Chapter 4

Experiment 1: Wind Tunnels and Associated Instrumentation

4.1 Objectives

Wind tunnel experiments provide invaluable data for design of aerodynamic bodies and can serve as a baseline for computational fluid dynamics (CFD) code validation, provided the experimenter took great care to collect accurate data. Collecting reliable and useful data requires an understanding the use of proper equipment necessary to make a measurement and its limitations. In experiment one, students will characterize the flow inside UCI's low-speed wind tunnel using a **pitot-tube** to determine flow uniformity and a **yaw-probe** to determine the flow angle. In doing so, the students will learn the limitations of the two instruments. Additionally, the students will understand the difference between utilizing the **integrated static taps** on the wind tunnel versus using the pitot-tube to measure flow speed. Experiment one will provide the student with familiarity of UCI's low-speed wind tunnel, measurement devices, and techniques required to characterize the flow inside of a wind tunnel. Students will draw on this knowledge for the subsequent experiments.

4.2 Introduction

Experiment one will introduce students to UCI's low-speed wind tunnel and several measurement devices. In this section, students will find an overview of the wind tunnel, a review of the physics behind velocity measurements in a wind tunnel, a description of a pitot-tube and yaw-probe, the behavior of the flow inside the wind tunnel, and an introduction to data acquisition.

4.2.1 Description of Wind Tunnel

The wind tunnel used in this course is a low-speed "open return" wind tunnel with a "closed" test section shown schematically in figure 4.1. The wind tunnel can achieve velocities of 35 m/s with nothing in the test section. The larger the object/blockage in the test section, the lower the true speed will be. The term "open return" refers to the fact that air is drawn into the tunnel from the open room and generally exhausts back to the same room. The test section is described as "closed" because the test section is surrounded by four solid walls, which isolate the flow in the test section from the surrounding environment.

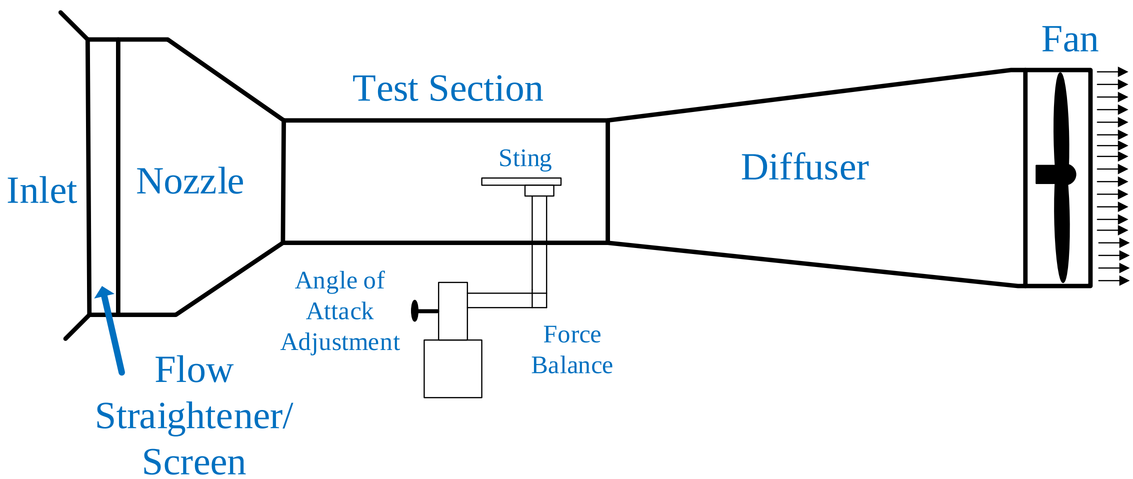

Figure 4.1: Schematic of the MAE 108 Wind Tunnel

Free stream turbulence, swirl, unsteadiness, and non-uniformity of the flow in a vertical plane can have a significant effect on planned measurements. Thus, to take accurate measurements, the flow in the test section must be steady and move uniformly in the downstream direction. Generally, the air inside a room is unsteady and swirling-for example caused by the air conditioning in the room. Therefore, wind tunnels come equipped with devices to make the flow steady, uniform, and to remove any swirling motion. Figure 4.1 shows these flow-management devices and the other major subsections of the wind tunnel used in this laboratory. Starting at the entrance to the tunnel and proceeding in the downstream direction (i.e., the flow direction), the flow management devices and important subsections consist of:

