MAE 253 - Experimental Aerodynamics I

Lab 3/4/5 – Airfoil Aerodynamics

Final report due date: 04/01/2019

Objective: Using the airfoil model, wake-rake, and the Scanivalve pressure measurement system:

- Calculate the lift and drag coefficients of the airfoil at various angles of attack.
- Compare experimental force characteristics with XFOIL data.

Theory: An airfoil is a streamlined surface designed in such a way that air flowing around it produces useful motion. The component of the net force perpendicular (or normal) to the flow direction is called the lift; the component of the net force along the flow direction is called the drag, as shown in Fig. 1.

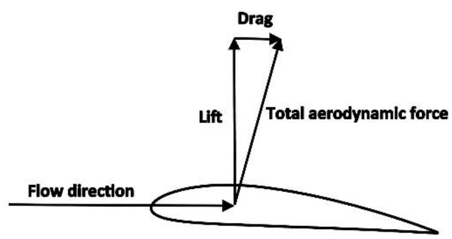

Figure 1: Forces on an airfoil.

To elaborate, when two solid objects interact in a mechanical process, forces are transmitted, or applied, at the point of contact. But when a solid object interacts with a fluid, things are more difficult to describe because the fluid can change its shape. For a solid body immersed in a fluid, the "point of contact" is every point on the surface of the body. The fluid can flow around the body and maintain physical contact at all points. The transmission, or application, of mechanical forces between a solid body and a fluid occurs at every point on the surface of the body. And the transmission occurs through the fluid pressure. Pressure acts perpendicular to the surface of an object. To obtain the net mechanical force on the solid object, we have to multiply the pressure (perpendicular to the surface) times the area around the entire body. We also have to keep track of the direction of the pressure times the area. As for an airfoil in a static fluid, the pressure is a constant all around the airfoil. For the simple, closed surface around the airfoil, the normal (perpendicular) component of the pressure times the area will cancel out. However, if the fluid is not static, but is in motion, the pressure varies around the closed surface, and the sum of the pressure (perpendicular to the surface) times the area around the body produces a net force. Since the fluid is in motion, we can define a flow direction along the motion and the component of the net force perpendicular to the flow direction is the lift and the component of the net force along the flow direction is the drag. These are definitions. In reality, there is only a single, net, integrated force caused by the pressure variations along a body. We can break the surface up into a large number of small areas and sum up the pressure times the area around the whole surface.

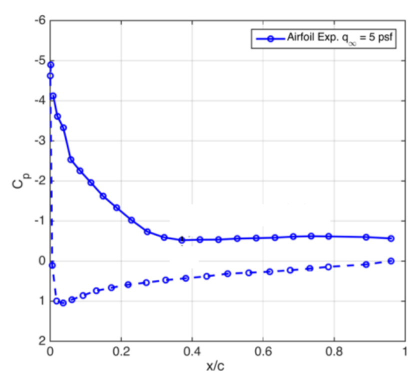

Figure 2: Pressure coefficient distribution over an airfoil.

In order to obtain the lift coefficient (C_l), we will need to experimentally/computationally obtain the coefficient of pressure (C_p) curve. C_p is a parameter for studying low-speed flow of compressible fluids such as air and is given by the equation,

$$C_p = \frac{p - p_{\infty,\,static}}{\frac{1}{2}\rho_\infty V_\infty^2}$$

where p is the static pressure on the airfoil surface, p_∞, ρ_∞, and V_∞ are the freestream static pressure, density, and velocity respectively. A typical C_p distribution on the upper and lower surface across the airfoil chord (c) is shown in Fig. 2. The area under the C_p curve, evaluated using the below equation, gives us C_l.

$$C_l = \frac{1}{c}\int_0^c \left(C_{p,\,lower} - C_{p,\,upper}\right)dx$$

While lift can be calculated with good accuracy using the pressure data, determining the value of the drag coefficient (C_d) is more difficult because of the multiple sources of drag. The drag coefficient for an airfoil includes pressure drag and skin friction drag. While pressure drag can be determined using the pressure data, calculation of skin friction drag poses a more complex issue as it requires complicated and difficult-to-calibrate instrumentation. Drag coefficients are almost always determined experimentally in a wind tunnel using the wake-rake system to determine the momentum/pressure deficit due to the airfoil, as shown in Fig. 3.

