ASEN 2002
Aerodynamics Experimental Laboratory 1
Calibration of the ITLL Low-Speed Wind Tunnel

Assigned: Wednesday 24 October

Lab Reports due: **Wednesday 14 November 12:01 AM**

OBJECTIVES

- *Learn basic concepts and definitions associated flow measurements and wind tunnel testing.*
- *Apply the conservation of mass and Bernoulli's equation to measure the airspeed.*
- *Develop an awareness of sources of error and error analysis.*
- *Observe the development of viscous boundary layers in the test-section and understand the impact they have on the airspeed in the test-section.*

REQUIRED DELIVERABLES

- *Attendance at every lab period is required. Instructions for weekly tasks and the individual report will be presented during the scheduled lab time.*
- *Prepare a written brief report of the results of your laboratory exercises. Use the guidelines that will be provided to complete your report.*

TEXT REFERENCES

"Introduction to Flight" 8th ed. by Anderson

- ***Fundamentals:*** *2.1, 2.3, 2.4*
- ***Conservation Equations:*** *4.1, 4.3,*
- ***Wind Tunnels and the Measurement of Velocity:*** *4.10, 4.11*
- ***Viscous Flow and Boundary Layers:*** *4.15, 4.16, 4.18*

"Fundamentals of Thermal Fluid Sciences" 4th ed. by Cengel, Cimbala, and Turner

- ***Measurements:*** *2-6, 2-7, 2-8*

"Introduction to Error Analysis" 2nd ed. by Taylor

- ***Error and Uncertainty Analysis:*** *Chapters 1-4*

SUMMARY

Wind tunnels are tools utilized in the aeronautical testing world to reveal a detailed understanding of how a flowing gas physically interacts with a "stationary" test article. As with any tool you must first understand how it performs and what its limitations are before you can be confident that you have selected the appropriate tool and that the results will be accurate.

You will be using the ITLL Low-Speed Wind Tunnel regularly throughout the aerospace engineering curriculum here at CU. Thus this laboratory assignment will serve as a foundational component developing your fundamental understanding of how the wind tunnel performs through a "calibration" of the test-section. Specifically you will focus on understanding how the wind tunnel operates and how its speed is measured in the test-section. Then you must understand the limitations on this measurement through a detailed quantification of the uncertainty in the air-speed measurement. Finally, it is typically assumed that the velocity throughout the test-section is uniform and constant. This is often not true! You must measure the variation in the airspeed and discover how it is governed by the fundamental theories that we discuss in class. All of this will help you as you progress through the curriculum and perform more complex measurements in the wind tunnel during this and future courses.

ITLL LOW-SPEED WIND TUNNEL BACKGROUND

Configuration

The ITLL Low-Speed Wind Tunnel is an Eiffel or open-circuit suction type wind tunnel. A schematic of the wind tunnel is presented below in Figure 1. This schematic includes labels for each of the sections of the wind tunnel and nominal dimensions, in inches, from the manufacturer: Aerolab LLC.

The wind tunnel has a “closed” test-section that is nominally 12 in. by 12 in. by 24 in. long. Air is “pulled” through the test-section by a 9 bladed fan driven by a10 HP electric motor that is located downstream from the test-section at the wind tunnel exit. It is also worth noting that the airspeed is accelerated theoretically from rest in the surrounding room into the “test-section” by way of the inlet, flow conditioners, stilling chamber, and contraction (or nozzle) that has a 9.5 to 1 area ratio. Each of these sections plays an important role in ensuring that the flow is uniform, steady, and at the right speed in the test-section.