1. Flow Management (flow straightener) composed of :
   (a) A honeycomb section to reduce swirl in the flow.
   (b) A screen to damp out velocity fluctuations in the downstream direction.
2. A contraction section (nozzle) to accelerate the flow, reduce the thickness of the boundary layer — making the flow more uniform — and reduce the background turbulence level.
3. A test section where the model is placed and which must be sealed to prevent air from being drawn in from the room.
4. A diffuser section to minimize the pressure drop between the test section and the fan.
5. A variable-speed fan that can be set to operate at a steady, user-specified speed. Student's specify the fan speed using a potentiometer on the wind tunnel control panel.

4.2.2 Velocity Measurement

Measuring the speed of the wind tunnel is essential to wind tunnel experimentation. However, students will not directly measure velocity. Rather students will measure a pressure difference and relate the pressure to velocity. The equation that relates the pressure to the velocity can be obtained from the pipe-flow energy equation (see your Fluids book) as

$$\frac{p_a}{\rho} + \alpha_a \frac{V_a^2}{2} + g z_a = \frac{p_{ts}}{\rho} + \alpha_{ts} \frac{V_{ts}^2}{2} + g z_{lt} \tag{4.1}$$

where p is the pressure, α is the velocity coefficient, V is the velocity, g is the gravitational constant, z is the elevation above some datum, and h_{lt} is the total head loss due to viscous losses through the contraction section and flow losses through the screens and honeycomb. These losses are indicated, respectively, as h_{lc}, h_{ls}, and h_{lh}. The subscript "a" refers to the ambient conditions in the room, and the subscript "ts" refers to the conditions in the test section. Equation 4.1 is simplified by assuming the following are true:

1. Height changes are negligible, i.e. $g(z_a - z_t s) = 0$.
2. Constant density.
3. Neglect V_a since the entrance area is large compared to the tunnel area.
4. Uniform entrance velocity to the test section, implying $\alpha_{ts} = 1$.

With these assumptions and some rearrangement, the energy equation becomes

$$V_{ts} = \sqrt{2\left[\left(\frac{p_a - p_{ts}}{\rho}\right) - h_{lt}\right]} \tag{4.2}$$

Under assumptions (1) and (3), the static pressure in room would equal the total ambient pressure. the If h_{lt} were negligible and the assumptions 1−4 above were sufficiently correct, the flow would be isentropic and the velocity in the test section could be determined precisely by measuring the difference between the total pressure in the room, p_a, and the test-section pressure, p_{ts}. This represents one technique to measure the velocity in the tunnel, in which the static pressure in the test section comes from the static ports mounted in a ring around the test section inlet. Unfortunately, h_{lt} is not negligible compared to the pressure term. Thus, accurate measurement of the velocity in the test section must be determined using other means, specifically using a pitot-static tube.

4.2.3 Pitot-Static Velocity Measurements

A common and reasonably accurate instrument to obtain the mean flow velocity is a Pitot-static tube connected to a differential pressure transducer. Figure 4.2 shows the construction of a Pitot-static tube. Pitot-static tube consists of two tubes within a tube. The interior tube connects to a small port at the tip of the Pitot-static tube. The outer tube connects to six or eight small ports, circumferentially located about three to ten probe diameters from the tip. When the axis of the Pitot-static tube aligns with the velocity vector, the flow will stagnate at the pressure hemispherical tip, resulting in a total (stagnation) pressure Po reading. In which the total pressure equals:

$$P_\circ = p_{ts} + \frac{1}{2}\rho V_{ts}^2 \tag{4.3}$$

The circumferential ports will sense the static pressure, p_{ts}. Subtracting p_{ts} from equation 4.3 gives the dynamic pressure:

$$\Delta P = P_\circ - p_{ts} = \frac{1}{2}\rho V_{ts}^2 \tag{4.4}$$

The pressure difference, Δp, is measured by means of a differential pressure transducer. Therefore, in a steady flow field, the Pitot tube senses the free stream velocity by measuring

