AerE545/AerE445: Experimental Fluid Mechanics and Heat Transfer

Lab #01 Quantifications of airfoil aerodynamic performance by using pressure transducers and hotwire anemometer probe

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 model based on the measured surface pressure distribution over the airfoil model.
3. To measure the boundary layer profiles from the top and bottom surfaces of an airfoil model by measuring velocities just downstream of the airfoil trailing edge using a hotwire anemometer probe.
4. To know how to do raw data acquisition, experimental data reduction, and processing, measurement error estimation, result analysis, and discussion of an experimental study.

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Technical Background:

1. **The pressure-measuring instrumentations:**
   a. Mechanical pressure gauge: to measure the atmospheric pressure to calculate the air density.
   b. Pitot-static pressure probe: to measure the static pressure and total pressure inside the wind tunnel to determine the dynamic pressure and airflow 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 H_2O).
      iii. See the manual for further detailed information.

2. **The test airfoil model:**

The airfoil used in the present experiment is a DU-96-W-180 airfoil. The DU-96-W-180 has the maximum thickness of 18% of the chord length. Compared with standard NACA airfoils, the DU-96-W-180 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 chord length of the airfoil model is 152.4 mm, i. e., C = 152.4 mm. The airfoil is equipped with 42 pressure taps at its median span, and the locations of the pressure taps are indicated in Fig.1.

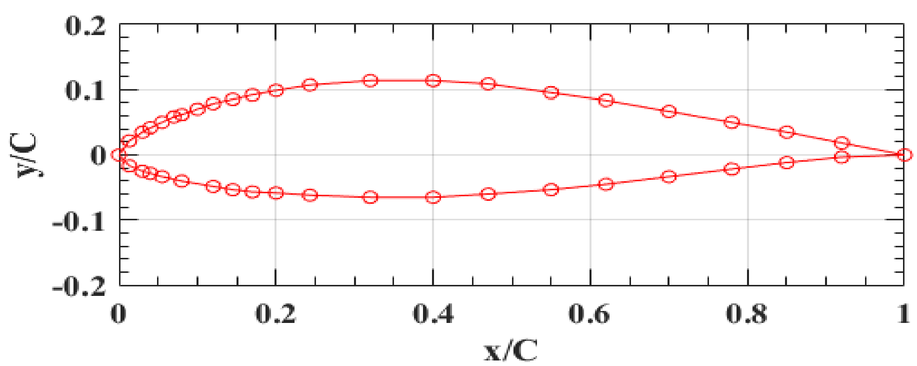

Figure 1. DU-96-W-180 airfoil and pressure tap locations.

Table 1: The coordinate of the pressure taps on the DU-96-W-180 airfoil.

Lower Surface			Upper Surface		
Tap	x/c	y/c	Tap	x/c	y/c
1	0.000	0.000	22	0.920	0.018
2	0.013	-0.017	23	0.850	0.035
3	0.030	-0.025	24	0.780	0.050
4	0.040	-0.028	25	0.700	0.067
5	0.055	-0.033	26	0.620	0.083
6	0.080	-0.040	27	0.550	0.095
7	0.120	-0.048	28	0.470	0.108
8	0.145	-0.053	29	0.400	0.113
9	0.170	-0.057	30	0.320	0.113
10	0.200	-0.058	31	0.243	0.107
11	0.243	-0.062	32	0.200	0.0983
12	0.320	-0.065	33	0.170	0.092
13	0.400	-0.065	34	0.145	0.085
14	0.470	-0.060	35	0.120	0.078
15	0.550	-0.053	36	0.100	0.070
16	0.620	-0.045	37	0.080	0.062
17	0.700	-0.033	38	0.070	0.058
18	0.780	-0.022	39	0.055	0.050
19	0.850	-0.010	40	0.040	0.042
20	0.920	-0.003	41	0.030	0.035
21	1.000	0.000	42	0.013	0.022