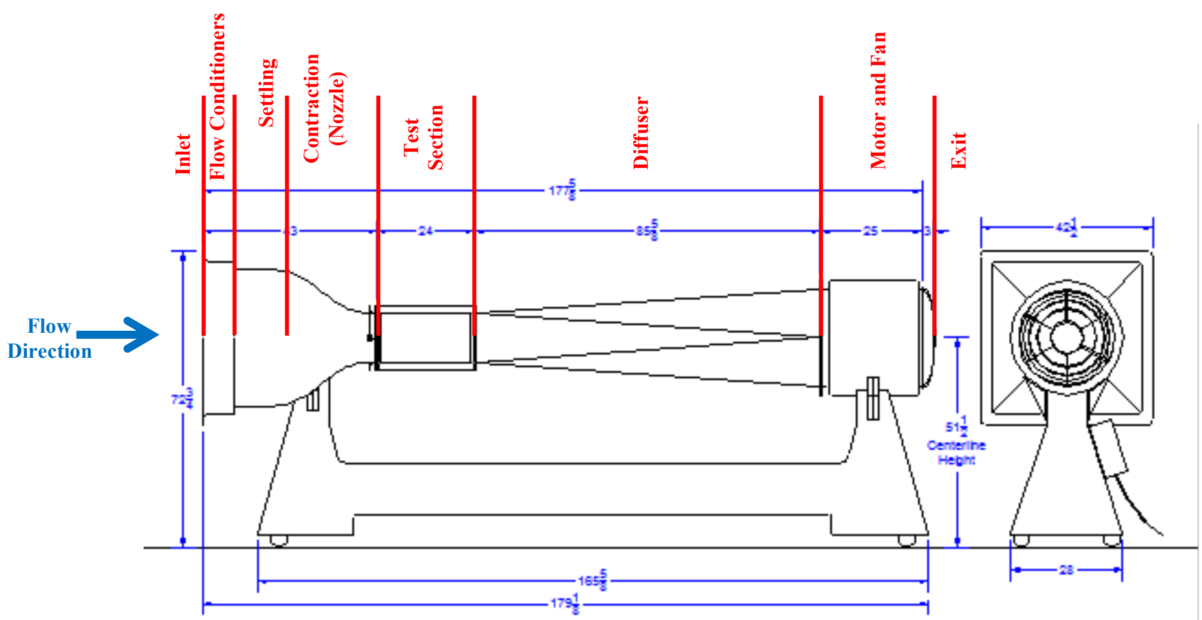


Figure 1: Engineering drawing views of the ITLL Low-Speed Wind Tunnel. Flow is from left to right in the side view (left) drawing and out of the page in the rear (right) drawing.

Measurement Devices

There are a variety of different measurements that can be made in the wind tunnel. For this laboratory we will focus on quantifying the airspeed in the test-section from the direct measurement of temperature and pressure.

Temperature

The physical measurement of temperature was discussed in the Thermodynamics Experimental Laboratory 1 Assignment. As a result it is assumed that you have developed a fundamental understanding of how temperature measurements can be made. For the wind tunnel facility, ambient or atmospheric temperature, T_{atm}, measurements are made with an LM35 Precision Centigrade Temperature Sensor from National Semiconductor. Note that the manufacturer states that this device has a range -55º to +150ºC and a typical accuracy of ±¼ºC at room temperature.

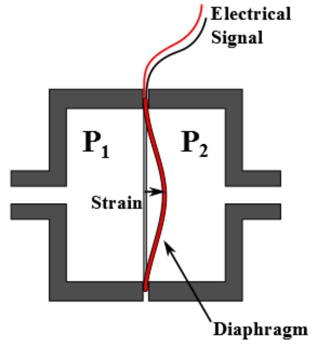


Figure 2 Schematic showing the fundamental configuration of a piezo resistive pressure transducer.

Pressure

As with temperature, pressures are always physically measured as a relative quantity. That said when discussing pressure measuring devices there are three common terms often used: (1) absolute, (2) gauge, and (3) differential. Each of these implies a different relative measurement. Specifically, an **absolute** pressure measurement device quantifies the pressure magnitude at a certain point of interest relative to a perfect vacuum. A **gauge** pressure measurement device quantifies the pressure of interest relative to the ambient or atmospheric pressure. Finally, a **differential** pressure measurement device quantifies the relative difference in pressure between two specific locations of choice. In the current laboratory assignment, three different pressure measurement devices will be used with the wind tunnel. These include a U-tube manometer, a differential pressure transducer, and an absolute pressure transducer, each of which is discussed below.

<u>U-tube manometers</u>

U-tube manometers represent the simplest and most traditional means of quantifying a differential pressure. They quantify the change in pressure through displacements in the static head of a known fluid (typically either water, oil or mercury). For more information on the operation of manometers refer to section 2-8 in the Thermo-Fluids text by Cengel et al. and section 4.10 in the Aero text by Anderson. The Dwyer Flex-Tube U-Tube manometer attached to the ITLL Low-Speed Wind Tunnel is filled with a red fluid which has a specific gravity of 0.826. The manometer ruler is calibrated to read inches of water and has a maximum range of ±6 in with 0.1 inch gradations.