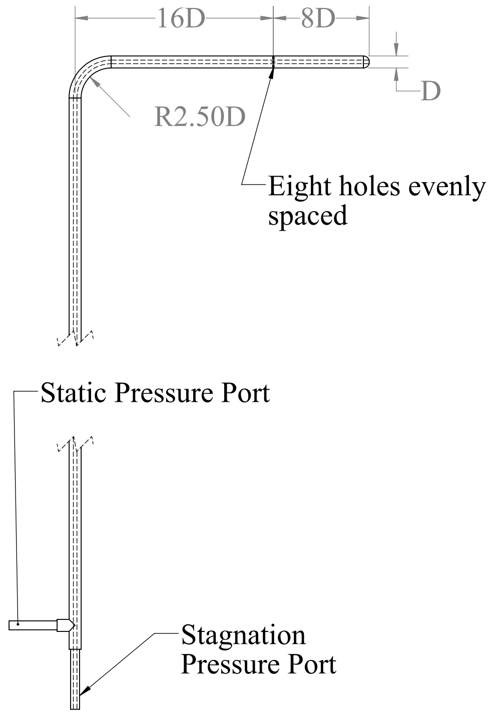

Figure 4.2: Sketch of a Pitot-static tube. Typically $D = \frac{1}{8}$ inches. Flow flows right to left for this configuration.

the pressure difference:

$$V_{ts} = \sqrt{\frac{2\Delta p}{\rho}} \tag{4.5}$$

To use equation 4.5, the density must be constant. In a gas flow such as air, this means that the flow must be incompressible, i.e., at a Mach number less than 0.3.

Often, Δp and ρ are not measured in the same system of units. For example, pressure is often measured in inches of water. From your study of hydrostatics, it is important to recall that, if h is the height in units of inches of water, then the pressure difference corresponding to this height can be computed using

$$\Delta p = \rho_{water} g h \tag{4.6}$$

where g is the local gravitational constant. Take care to ensure a consistent set of units in both equations 4.5 and 4.6.

Misalignment of the Pitot tube will lead to errors in both the measurement of the stagnation and static pressure as indicated in figure 4.11 in Barlow, Rae and Pope (3rd ed.).

This results in uncertainty in the measurement of the velocity. In many situations the flow direction may be unknown. To first order, one may assume the fluid flow parallel to the tunnel walls. However, imperfections and/or misalignment of the contraction section can cause the flow to deviate from parallel. By varying the angle of the Pitot tube and measuring the corresponding total pressure and $\Delta p(\theta)$, the flow angle can be determined since the maximum value of the total pressure will occur when the axis of the Pitot tube is aligned with the velocity vector. While the maximum total pressure indicates alignment with the flow, the maximum value of the dynamic pressure (Δp) occurs at a slightly positive yaw value (see figure 4.11 in Barlow et al., 1999).

4.2.4 Yaw Probe

A more sensitive means to determine the flow direction is to use a special probe called a yaw probe. The yaw probe used in this course consists of a cylinder with three pressure taps spaced at 45° intervals, attached to an alignment block. Ninety degrees separate the outer two taps and denoted as output taps 2 and 3 in figure 4.3. Output taps 1, 4, and 5 are not used in this experiment. The static pressure measured at taps 2 and 3 should be the same if the velocity vector bisects the angle between the holes. For this orientation, the pressure difference measured between taps 2 and 3 (Δp_{yaw}) would equal zero. In general, Δp_{yaw} equals a function of the angle between the flow direction and the bisector. Therefore, determining the flow angle simply requires adjusting the yaw probe until $\Delta p_{yaw} = 0$. Ideally, The angle of the flow equals the angle of the alignment block. However, One problem with the surface of the alignment block may not be parallel to the bisector of the angle between taps 2 and 3, giving rise to an "instrument uncertainty". One way to determine the magnitude of the uncertainty is to insert yaw probe from the opposite side of the wind tunnel where it will be inverted relative to its initial position and then find out the indicated angle where $\Delta p_{yaw} = 0$. This generates two Δp_{yaw} versus angle curves, one for the normal and one for the inverted positions. The angle of the flow equals the value of the angle where the two curves cross.