- TAP 1 is at the airfoil leading edge (LE) and TAP21 is at the airfoil trailing edge (TE)
- TAPs 2~20 are along the lower surface, TAP 22~42 are along the upper surface

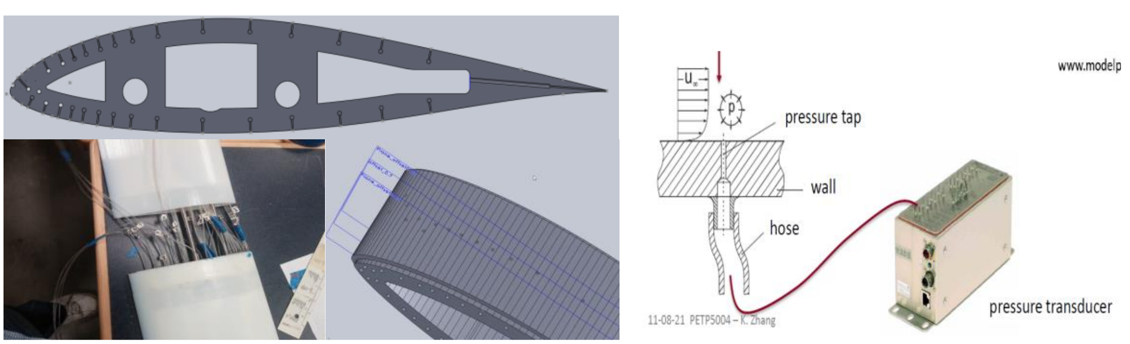

Fig. 02: Experimental setup for surface pressure measurements around an airfoil model

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:

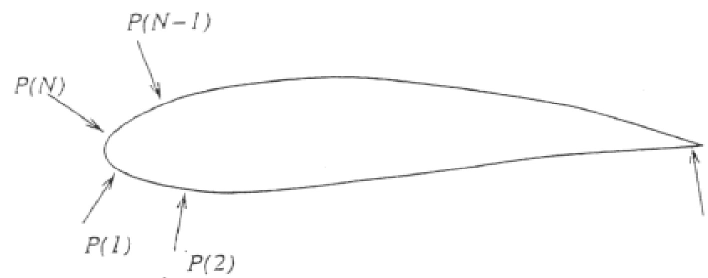

Figure 03. Pressure tap numbering convention

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 42 pressure tap locations are given by their Cartesian given in table 1.

$N = 42$, Total Number of Pressure Taps
x_i, y_i, as i = 1,...,21 lower surface, from LE to TE
x_i, y_i, as i = 22,...,42 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

$$\begin{cases} p_{i+1/2} = \dfrac{1}{2}\left(p_i + p_{i+1}\right) \\ p_{N+1/2} = \dfrac{1}{2}\left(p_N + p_1\right) \end{cases} \tag{1}$$

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

$$\begin{cases} \Delta x_i = x_{i+1} - x_i, & \Delta \mathrm{y_i} = y_{i+1} - y_i \\ \Delta x_N = x_1 - x_N, & \Delta \mathrm{y_N} = y_1 - y_N \end{cases} \tag{2}$$

