numbered in the counterclockwise direction as shown in Fig. 1. Although it may seem somewhat unintuitive at first, this numbering convention allows us to formulate relevant equations in a very generic way. A total of 43 pressure tap locations are given by their Cartesian given in table 1.

\[ N = 43, \text{ Total Number of Pressure Taps} \]
\[ x_i, y_i, \text{ as } i = 1, ..., 21 \text{ lower surface, from LE to TE} \]
\[ x_i, y_i, \text{ as } i = 22, ..., 43 \text{ upper surface, from TE to LE} \]
With the convention, the airfoil surface is broken into \( N \) panels. The \( i \)-th panel is bounded by the \( i \)-th and \( i+1 \)-th taps at \((x_i, y_i)\) and \((x_{i+1}, y_{i+1})\) respectively. The exception is that the \( N \)-th panel is defined by \((x_N, y_N)\) and \((x_i, y_i)\), but in your spreadsheet or program, you can treat this by adding a fictitious \( N+1 \)-th tap which simply takes on the value from the first tap.

Consider the \( i \)-th panel shown in Fig.2, where \( p_{i+1/2} \) represents pressure (assume to be) acting on the \( i \)-th panel. Let

\[
\begin{align*}
 p_{i+1/2} &= \frac{1}{2} (p_i + p_{i+1}) \\
 p_{N+1/2} &= \frac{1}{2} (p_N + p_1)
\end{align*}
\] (1)

If we assume the pressure variation on the \( i \)-th panel to be constant at \( p_{i+1/2} \) as defined by Eq.1, this is equivalent to trapezoidal true integration. Furthermore, define

\[
\begin{align*}
 \Delta x_i &= x_{i+1} - x_i, \quad \Delta y_i = y_{i+1} - y_i \\
 \Delta x_N &= x_i - x_N, \quad \Delta y_N = y_i - y_N
\end{align*}
\] (2)

Figure 3. Discrete representation of airfoil surface element

Note that \( \Delta x \) and \( \Delta y \) can be negative because \( x \) and \( y \) are not monotonic in the index \( i \). Using Eqs.1 and 2, the normal and axial components of the pressure force acting on the \( i \)-th panel can be written as
\[
\delta N'_i = p_{i+1/2} \Delta x_i \quad (3)
\]

\[
\delta A'_i = -p_{i+1/2} \Delta y_i \quad (4)
\]

where the prime indicates a two-dimensional quantity (force per unit span). Similarly, the moment contribution from the \(i\)-th panel to the total moment about the leading edge can be written as

\[
\delta M'_{LE,i} = r \times \delta F_i
\]

\[
= (x_{i+1/2} + y_{i+1/2} k) \times (\delta A'_i + \delta N'_i k)
\]

\[
= (x_{i+1/2} + y_{i+1/2} k) \times (-p_{i+1/2} \Delta z_i + p_{i+1/2} \Delta x_i k)
\]

\[
= -[(p_{i+1/2} \Delta x_i) x_{i+1/2} + (p_{i+1/2} \Delta y_i) y_{i+1/2}] j
\]  

or

\[
\delta M'_{LE,i} = -(p_{i+1/2} \Delta x_i) x_{i+1/2} - (p_{i+1/2} \Delta y_i) y_{i+1/2}
\]

where

\[
x_{i+1/2} = \frac{1}{2} (x_i + x_{i+1}), \quad y_{i+1/2} = \frac{1}{2} (y_i + y_{i+1})
\]

Note that aerodynamic moment is defined to be positive in the pitch-up direction.

Now that we have derived the expressions for the differential force and moment from each panel, we can integrate them over the airfoil surface.

\[
N' = \sum_{i=1}^{N} \delta N'_i = \sum_{i=1}^{N} p_{i+1/2} \Delta x_i \quad (6)
\]

\[
A' = \sum_{i=1}^{N} \delta A'_i = -\sum_{i=1}^{N} p_{i+1/2} \Delta y_i \quad (7)
\]

\[
M'_{LE} = \sum_{i=1}^{N} \delta M'_{LE}
\]

\[
= -\sum_{i=1}^{N} (p_{i+1/2} \Delta x_i) x_{i+1/2} - \sum_{i=1}^{N} (p_{i+1/2} \Delta y_i) y_{i+1/2} \quad (8)
\]

Finally, the lift and drag per unit span can be obtained as follows.