4.2.5 Test Section Velocity Profile

Wind tunnel design strives to create a uniform velocity profile across the test section and experimenters typically assume a uniform flow except for the thin boundary layer along the walls. Nevertheless, several factors can cause flow non-uniformity. For example, dirt may accumulate on the inlet filter and/or imperfections of the walls. Therefore before using any tunnel for the first time, the flow uniformity should be checked. During experimentation, pay close attention to any changes in the configuration of the wind tunnel that might modify

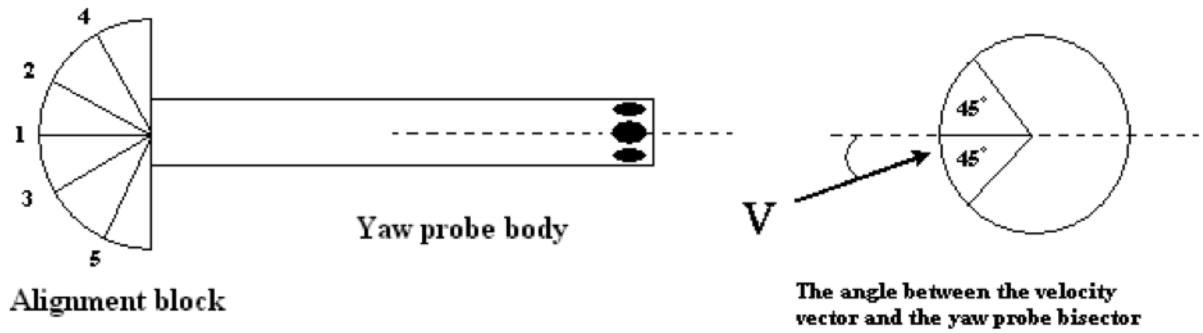

Figure 4.3: Yaw probe schematic

the uniformity such as failure to secure the test section doors?air will flow in from the open side of the test section, leading to a lower downstream velocity on the side opposite the open door. The boundary layer can provide insight into the flow behavior. Typically, the boundary layer spans from the wall to the point where the velocity achieves 95% of the free stream velocity. Characterizing the shape of the boundary layer velocity profile can indicate a laminar or turbulent flow. The Reynolds number, based on the distance from the nozzle exit plane to the plane where the velocity profile is determined (although, technically, there is some small amount of boundary layer formation within the nozzle as well), also indicates the type of flow.

4.2.6 Computer Data Acquisition System

With the advent of modern computing systems, acquiring data has become simpler. The typical computer- based data acquisition system consists of a computer, a control board, and appropriate software. In general, the control board can be an internal plug-in board or a board mounted externally to the computer but connected via cables. In lab, students will find a personal computer equipped with National Instruments' LabView that reads data from a National Instruments NI 9205 analog converter (DAQ). The DAQ converts the analog signal (voltage or current, depending on the device) into a digital signal. In most cases, the conversion is done in near real time, depending on the acquisition rate. The experimental equipment output the analog signal, traveling through cables to the DAQ, specifically in experiment one from the Setra Pressure transducer. Figure 4.4 shows a general schematic of this process. Processing certain signals may require the use of other interface electronics—such as filters, amplifiers, and/or signal conditioning devices—depending on the experiment and equipment.

Computer based data acquisition has a key ability to resolve temporal changes. The