<u>Pressure Transducers</u>

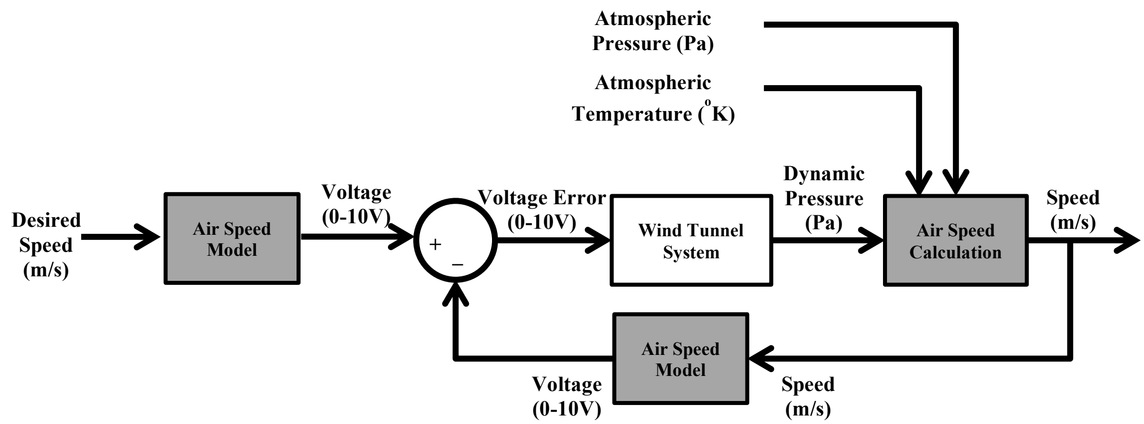
A pressure transducer is a device that converts the physical property of pressure into an electrically measurable signal. Be aware there are many different types of transducers available on the open market which can rely on drastically different means of measuring pressure. The type used with the wind tunnel, and one of the most common types, is a piezoresistive transducer. These are electro-mechanical transducers in that a pressure difference is applied across a thin diaphragm causing it to mechanically strain (or deform) under the applied force (see Figure 2). This strain results in a change in the electrical resistance of the diaphragm material (typically a piezo ceramic material) which through additional circuits (not discussed or displayed here) is measured as a change in voltage. To measure an absolute pressure the reference side of the transducer, P_2, is sealed and held at a fixed pressure. In contrast, P_2 in a gauge pressure measurement would be left open to the ambient environment to allow for the relative pressure between P_1 and the atmospheric pressure in the vicinity of the transducer.

For the current assignment we will be using three pressure transducers with the ITLL wind tunnel. The dynamic pressure in the wind tunnel can be measured with one of two separate Honeywell SCX01DN differential pressure sensors. The manufacture states that these devices have a full-scale operating range of 0 psid to 1 psid and that it has a calibrated accuracy of ±1% of the full scale span. The third transducer is used to measure the ambient or atmospheric pressure within the ITLL laboratory space. It is a Freescale Semiconductor MPX4250A Absolute Pressure Sensor, which has a full measuring range of 20 kPa to 250 kPa and an accuracy or ±1.5% of the full scale span, as quoted from the manufacturer.

FUNDAMENTAL OPERATION OF THE WIND TUNNEL

In future experiments you will operate the wind tunnel by commanding it to achieve a set test-section airspeed via a control program on the wind tunnel computer. The program will achieve this desired velocity through a “feed-back control system” that incorporates the computer software with wind tunnel measurement sensors and the wind tunnel fan-motor system. A general engineering schematic outlining this control system is presented in Figure 3 below. You will learn more about dynamics and control in your future courses, namely ASEN 2003, ASEN 3128, and

ASEN 3200. However, there are two functions within the control system that are pertinent to the goals of this class and they are required for the control system to function properly. The first is **an algorithm for calculating the airspeed** from the direct measurements of the atmospheric pressure, atmospheric temperature, and the dynamic pressure in the test-section. The second is **an airspeed model** that converts the desired speed into a voltage input for the wind tunnel fan-motor system. These two components are critical to calibrating a new wind tunnel facility and are thus the focus of the first part of this experimental laboratory assignment. More details on each are discussed



below.

Figure 3: Schematic of the wind tunnel feedback control system, highlighting the airspeed model and calculation functions.

