Georgia Institute of Technology
Daniel Guggenheim
School of Aerospace Engineering

AE3610 Experiments in Fluid and Solid Mechanics

PRESSURE MEASUREMENTS AND FLOW VISUALIZATION IN SUBSONIC WIND TUNNELS

Objective

The primary objective of this experiment is to familiarize the student with the measurement of static and stagnation pressures, and (indirectly) velocity, in a subsonic wind tunnel. Static taps and stagnation (Pitot) probes will be used to measure pressures on the surface of a 2-D airfoil, in the wake region behind the airfoil and in a boundary layer next to the wind tunnel wall. In addition, this lab demonstrates some techniques used in flow visualization, specifically tufts (attached to the airfoil) and smoke visualization (in a separate wind tunnel). Students should gain experience in observing flows and drawing conclusions about them from the observed behavior.

Background

a) The Aerodynamic Problems

i) **Airfoil Surface Pressure Distribution** - When a 2-D airfoil is placed in a uniform subsonic freestream, the flow velocity near the airfoil is modified and, as evidenced by the Bernoulli equation, so is the local static pressure. The resulting chordwise pressure distribution on the surface of the airfoil may be calculated by various methods using an inviscid fluid model.[*] At moderate angles of attack, the flow accelerates over the upper surface of the airfoil, the surface static pressure is less than freestream over most of the chord, and the pressure coefficient, which is defined as

$$C_p = \frac{p - p_\infty}{q_\infty},$$

along the airfoil upper surface has mostly negative values. Normally, there is a large suction peak (large negative value of C_p) very near the leading edge on the upper surface, followed by a region of increasing static pressure (adverse pressure gradient) from there to the trailing edge. On the lower surface of the airfoil, there is a stagnation point near the leading edge,

---

[*] From AE 3030 and Chapter 4 (Fig. 4.25) in Andersen's *Fundamentals of Aerodynamics*.

where C_p = 1.0, and the flow accelerates thereafter. When the two pressure coefficient distributions are plotted versus chordwise location, (x/c), the area between the two curves is a measure of the normal force coefficient on the airfoil and hence of the airfoil lift coefficient.

As the angle of attack is increased, the suction peak on the upper surface grows larger and the adverse pressure gradient becomes larger as well. At some value of angle of attack, the adverse pressure gradient on the airfoil upper surface becomes strong enough that the boundary layer separates from that surface. At a sufficiently high angle of attack, the oncoming freestream flow perceives a radically modified airfoil shape. The resulting effect is termed airfoil (or wing) stall, and the included area between the upper and lower pressure distribution curves collapses. The presence of stall was evident in the force measurements on the airfoil that were conducted in a previous laboratory.

The airfoil used in this experiment (see Figure 1) has an NACA 64-212 section. The chord is 14 inches and it has a thickness ratio of 14%. The airfoil extends from one side wall of the wind tunnel to the other. Therefore, it should behave like a 2-d airfoil.

ii) **Velocity Profiles in a Boundary Layer and Wake** - In the flow of a viscous fluid such as air, the flow velocity right at a solid surface is zero; i.e., the fluid can be thought of as adhering to the surface (the *no slip condition*). Within a small interval above the surface, the flow velocity increases rapidly from zero to a value that is of the order of the freestream velocity. The result is a velocity profile which exhibits a large velocity gradient in the direction normal to the surface. This velocity gradient gives rise to significant shear stresses, and the region within which this takes place is termed a **boundary layer**. Using boundary layer theory[*] one may show that the static pressure is constant through the boundary layer in a direction normal to the surface and that the boundary layer is a region of rotational flow so that the stagnation pressure is not constant everywhere. However, the Bernoulli equation may be used locally to find the dynamic pressure distribution within the boundary layer and hence the velocity profile *if the flow is incompressible*.

In the case of viscous flow over an airfoil at a moderate angle of attack, the attached boundary layers on the upper and lower surfaces join at the trailing edge. The resulting viscous-dominated flow region downstream of the trailing edge is termed a **wake**, within which there is a velocity deficit compared to the freestream. This deficit is a result of the flow being retarded in the airfoil boundary layers.