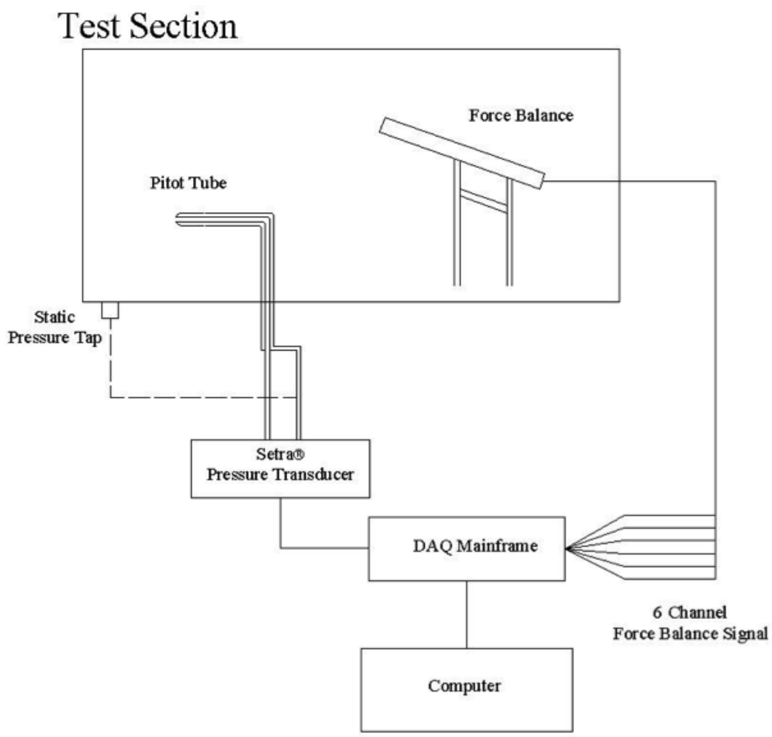

Figure 4.4: Experimental setup of experiment 2

NI 9205 can take up to 250,000 samples per second for a fixed sample time set by the experimenter in LabView. Therefore, the experimenter can recreate the signal in time to understand how the value (for example velocity) changes with time?if the rate of change of the signal does not exceed the sample rate. In this lab, however, students will focus on average quantities, in which the high sampling rate provides a good statistical average. Figure 4.5 shows the LabView module for determining the average speed of the wind tunnel. In ever lab, students will use this module to set the wind tunnel speed. The procedural section of this chapter details using the module.

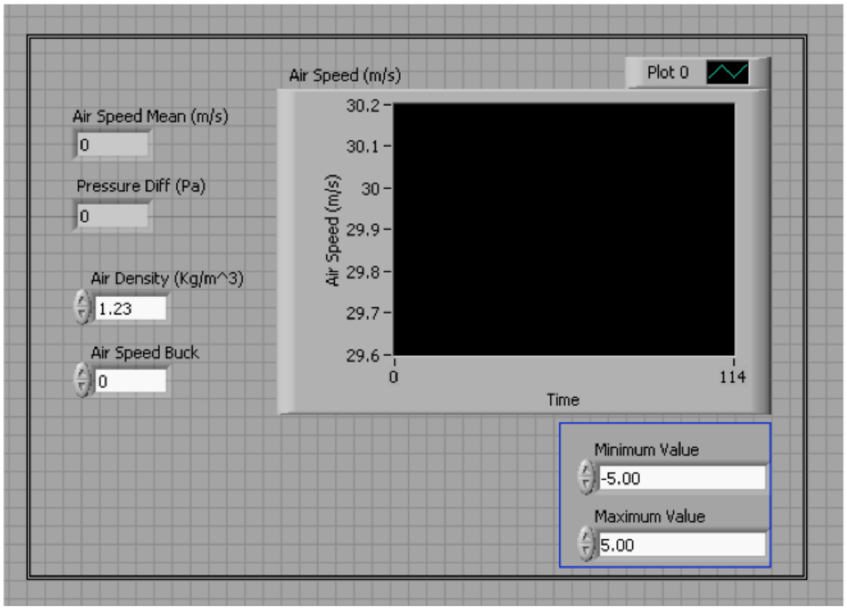

Figure 4.5: LabView Code used in all experiments

4.3 Description of Experiment 1

4.3.1 Objective

The objectives of this experiment are as follows:

1. To measure the sensitivity of a Pitot-static tube to misalignment.
2. To quantify the difference between the velocity reading from the Pitot-static tube versus that determined from the static pressure tap at the test section inlet.
3. To determine the flow angle using a cylindrical yaw probe and the misalignment of the alignment block of the yaw probe.
4. To measure the wind tunnel velocity profile near the test section entrance.

4.3.2 Procedure

1. Before you come to the lab period, create a data sheet using a spreadsheet program (e.g., Excel) with the equations and plots coded into the spreadsheet. A sample spreadsheet for this lab is shown at the end of the procedure. **Show the laboratory assistant the spreadsheets at the beginning of the laboratory period.**
2. Before you come to the lab period, create a calculator that takes in the relative humidity, total pressure, and temperature and outputs the density of humid air. textbfShow

this calculation to the laboratory assistant. Students will use this calculation before every experiment.

3. Using the hygrometer/barometer/thermometer in the lab to record the relative humidity, total pressure, and temperature in the room.