Airspeed Calculation

Unfortunately there is no way to directly measure the airspeed. Airspeed is a quantity that is typically derived from a combination of other direct measurements. This is discussed in detail in sections 4.10 and 4.11 of Introduction to Flight by Anderson. Specifically, for the ITLL Low-Speed Wind Tunnel we can utilize Bernoulli's Equation for incompressible flow to relate the pressure at various locations to the square of the velocity (or airspeed).

$$p_1 + \tfrac{1}{2}\rho V_1^2 = p_2 + \tfrac{1}{2}\rho V_2^2 = p_3 + \tfrac{1}{2}\rho V_3^2$$

This equation relates pressure and velocity; however it also requires knowledge of the fluid density. Unfortunately the fluid density is another quantity that is also not directly measured. Instead we rely upon our understanding of the thermodynamics and employ the equation of state for a perfect gas to relate the density to the direct measurements of temperature and pressure.

$$\rho = \frac{p}{RT}$$

For incompressible flow we assume that the density is constant at each location within the wind tunnel. Thus to compute density we need to know both pressure and temperature at only one location in the system. Typically we will use the atmospheric pressure and temperature measurements outside of the wind tunnel under similar stagnant flow conditions to accomplish this.

$$\rho = \frac{p}{RT} = \frac{p_{atm}}{RT_{atm}}$$

Through combining Bernoulli's Equation and the Equation of State for a Perfect Gas we can now develop a single equation that relates wind tunnel airspeed directly to the quantities that we directly measure in the wind tunnel system. The next step is to consider where the direct measurements are acquired in the wind tunnel system and what assumptions we can make about the velocity at those locations. For the ITLL Low-Speed Wind Tunnel there are two standard air-speed measurement configurations that we can use, each of which is detailed in Figure 5 below.

First we can measure the differential pressure, Δp, across a Pitot-Static probe mounted in the wind tunnel (Figure 5a) as discussed by Anderson in section 4.11. This method allows for a direct measure of the difference between the static pressure, p_s, and total pressure, p_0, at effectively the same location in the flow field. Furthermore, this differential pressure is then equivalent to the dynamic pressure, q; assuming that we have minimal losses between the total and static measurement locations. As a result from Bernoulli's Equation:

Figure 4 Cross-sectional view of a Pitot-Static Probe configuration. In this case the static pressure is denoted as p_∞ and the total is denoted as p_0.

$$p_0 + \tfrac{1}{2}\rho V_0^2 = p_s + \tfrac{1}{2}\rho V_s^2$$

but,

$$V_0 \to 0$$

and

$$V_s = V_\infty$$

so

$$p_0 - p_s = \Delta p = q = \tfrac{1}{2}\rho V_\infty^2 = \tfrac{1}{2}\left(\frac{p_{atm}}{RT_{atm}}\right)V_\infty^2.$$

This can be rearranged to provide:

$$V_\infty = \sqrt{\frac{2\,(p_0 - p_s)}{\rho}} = \sqrt{\frac{2\,\Delta p}{\rho}} = \sqrt{2\,\Delta p\left(\frac{R\,T_{atm}}{p_{atm}}\right)}.$$

One negative effect of using a Pitot-Static Probe to measure the wind tunnel speed is that this requires the insertion of the probe into flow upstream of where you may want to test a model. As a result the blockage and wake of your probe can influence your model and potentially bias other results.

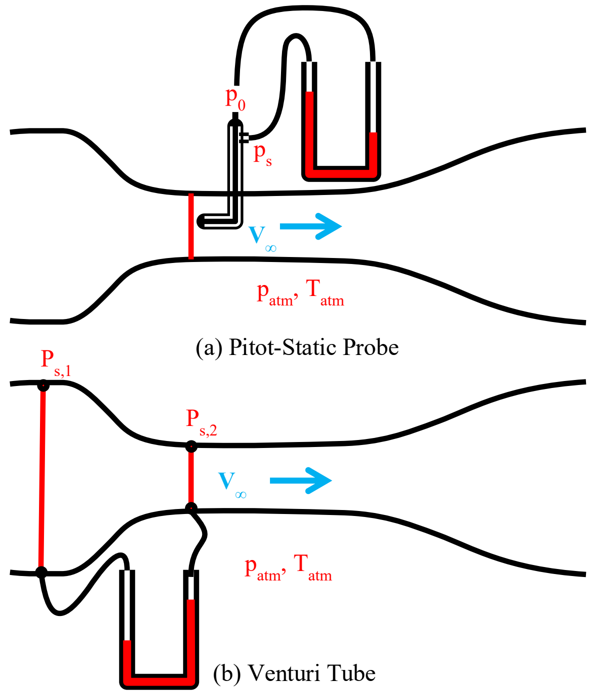


Figure 4: Schematic displaying the two standard air-speed measurement configurations for the ITLL Low-Speed Wind Tunnel. Note the static pressure is denoted as p_s.