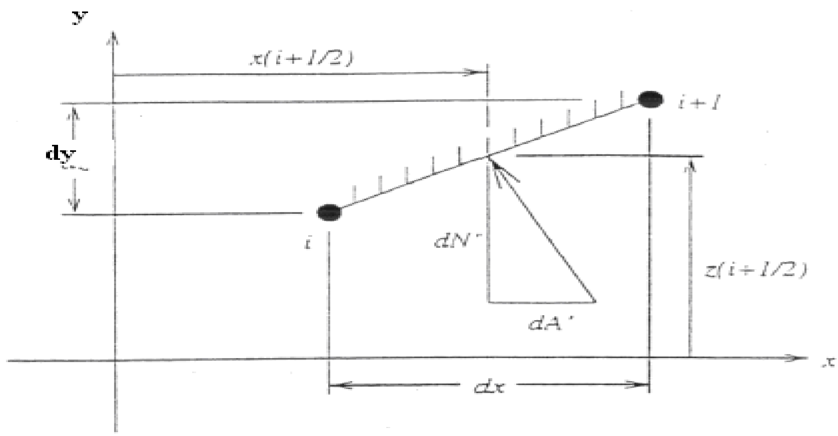

Figure 04. Discrete representation of airfoil surface element

Note that Δx and Δy 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

$$\delta N'_i = p_{i+1/2} \Delta x_i \tag{3}$$

$$\delta A'_i = -p_{i+1/2} \Delta y_i \tag{4}$$

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

$$\begin{aligned} \delta M'_{LE,i} &= \mathrm{r} \times \delta \mathrm{F_i} \\ &= (x_{i+1/2}\mathrm{i} + y_{i+1/2}\mathrm{k}) \times (\delta A'_i \mathrm{i} + \delta N'_i \mathrm{k}) \\ &= (x_{i+1/2}\mathrm{i} + y_{i+1/2}\mathrm{k}) \times (-p_{i+1/2} \Delta \mathrm{z_i} \mathrm{i} + p_{i+1/2} \Delta \mathrm{x_i} \mathrm{k}) \\ &= -[(p_{i+1/2} \Delta x_i) x_{i+1/2} + (p_{1+1/2} \Delta y_i) y_{i+1/2}]\mathrm{j} \end{aligned} \tag{5}$$

or

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

where

$$x_{i+1/2} = \frac{1}{2}(x_i + x_{i+1}), \qquad y_{i+1/2} = \frac{1}{2}(y_i + y_{i+1})$$

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.

$$N' = \sum_{i=1}^{N} \delta N'_i = \sum_{i=1}^{N} p_{i+1/2} \Delta x_i \tag{6}$$

$$A' = \sum_{i=1}^{N} \delta A'_i = -\sum_{i=1}^{N} p_{i+1/2} \Delta y_i \tag{7}$$

$$\begin{aligned} M'_{LE} &= \sum_{i=1}^{N} \delta M'_{LE} \\ &= -\sum_{i=1}^{N} \left(p_{i+1/2} \Delta x_i\right) x_{i+1/2} - \sum_{i=1}^{N} \left(p_{i+1/2} \Delta y_i\right) y_{i+1/2} \end{aligned} \tag{8}$$

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

$$L' = N' \cos\alpha - A' \sin\alpha$$
$$D' = N' \sin\alpha + A' \cos\alpha$$

4. Measurements of the turbulence characteristics in the airfoil wake by using a Hotwire Anemometer probe

The objective of this lab is to quantify the turbulence characteristics of the boundary layer flow over the top and bottom surfaces of the airfoil model by measuring the flow velocities just downstream of the airfoil trailing edge.

What will be available to you for this lab:

- A thermometer and barometer for observing ambient lab conditions (for calculating atmospheric density).
- A computer with a data acquisition system capable of measuring the voltage from the hot wire anemometer.