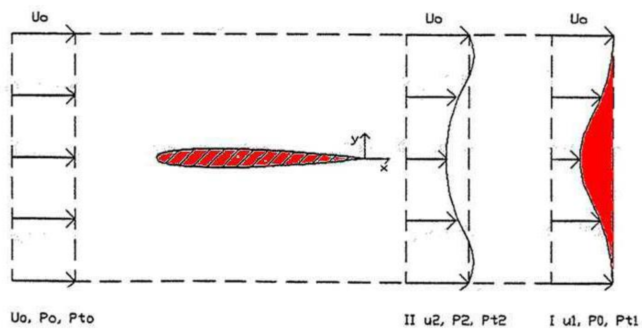

Figure 3: Momentum deficit behind an airfoil.

The area under the pressure deficit curve, calculated using the below equation, gives us the drag coefficient.

$$C_d = \frac{1}{cq_\infty}\int_{wake} \left(p_{\infty,total} - p_{wake,total}\right)dy$$

For accurate drag measurements, the wake-rake needs to be placed far enough from the trailing-edge to allow the recovery of the freestream static pressure. While research has shown that this distance needs to be at least 70% of the airfoil's chord, wind tunnel walls and other factors can cause the freestream static pressure recovery distance to be higher. In the event space restrictions in wind tunnels prevent the wake-rake from being placed far enough from the airfoil, further corrections need to be applied during post-processing to correct for freestream static pressure recovery.

While proper experimenting techniques can yield accurate aerodynamic force results, it can be expensive, both in terms of cost and time. For rapid design and analysis purposes, we need low-order aerodynamic models. One of the popular 2-D subsonic airfoil aerodynamic low-order solvers is XFOIL, an interactive program for the design and analysis of subsonic isolated airfoils. Given the coordinates specifying the shape of a 2D airfoil, Reynolds number, and Mach number, XFOIL can calculate the pressure distribution on the airfoil and hence lift and drag characteristics. The program also allows inverse design - it will vary an airfoil shape to achieve the desired parameters.

Experiment: Using the airfoil, wake-rake, and Scanivalve pressure measurement system, collect the following data at Reynolds numbers $2.5\text{x}10^5$, $5\text{x}10^5$, $6\text{x}10^5$, and $7\text{x}10^5$ for the lift and drag experiments:

Table 1: Data collected to evaluate airfoil lift for a given angle of attack.

Tap Number	Tap X-Coordinate (mm)	Tap Y-Coordinate (mm)	$P_{transducer}$ (psf)	$T_{transducer}$ (ºF)	Atmospheric Pressure (inches of Hg)	10 Static Gauge Pressure Readings (psf)
from airfoil model	from airfoil model	from airfoil model	from WT transducer (dynamic pressure)	from WT transducer	From barometer	from Scanivalve system

Table 2: Data collected to evaluate airfoil drag for a given angle of attack.

Spanwise Tap Location (mm)	Dynamic Pressure (psf)	$P_{transducer}$ (psf)	$T_{transducer}$ (ºF)	10 Wake Static Gauge Pressure (psf)	10 Total Gauge Pressure Readings (psf)
from wake rake	from WT transducer	from WT transducer (dynamic pressure)	from WT transducer	from Scanivalve system	from Scanivalve system

The following constants can be used to help with your analysis:

1. Airfoil chord, c = 0.3048 m
2. Dynamic viscosity of air, $\mu_{air} = 1.825 \times 10^{-5}$ Ns
3. Density of mercury, ρ_{Hg} = 13,593 kg/m^3

In the final report,

- Co-plot the mean C_p distributions at all angles-of-attack for a given Reynolds number.
- Plot the C_l vs. α curve for the airfoil with error bars and compare the data to XFOIL predictions for the corresponding Reynolds number.
- Co-plot the wake pressure-deficit distributions at all angles of attack for a given Reynolds number.
- Plot the C_d vs. α curve for the airfoil with error bars and compare the data to XFOIL predictions for the corresponding Reynolds number.
- Plot the drag polar for the airfoil and compare the data to XFOIL predictions for the corresponding Reynolds number.
- Show the experimental flow diagram for the lift and drag experiments in your methodology sections.
- *EXTRA CREDIT:* Due to wind tunnel restrictions, static pressure at the point of measurement was unable to recover to freestream conditions. Schlichting [1] elaborates on two popular methods formulated by A. Betz and B. M. Jones, respectively, to correct the drag data in such a scenario. Using the provided reference, correct the drag data obtained from our experiment. (5 credit points on a scale of 20)
- *NOTE:* The turbulence factor correction has already been incorporated while setting our dynamic pressure during the experiment. You will not need to correct for the same during post-processing.
- Present your code in the Appendix.

References: [1] Schlichting, H., "Boundary-Layer Theory, 7th Edition," McGraw-Hill, Inc., New York, NY.