The second configuration eliminates the need for a probe through comparing the average static pressure at two different locations in the wind tunnel. Typically this comparison is made between the test-section and the settling chamber as discussed by Anderson in section 4.10 and presented in Figure 5b. Again in this case we can use Bernoulli's equation:

$$p_{s,1} + \tfrac{1}{2}\rho V_{s,1}^2 = p_{s,2} + \tfrac{1}{2}\rho V_{s,2}^2,$$

and,

$$p_{s,1} - p_{s,2} = \Delta p = \frac{1}{2}\rho\left(V_{s,2}^2 - V_{s,1}^2\right)$$

where

$$V_{s,2} = V_\infty.$$

However in this case the velocity in the settling chamber, $V_{s,1}$, does not go to zero; as with the Pitot-Static Probe. So to reduce the number of unknowns we need to find a way to relate the velocity in the settling chamber to the velocity in the test-section. To due this we apply our understanding of the conservation of mass and our assumption that the flow is incompressible. Thus we arrive at:

$$A_1 V_{s,1} = A_2 V_{s,2},$$

or

$$V_{s,1} = \frac{A_2}{A_1} V_{s,2} = \frac{A_2}{A_1} V_\infty,$$

where A_1 and A_2 are the cross-sectional areas of the settling chamber and the test-section of the wind tunnel. We can now relate the pressure difference to the test-section velocity:

$$p_{s,1} - p_{s,2} = \Delta p = \frac{1}{2}\rho\left(1 - \left(\frac{A_2}{A_1}\right)^2\right) V_{s,2}^2 = \frac{1}{2}\left(\frac{p_{atm}}{RT_{atm}}\right)\left(1 - \left(\frac{A_2}{A_1}\right)^2\right) V_\infty^2.$$

Now as before, this can then be reorganized to provide the test-section velocity:

$$V_\infty = \sqrt{\frac{2\,(p_{s,1} - p_{s,2})}{\rho\left(1 - \left(\frac{A_2}{A_1}\right)^2\right)}} = \sqrt{\frac{2\,\Delta p\; R\; T_{atm}}{p_{atm}\left(1 - \left(\frac{A_2}{A_1}\right)^2\right)}}.$$

This is known as the Venturi Tube equation. Where a Venturi Tube, is a general measurement probe/device that computes the velocity through relating the pressures and cross-sectional areas at two different stations within a channel or pipe. Fundamentally, in this case we are treating the wind tunnel as a large Venturi Tube.

QUESTIONS TO ADDRESS: *How well do the two velocity measurement methods compare? Are there any differences between the velocity results? If so, what do you think is causing them? What happens as the area ratio, A_2/A_1, between the settling chamber and the test-section changes? Do you think there would be a benefit to having a larger or smaller area ratio, why?*

Airspeed Model

As highlighted above the wind tunnel airspeed is directly controlled by the fan. More specifically, as with a standard household fan the velocity in the test-section will increase with the fan rotational speed (i.e. RPM). The fan speed is driven and controlled by a 10 HP electric motor and a variable frequency speed controller, respectively. The details of how the controller operates are not critical for this laboratory assignment. What is important to understand is that the fan speed is set by a DC voltage command to the controller between a minimum of 0 volts and maximum of 10 volts. These correspond to zero RPM and the maximum safe operating RPM for the wind tunnel motor –fan assembly. In order to accurately predict the voltage required to achieve a desired velocity we need to first develop a model or a mathematical equation that relates the wind tunnel speed to the input voltage for the current ambient conditions (i.e. atmospheric pressure and temperature).

To build this model you will need to measure the wind tunnel airspeed at multiple fixed voltage settings distributed across the full voltage range (i.e. 0 – 10 VDC). Then you will have to post-process and analyze these results through applying an appropriate curve fit through the data to develop a mathematical model that relates the direct measurements (i.e. pressure and temperature) to the motor-controller command voltage. This process should be done for each of the air-speed measurement configurations and a comparison should be made.

QUESTIONS TO ADDRESS: *How does the velocity change with the input voltage? What type of relation best matches the response (i.e. linear, quadratic, cubic, logarithmic, etc)?*

Wall Boundary Layer Influence

Boundary layers are regions of retarded flow (or velocity deficit) concentrated around bodies due to the enforcement of the no-slip condition at the body's surface as a fluid flows past it. Furthermore you should be aware that the thickness of a boundary layer will grow as the flow moves downstream due to the inherent viscosity within the flowing fluid. For additional details on the fundamentals of viscous flow and boundary layers you should refer to Sections 4.15, 4.16, and 4.17 in the text book by Anderson.