4. Enter the values taken in step 3 into the program in step 2 to determine the density of humid air.

5. Enter the calculated density of humid air into the LabView program (figure 4.5) under "Air Density".

6. Zero the Setra pressure transducer by connecting the reference port to the positive pressure port.

   (a) Run the LabView program

   (b) Record the measured velocity into the "Air Speed Buck" input in the code (figure 4.5).

   (c) Run the LabView program again to ensure the velocity reading ("Air Speed Mean (m/s)") equals zero ± 0.1 m/s.

7. Place the digital level on the floor of the wind tunnel test section. Record the value.

8. Insert the Pitot-static tube into one of the threaded fittings in the side of the test section so that the sensing head is in the center of the test section.

9. Connect the reference tube of the Setra pressure transducer to the static port of the Pitot-static tube.

10. Connect the reference tube of the Setra pressure transducer to the static port of the Pitot-static tube.

    (a) The Setra pressure transducer calculates the difference in pressure as the positive port minus the reference port, which if set-up properly will give a positive velocity. If the LabView program reads a negative velocity, simply switch the connects.

11. Set the Pitot-static tube so that the tip is horizontal using the digital level.

    (a) Any means – a protractor or a Bevel Gauge – can be used to measure the angle of the Pitot-static tube. However, the measurement must be taken outside of the test section.

12. Using the potentiometer adjust the speed until the LabView program reads 30 m/s.
    (a) The LabView program calculates an average, and thus students will not achieve exactly 30 m/s. Having the average within ± 0.5 m/s of 30 m/s works. Record the true wind tunnel velocity.
    (b) When setting the speed, run the LabView program continuously. However, when determining the average or taking a data point, run the LabView program for one iteration.
13. Using the digital level, set the Pitot-static tube at successive clockwise two-degree increments from the initial position until an appreciable drop in dynamic pressure occurs. Record at each angle:
    (a) The value of the dynamic pressure (Δp)
    (b) The total (stagnation) pressure.
        i. Do this leaving the positive pressure port of the Setra connected to the total pressure port of the Pitot-static tube and removing tube connected to the static port. Leave the reference port open to the atmosphere. This gives the difference between the apparent total pressure and the room pressure (which is constant), or $P_\circ - P_a$.
    (c) Plot the dynamic pressure versus angle and the total stagnation pressure versus angle as the data is collected.
14. Rotate the probe at one- or two-degree increments in the counterclockwise direction, recording and plotting the same data as step 13.
15. Orient the Pitot-static tube so that $P_\circ$ (i.e., $P_\circ - P_a$ from the Setra transducer) is a maximum,
16. Adjust the tunnel speed to 2 m/s.
17. Record the dynamic pressure and velocity from the LabView Program for:
    (a) The Pitot-static tube connected to the Setra pressure transducer.
    (b) The static pressure taps on the wind tunnel hooked up to the reference port of the Setra pressure transducer while the positive pressure port is left open to atmosphere
18. Repeat step 17 for the velocities 5, 10, 15, 20, 25, 30, and 35 m/s.

19. Bring the tunnel speed back to about 30 m/s and record the true velocity from the LabView program

20. Remove the Pitot-static tube and place the yaw probe in the wind tunnel with the pressure taps pointing upstream. **Do not change the tunnel speed when exchanging the Pitot and yaw tubes.**

21. Place the digital level on the alignment block and adjust the yaw probe until the angle reading is the same as that measured for the floor of the tunnel.

22. Connect the tubing from the Setra pressure transducer to the yaw probe ports 2 and 3.

23. Rotate the yaw probe in clockwise one-degree increments to plus ten degrees, recoding the Δp_{yaw} value and the angle value for each angle. This will be the "erect" position.

24. Then rotate the yaw probe in counterclockwise one-degree increments from the starting position to minus ten degrees. Record the angle and corresponding Δp_{yaw} value.

25. Insert the yaw probe through the threaded hole in the opposite side of the wind tunnel (thereby inverting the instrument) and repeat steps 23 and

26. This will be the "inverted" position. Make sure to maintain a consistent angle convention between the erect and inverted positions.

27. Replace the yaw probe with the Pitot-static tube, connecting the pitot-static tube as done in steps 9 and 10 to the Setra pressure transducer.