\[
L' = N' \cos \alpha - A' \sin \alpha
\]

\[
D' = N' \sin \alpha + A' \cos \alpha
\]
Requirements for the Lab Report

You are required to prepare a formal lab report with following results included:

1. **Using your data:**
   a. A table showing all the data you obtained.
   b. A plot of pressure coefficient \( C_p = \frac{P - P_\infty}{\frac{1}{2} \rho V^2} \) distribution for upper and lower surface of the airfoil for the angles of attack \( (\alpha) \) you used.
   c. Comments on the characteristics of the pressure distribution
   d. Calculate lift coefficient \( C_L = \frac{L}{\frac{1}{2} \rho V^2 c} \), drag coefficient \( C_D = \frac{D}{\frac{1}{2} \rho V^2 c} \), and moment (coefficient) \( C_{m,LE} = \frac{M_{LE}}{\frac{1}{2} \rho V^2 c^2} \).
   e. The velocity at the test section and Reynolds number of the flow.

2. **Using the entire group data to plot the curves of** \( C_L vs \alpha \), \( C_D vs \alpha \) and \( C_{m,LE} vs \alpha \).

3. **Report requirement:**
   a. Calculations for all the steps leading up to the final answer
   b. Raw data shown as spreadsheet
   c. A brief discussion about the measurement error estimation of your results

Some helpful information related to this lab can be found from:

The Experimental Data Needed for the Lab #1

Atmosphere pressure in the lab, \( P_{atm} = \) ?

The temperature in the wind tunnel, \( T = \) ?

The density of air in the wind tunnel, \( \rho = \) ?

The static pressure of the incoming flow \( P = \) ?

The total pressure of the incoming flow \( P_{total} = \) ?

The velocity of the incoming flow, \( V = \) ?

The angle of attack of the airfoil \( \alpha = \) ?

The surface pressure data from the 43 pressure taps around the airfoil
\[ P_1 = ? \]
\[ \vdots \]
\[ \vdots \]
\[ P_{43} = ? \]

Note: For the airfoil surface pressure distribution measurements, it is recommended to run the DSA 3217 unit with the data acquisition of 300 ~ 400Hz for about 20 seconds in order to calculate the averaged pressure for each pressure tap.
The experimental parameter settings for the Lab#1:

<table>
<thead>
<tr>
<th>First Name</th>
<th>Last Name</th>
<th>angle of attack</th>
<th>motor speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunil</td>
<td>Arolla</td>
<td>AOA=5,10,15</td>
<td>25Hz</td>
</tr>
<tr>
<td>Daniel</td>
<td>Dvorak</td>
<td>AOA=6,11,16</td>
<td>25Hz</td>
</tr>
<tr>
<td>Daniel</td>
<td>Garrick</td>
<td>AOA=7,12,18</td>
<td>25Hz</td>
</tr>
<tr>
<td>Xuan</td>
<td>Ge</td>
<td>AOA=8,13,19</td>
<td>25Hz</td>
</tr>
<tr>
<td>Christopher</td>
<td>Karstens</td>
<td>AOA=9,14,20</td>
<td>25Hz</td>
</tr>
<tr>
<td>Meng</td>
<td>Lo</td>
<td>AOA=5,10,15</td>
<td>20Hz</td>
</tr>
<tr>
<td>John</td>
<td>Meyer</td>
<td>AOA=6,11,16</td>
<td>20Hz</td>
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<tr>
<td>Katrine</td>
<td>Nilsen</td>
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<td>20Hz</td>
</tr>
<tr>
<td>Ahmet</td>
<td>Ozbay</td>
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<td>20Hz</td>
</tr>
<tr>
<td>Suganthi</td>
<td>Selvaraj</td>
<td>AOA=6,11,16</td>
<td>20Hz</td>
</tr>
<tr>
<td>Jason</td>
<td>Ryon</td>
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<td>15Hz</td>
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<tr>
<td>Spencer</td>
<td>Pack</td>
<td>AOA=9,14,20</td>
<td>15Hz</td>
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<tr>
<td>Lei</td>
<td>Shi</td>
<td>AOA=7,12,18</td>
<td>15Hz</td>
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<tr>
<td>Hephzibah</td>
<td>Thampi</td>
<td>AOA=8,13,19</td>
<td>15Hz</td>
</tr>
<tr>
<td>Kai</td>
<td>Zhang</td>
<td>AOA=9,14,20</td>
<td>15Hz</td>
</tr>
</tbody>
</table>