It should come as no surprise then that boundary layers will form and grow on each of the test-section walls within the wind tunnel. As these boundary layers grow they will effectively produce a blockage to the main flow in the wind tunnel. This is graphically depicted in Figure 6 below. Since the flow is confined within the walls of the "closed" test-section this boundary layer induced blockage will create a reduction in the effective cross-sectional area of the wind tunnel. From the application of the conservation of mass it should be clear that the velocity in the test-section must accelerate to compensate for this reduction in the effective test-section area. Thus to completely understand how our wind tunnel behaves we must quantify how the flow naturally accelerates through the test-section. This will allow us to determine the limitations on where we can effectively mount models and sensors in the wind tunnel. Additionally it will also provide us an understanding of what the true airspeed is at those locations.

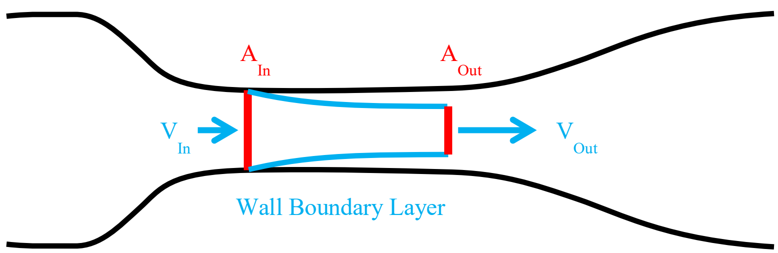


Figure 5 Schematic displaying the influence of the wall boundary layers on the airspeed in the wind tunnel test-section.

As a result, during the wind tunnel calibration we must measure centerline airspeed at multiple locations downstream from the test-section inlet. We will do this using the Pitot Probe mounted on the two axis traverse located on the ceiling of the test-section. Note that a Pitot probe only measures the total or stagnation pressure in contrast with the Pitot-Static probe we used earlier. However to calculate the airspeed we need the differential pressure between the total and a static pressure at the same streamwise position. Thus we will measure the static pressure from a port on the wind tunnel floor and use our fundamental understanding of boundary layer theory to assume that the static pressure will be constant vertically across the boundary layer and thus vertically constant across the test-section.

In order to relate the increase in centerline velocity back to the influence of the viscous boundary layers we must also quantify the thickness of the wall boundary layers at the same locations. Again we will use the same Pitot probe configuration discussed above in conjunction with the traversing system to precisely measure the velocity distribution away from the test-section wall. For these measurements, we will define the edge of the boundary layer at the point where we reach 95% of the free-stream velocity. Mathematically that is:

$$\delta = y \ @ \ V = 0.95 \cdot V_\infty.$$

Then using our understanding of the conservation of mass and physical measurements of the test-section size we can attempt to relate the boundary layer growth to the acceleration in the test-section airspeed.

QUESTIONS TO ADDRESS: *Does the measured increase in the centerline velocity match the expected flow acceleration due to the measured wall boundary layer thickness at your streamwise measurement location? If not why do you think they differ? When you compare the results at multiple streamwise measurement locations do you see a trend?*

Airspeed Uncertainty Analysis

Up to this point we have discussed the measurements that we are taking as steady-state individual values with exact precision. By now you should be aware that no measurement has exact precision and very few (if any) are perfectly constant in time. Thus we must develop some level of confidence in our measurements by quantifying a mean value and level of uncertainty (or range) within which we expect that mean value to reside.

Statistically we will quantify the mean of each physical measurement by taking the time-average of a series of measurements acquired at a set frequency for a defined period of time. For this laboratory experiment we will sample all of the electronic sensors at a rate of 500 Hz for 0.04 seconds giving us 20 samples. From this we can then calculate the mean measurement for each signal and then compute the average airspeed using the previously developed analytical function (see Airspeed Calculation section above).