28. Adjust the pitot-static tube to be parallel to the test section floor using the angle determined in step 7.

29. Adjust the wind tunnel speed to 30 m/s.

30. Adjust the length of the pitot-static tube such that the sensing head touches the near wall.

31. Record the velocity reading from the LabView Program and denotes this as transverse distance zero.

32. Adjust the length of the pitot-static tube in 1 mm increments for the first 2 cm, recording the velocity and transverse distance at each point.

33. After traversing 2 *cm* move the pitot-static tube in 4-*cm* intervals until reaching 2 *cm* away from the far wall.

34. Turn off the wind tunnel.

35. Open onside of the test section to record the approximate downstream distance between the nozzle exit plane/test section entrance and the location of the tip of the probe.

36. Also, measure the height and width of the test section.

37. Return everything to its proper place for the next lab.

4.3.3 Data Reduction

Figures and Tables

1. Draw a block diagram of the system used in this experiment.

2. List the equipment used in the lab and briefly describe it. A table works well for this.

3. Plot the dynamic and total pressures from the Pitot tube as a function of angle relative to the angle of the tunnel floor. To obtain the total pressure, add the measured ambient pressure term back into the measured value $P_\circ - P_a$. Make the reading non-dimensional by dividing by the maximum value of the dynamic pressure, as done in figure 4.11 of Barlow. Note the sign convention on each pressure term! All of these plots are to appear on one, clearly annotated graph, as done in figure 4.11.

4. First, plot Δp_{yaw} divided by the maximum dynamic pressure measured by the Pitot tube as a function of attack angle for both the "erect" and "inverted" positions. Secondly, on the same figure, show the corresponding value that would be predicted from potential flow theory using equation 4.7, using the following steps:

$$\frac{p(\beta) - p_{ts}}{\frac{1}{2}\rho V_{ts}^2} = 1 - 4\sin^2\beta \tag{4.7}$$

   (a) Determine the yaw probe angle corresponding to the flow direction. See figure 4.3.

   (b) Determine the corresponding flow angles for the pressure taps located at locations "2" and "3" in figure 4.3. Call these β_1 and β_2.

   (c) Substitute β_1 and β_2 into equation 4.7 for every data point to get the normalized pressure at each of the two locations.

(d) Subtract the difference to get $dP_{theoretical}$, which can then be compared to the normalized measured dP.

5. Plot the velocity obtained from the wind tunnel static taps immediately upstream of the test section as a function of the velocity indicated by the Pitot-static tube.

6. Plot the measured wind tunnel velocity normalized by the centerline velocity as a function of distance from the far wall.

7. On a second plot, plot the near wall, i.e., only the measurements of the normalized velocity that are less than 0.95 in value.

Questions

1. Based on the yaw measurements in the "erect" and "inverted" positions, determine the misalignment or instrument error of the alignment block.

2. Based on the Pitot tube measurements as a function of angle, determine the angle of the flow relative to the tunnel floor.

3. Based on the yaw probe measurements, determine the angle of the flow relative to the tunnel floor.

4. Determine the maximum misalignment possible for the Pitot tube so that the velocity will be within 1% of the value indicated when the probe is aligned with the flow. Do you think that you can obtain the required alignment by "eye", or do you need an alignment aid?

5. Determine the maximum difference between the velocity measured by means of the Pitot tube and the velocity using the static taps at the wind tunnel inlet. Determine the velocity range where the velocity measured using the static taps is within 1% of the corresponding velocity measured using the Pitot tube.

6. Explain any differences between the theoretically (i.e., potential flow) and experimentally determined Δp_{yaw} *vs* angle of attack curves. (In future labs, you will use an uncertainty analysis to guide your answer, but for now just give some qualitative reasons.)

7. Based on the length from the nozzle exit/test section entrance to the measurement plane of the Pitot-static tube calculate the Reynolds Number of the flow and state if the is flow laminar or turbulent?

8. Based on the velocity profile near the wall (plotted for data reduction question 7), does the profile show a turbulent boundary layer or a laminar Boundary layer. Is this consistent with the Reynolds Number calculated in question 7?