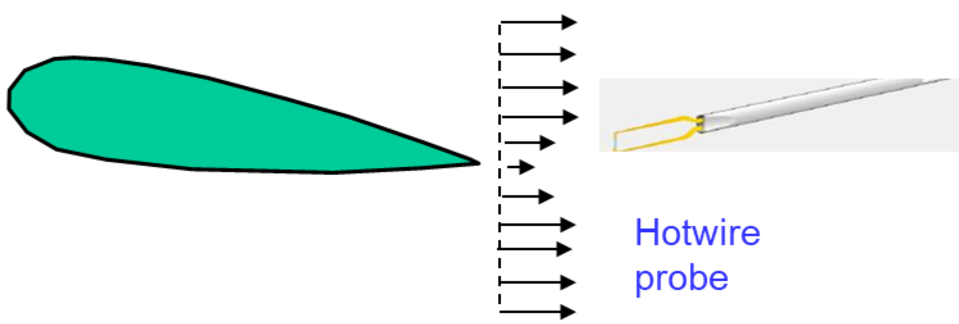

Fig. 05: Experimental setup for hotwire anemometry lab

The Hotwire anemometry measurement instructions

- A hotwire anemometer probe is placed just downstream of the trailing edge of the airfoil. This probe is mounted on a traverse that can be moved vertically through the airfoil wake.
- Conduct your wind tunnel experiments at the motor speed of f =30 Hz.
- Acquire wake velocity profiles for AOA=-2, 0, 2, 4, 6, 8, 10, 12, 14, and 16 degrees. BE SURE that you start from outside the wake and go all the way to the other side of the wake.

Requirements for the Lab Report

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

1. **Using your pressure measurement data:**
   a. A table showing all the data you obtained.
   b. A plot of pressure coefficient ($C_p = (P - P_\infty)/(\frac{1}{2}\rho V)$) distribution for upper and lower surface of the airfoil for the angles of attack (α) you used.
   c. Comments on the characteristics of the pressure distribution
   d. Calculate the 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 α, C_d vs α and $C_{m,LE}$ vs α.**
3. **Using your hotwire anemometer measurement data:**
   a. The velocity distributions for your group's data involve plotting the mean velocity profiles based on your hotwire anemometer measurements. Plot $^{y}/_{\delta}$ vs $^{U}/_{U_e}$ where U_e is the velocity external to the boundary layer (the freestream value). δ is the thickness of the boundary layer. Plot the boundary layer from the top surface and the bottom surface as separate curves with "y" indicating the positive distance from the surface—NOT positive for the top surface and negative for the bottom surface.
   b. Turbulence intensity profiles also come from the hot wire measurements:
      - "Turbulence intensity" is defined as the RMS of the velocity fluctuations divided by the mean velocity.
      - NOTE: To calculate the RMS velocity from your RMS voltage calculation, you can use a Taylor series expansion of your hot wire calibration polynomial:
        - If your calibration polynomial is of the form: $\bar{U} = C_0 + C_1\bar{v} + C_2\bar{v}^2 + C_3\bar{v}^3 + C_4\bar{v}^4$, where $\bar{U}$ is mean velocity and $\bar{v}$ is the mean voltage. Then the rms velocity can be expressed as: $u_{rms} = \frac{\partial \bar{U}}{\partial v}\Big| v_{rms} = [C_1 + 2C_2\bar{v} +$

$3C_3\bar{v}^2 + 4C_4\bar{v}^3]v_{rms}$ where u_{rms} is the rms velocity, and the term in parenthesis is evaluated at the mean velocity.

c. The power spectrum plots of the hotwire measurements. By using the FFT transformation of the time sequences of the hotwire measurement data, the vortex shedding frequency in the wake of the airfoil can be determined. Please include 2 representative plots for each tested AOA case.

4. 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

d. Calculate momentum thickness, θ , according to the following equation: $\theta = \int_0^y \frac{u}{U_e}(1 - \frac{u}{U_e})dy$ where Y is some point outside the boundary layer. From the momentum thickness calculate the drag coefficient according to the relation $C_d = \frac{2\theta}{L}$, where the L is the chord length of the airfoil.

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

- About the airfoil aerodynamics for the textbook of *John Anderson, "Fundamentals of Aerodynamics" 3rd or 4th Edition, McGraw-Hill*
- About the DU-96-W-180 airfoil and wind tunnel experiment:
  - *Veerakumar, R., Raul, V., Liu, Y. et al. Metamodeling-based parametric optimization of DBD plasma actuation to suppress flow separation over a wind turbine airfoil model. Acta Mech. Sin. 36, 260–274 (2020). (https://www.aere.iastate.edu/~huhui/paper/journal/2020-AMS-Plasma-Flow-Control.pdf)*
- About the DSA3217 pressure transducer at *http://scanivalve.com/pdf/prod_dsa3217_18_0311.pdf*.

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 42 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.