Estimating the uncertainty in the airspeed is a multistep task. Since the airspeed is a measurement that is derived from other direct measurements we must consider the propagation of the uncertainties from each of these measurements into the calculation of airspeed. For more information on uncertainty you should refer to chapters 1- 4 from the textbook "*Introduction to Error Analysis"* by Taylor that is used in ASEN 2012. Specifically in Section 3.11 a general formula for computing the propagation of uncertainty in a function of several variables is developed. Specifically it states:

$$\delta q = \sqrt{\left(\frac{\partial q}{\partial x}\delta x\right)^2 + \cdots + \left(\frac{\partial q}{\partial z}\delta z\right)^2}$$

where δq is the total uncertainty for the function of interest and $x \ldots z$ are the independent variables governing q. When we apply this for our case to determine the uncertainty in airspeed we find:

$$\delta V = \sqrt{\left(\frac{\partial V}{\partial \Delta p}\delta \Delta p\right)^2 + \left(\frac{\partial V}{\partial p_{atm}}\delta p_{atm}\right)^2 + \left(\frac{\partial V}{\partial T_{atm}}\delta T_{atm}\right)^2}.$$

Now to be rigorous, the uncertainties in each of the independent variables (i.e. $\delta\Delta p, \delta p_{atm}, and\ \delta T_{atm}$) should include the errors associated with the random fluctuations (or statistical variation) of the measurement, the errors associated with the measurement hardware, and errors provided by the sensor manufacturer relating to the sensor calibration and performance. For now let's neglect the errors associated with the random fluctuations and the measurement hardware. Instead focus on only the manufacture quoted error (refer to the ***Measurement Devices*** section above) and assess how the uncertainties in each of the independent variables propagate into the uncertainty in the airspeed calculation. Compute the uncertainty in velocity for both differential pressure measurement devices: (1) the differential pressure transducer and (2) the U-tube manometer.

QUESTIONS TO ADDRESS: *Is the uncertainty in airspeed constant with the wind tunnel airspeed? If not how does it change? Does it improve or degrade as we increase the mean tunnel airspeed? Does the U-tube manometer provide a more or worse accurate measure of the velocity? Which independent variable contributes the most to our uncertainty in airspeed? Or asked another way: If you could improve the accuracy of one sensor which one would give you the largest improvement in the airspeed uncertainty?*

LABORATORY PROCEDURE

!!!! Take good notes of experimental setup, record data, and consider possible errors in the measurements. You are encouraged to take pictures of the tunnel and your experimental setup with your own devices to help you document your work!!!!

Experimental Section 1: *(Measurement of Airspeed)*

Prelab Tasks:

1. Read the lab assignment in detail and ask questions prior to your assigned measurement period.
2. Review the group assignments spreadsheet to determine the measurement configuration your team has been assigned and the voltages you are required to test at.
3. Review the group assignments spread sheet to determine the filename you are required to use for your data. This is important since data will be shared with the entire class.
4. Meet with your group and assign tasks and roles for each student to perform during the wind tunnel measurement period. Develop a plan to ensure you perform your tasks most efficiently.

Procedure:

1. Visually inspect the tunnel and compare the facility to the theoretical expectations.
2. Locate the pressure tubes for the pitot-static tube, the static pressure ring, the Airspeed Pressure Transducer, and the U-tube Manometer.
3. Connect the pressure tube disconnects according to the configuration that was assigned to your team. Ensure that you connect the tubes to the Airspeed Pressure Transducer in the proper orientation.
4. Ensure there are no objects left in the wind tunnel. Close and lock the wind tunnel door.
5. Open then Start the LabVIEW control program by clicking the white arrow in the top left corner of the window named **WT2015_voltage_control - Shortcut.vi** which is located in the ITLL Courses Folder (**Courses/Fall 2015/ASEN 2002/Wind Tunnel Lab**).
6. Set your data file path according to the naming convention assigned in the group assignment spreadsheet. All data should be saved in the **"Group Data Save Here/Lab_1"** directory. ***Note: Be careful not to overwrite another group's data file!!!***
7. Once the LabVIEW VI that controls the wind tunnel and logs the measurements is open and running, zero the airspeed and pressure transducers using the green button on the VI front panel in the bottom left.
8. Type the first voltage that was assigned to your team into the LabVIEW VI and bring the wind tunnel up to speed.
9. Once the wind tunnel has reached equilibrium (typically between 30 and 60 sec), acquire measurements with the pressure transducer by clicking the ***Send Samples to File Button*** in the upper left corner of the VI.
10. Visually measure the displacement of the U-tube manometer. ***Note: Be sure to measure the <u>manometer from the bottom of the meniscus</u> in each of the fluid columns!***
11. Document the differential pressure from the U-tube manometer in your notebook!
12. Repeat the pressure measurements for each voltage assigned to your team. Note: You should be measuring five voltages in total.
13. Once the voltage survey is complete, slowly bring the tunnel back to zero voltage (and velocity).
14. Allow time for the tunnel to completely stop, then Stop the VI to save and close your current data file!
15. Use a USB stick to take a copy of your data file with you and provide a copy for the TA to post for the class online.