4.3.4 Sample Spreadsheet

Consider the data required for step 13 of section 4.3.2, in which the angle of the pitot-static tube varies to determine how the dynamic and stagnation pressure vary with a change in the alignment angle. Table 4.1 shows a table to take in angle, dynamic pressure, and stagnation pressure. Figure 4.6 has been set up to generate the plot of the data in table 4.1 by selecting the empty cells where data will be entered.

Table 4.1: Sample data table for step 13 of section 4.3.2

Angle (°)	Dynamic Pressure (Pa)	Stagnation Pressure (Pa)
0.00		
1.00		
2.00		
3.00		
4.00		
5.00		
6.00		
7.00		
8.00		
9.00		
10.00		
11.00		
12.00		

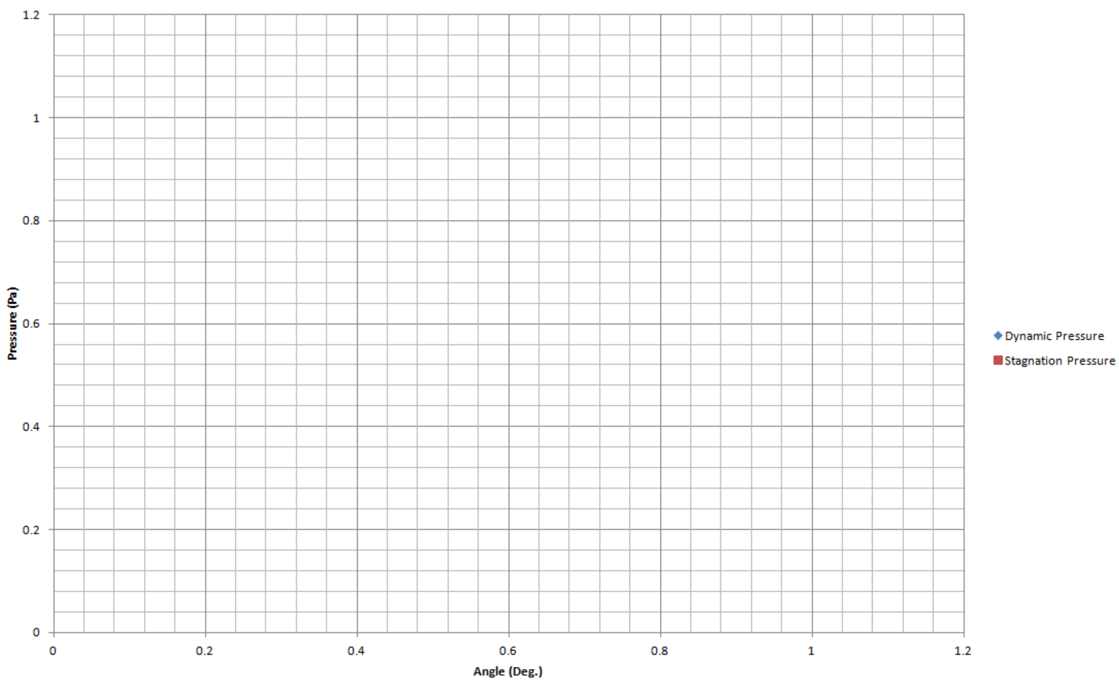

Figure 4.6: Blank plot ready to plot the data in table 4.1.

Chapter 5

Experiment 2: Drag of Simple Shapes and Calibration of Force Balance

5.1 Objective

The objective of this experiment is to determine the drag and drag coefficient on blunt and streamlined objects as a function of velocity and boundary layer type, i.e., laminar or turbulent.

5.2 Overview

Total drag on objects in high Reynolds number and incompressible flows consists of skin friction and pressure drag. Viscous forces at the surface of the object results in skin friction drag. At moderate Reynolds numbers, pressure drag dominates the total drag. For example, a sphere at a Reynolds number of 1000 has a skin friction drag approximately equal to 5% of the pressure drag. However, on streamlined objects, the skin friction drag can become a large fraction of the total drag. An unequal pressure distribution on the upstream- and downstream-facing surfaces of the object results in pressure drag. The unequal pressure distribution arises because of separation of the boundary layer. The point at which separation occurs, and hence the magnitude of the pressure drag, depends on the shape of the object and whether the boundary layer is laminar or turbulent. The chapter will discuss the effect of shape on drag and the instrumentation used to measure the drag force.