Experimental Section 2: *(Measurement of Boundary Layer Influence)*

Prelab Tasks:

1. Read the lab assignment in detail and ask questions prior to your assigned measurement period.

2. Review the group assignments spreadsheet to determine the streamwise location where your team has been assigned to make the boundary layer measurements. This is related to the port number that you were assigned. Refer to the supplemental drawings to determine the physical location of the measurement referenced from the entrance to the test-section.
3. Review the group assignments spread sheet to determine the filename you are required to use for your data.
4. Meet with your group and assign tasks and roles for each student to perform during the wind tunnel measurement period. Develop a plan to ensure you perform your tasks most efficiently.

Procedure:

1. Identify the static pressure port on the test-section floor and the corresponding streamwise position where your team was assigned to conduct your measurements.
2. Connect the pressure quick disconnects of the ELD Boundary Layer Probe and your identified static port to the total and static disconnects of the "Auxiliary" pressure transducer. The ELD Probe should be connected to the "Aux Meas" tube and your team's static port should be connected to the "Aux Ref" tube. Ensure that the pitot-static probe is connected to the Airspeed Pressure Transducer in the proper orientation ***Note: the pitot-static probe may or may not be connected already depending upon the orientation your group tested in Part 1***.
3. Align the leading edge of the ELD Boundary Layer probe just downstream of the identified port by moving the horizontal traverse by hand with the knurled adjustment knob.
4. Vertically traverse the probe by hand with the vertical control knob until the tip is just barely touching the wind tunnel floor. ***Be VERY careful not to bend or damage the ELD Boundary Layer probe by driving it into the floor!***
5. Ensure there are no objects left in the wind tunnel. Close and lock the wind tunnel door.
6. Start the LabVIEW control program named **WT2015_voltage_control.**vi which is located in the ASEN2002 courses folder.
7. Set your data file path according to the naming convention assigned in the group assignment spreadsheet. ***Note: Be careful not to overwrite another group's data file!!!***
8. Once the LabVIEW VI that controls wind tunnel and logs the measurements is open and running, zero the airspeed and pressure transducers using the green button on the VI front panel.
9. Zero the readout of the ELD Probe Location on the front panel of the LabVIEW control program. ***Note that the ELD Boundary Layer Probe has a diameter of 0.8 mm, thus your actual measurement height is offset 0.4 mm above the floor and will not actually be at zero.***
10. Set the wind tunnel speed control to 5 Volts using the desired voltage knob on the LabVIEW VI front panel (mid-range in the voltage control) and bring the wind tunnel up to speed.
11. Once the tunnel has reached a steady-state begin your measurement survey. Acquire measurements at locations according to your group's assignment. These will be every 1 mm, starting at either 0 mm or 0.5 mm. There should be a total of 11 points measured.
12. Take an additional measurement with the probe centered vertically in the wind tunnel test-section: (152.4 mm or 6 in).
13. Verify that 12 measurements have now been sent to the data file (11 from before and one from the centered measurement).
14. Bring the wind tunnel velocity back down to zero by slowly lowering the voltage.
15. After the wind tunnel has stopped, stop the VI to save and close your current data file!
16. Use a USB stick to take a copy of your data file with you and provide a copy for the TA to post for the class online.

ANALYSIS OF LABORATORY DATA

You can and should begin the analysis tasks for this lab even before you have collected your own data sets at the wind tunnel. Several of these items can be accomplished before your assigned testing period as they do not require experimental data. For example the quantification of the uncertainty in the velocity measurements and the prediction of the boundary layer's influence on the streamwise speed are both tasks that do not require experimental data. You should work on these tasks together with your group during your lab session. Use the background material, *Questions to Address* in this document, and the report grading rubric as a guide for your analysis.

It is recommended that you use Matlab to analyze and plot all of your experimental data. You can use the sample data files posted on the course website and your classmate's submitted data files to begin the process of building your data loading and post-processing scripts, even before you acquire your own data. Note that the data files collected with the wind tunnel are all stored in the same format as a csv file where each column contains a different measurement and the rows are the individual data points collected. To develop a complete understanding of how the wind tunnel performs you should also compare your measurements with that of your classmates. Your data is not complete on its own; you will need your classmate's data to complement your own in your analysis. Specifically when comparing the different measurement configurations: (1) pitot-static probe vs. (2) static ring; you will only have taken measurements with the airspeed transducer for one of these configurations and measurements with the U-tube manometer for the other. As such you will need another group's data that complements yours (i.e. the opposite measurement configuration) to make an accurate comparison!