---

[*] See your textbook from AE 2010 and 3030. It would be helpful if you review this material before coming to the lab if you do not know what the velocity profile in the boundary layer looks like.

iii) **Visualization of Flow Around Bodies -** Aerodynamics is a difficult science because the medium with which the aerodynamicist works (air) is not visible under normal conditions. Valuable insights into the physical features or behavior of an air flow can be achieved if the entire flow field or certain regions, e.g., streamlines (or streaklines or pathlines) could be seen by the eye or by a recording device. If the flow could be made visible by some kind of flow visualization technique, then it would be possible to observe flow phenomena which are essentially inviscid (e.g., vortical flows, flows distant from surfaces) as well as those phenomena which are dominated by the effects of viscosity (e.g., ***flow separation*** and ***wakes*** behind bodies).[*] Flow visualization in air may be broadly divided into surface flow visualization and off-the-surface visualization. Surface flow visualization methods include **tufts (**seen on the airfoil in Figure 1), fluorescent dye, oil or special clay mixtures that are applied to the surface of a model. Visual inspection of such tufts and coatings as a function of time, or after some time, will give valuable information on such things as the state of the boundary layer (laminar or turbulent), transition, regions of separated flow and the like. It must be remembered in such visualization that what is observed on the surface is not always indicative of what is happening away from the surface.

The second type of visualization is off the surface and involves the use of such tracers as smoke particles, oil droplets or helium-filled soap bubbles. The visualization medium must faithfully follow the flow pattern or it is not conveying the correct information. Smoke particles and oil droplets are very small and are light enough such that they will often follow the motion of the flow; soap bubbles are small and can be filled with helium to make them neutrally buoyant. Each of these methods requires appropriate lighting and some device for recording the image, such as the human eye or a camera. If the flowfield is illuminated in a plane by appropriate masking of the light source it is possible to examine discrete sections or slices of the flow. For example, a laser light beam can be expanded into a thin sheet by passing it through a cylindrical lens. This sheet then can be used to illuminate any cross-section of an airflow that has been seeded with particles. The laser light will reflect from the particles, but dark images will be observed where there is an absence of particles, such as in the center of a vortex. A vortex core is almost void of particles since they have been spun out by the action of centrifugal force.

---

[*] In addition to qualitative observations, under certain conditions it is possible to make quantitative measurements from flow visualization data as well. For example, a measurement of the distance between streamlines in a 2-D incompressible flow provides information on velocity ratios in the flowfield.

b) Measuring Devices

i) **Pressure Taps and Probes** - The surface pressure distribution on an airfoil will be measured by means of 24 static pressure **taps**. These are small holes on the surface of the model that are connected to stainless steel tubes within the model and thence to plastic tubing. The pressure taps on the airfoil are located on the upper and lower surfaces in the chordwise direction at mid-span. The plastic tubing from these orifices is connected to a pressure transducer.

The local velocity in the boundary layer on the ceiling of the wind tunnel and in the wake behind the airfoil will be measured indirectly by traversing a Pitot* tube through the region so as to measure local stagnation pressure; the velocity follows directly because the flow is incompressible. Since the static pressure is constant throughout the ceiling boundary layer, a single static tap on the ceiling (ideally at the measurement station) will yield the local static pressure anywhere in the boundary layer at that station. In the wake region, the local static pressure will be approximately constant through the wake and will be equal to the freestream static pressure. This is because the wake measurement station is located sufficiently far downstream of the airfoil that the pressure disturbance due to the airfoil is negligible.

The end of the Pitot probe is made of thin stainless steel tubing with a 0.063 inch outer diameter (OD) and a small orifice, so that the Pitot pressure data is a local measurement compared to most other dimensions. Generally Pitot probes such as ours may be oriented a few degrees (say 5-10 degrees) away from the local flow direction without any appreciable change in the measured pressure, hence a precise alignment of the probe with the local flow direction is not required. A Pitot-static probe (a Pitot tube with a downstream static pressure tap oriented normal to the stagnation hole) located upstream of the airfoil will be used to measure freestream dynamic pressure.

ii) **Pressure Transducers** - A pressure transducer is a device that converts a pressure to a quantity that may be readily measured. For example, a traditional U-tube manometer is a pressure transducer, where pressure difference is interpreted as the height of a column of liquid. This is an example of devices known as gravitational transducers. Modern electronic transducers, which convert pressure into a voltage that may be easily measured by means of a digital voltmeter or an analog-to-digital converter (ADC), are typically elastic transducers. The

---

*Named after its inventor, Henri Pitot (1695-1771), a French hydraulic engineer.

most common types of electronic pressure transducers use the deformation of a diaphragm or similar structural element to sense pressure.*

We can categorize this type of pressure transducer by the way the deformation of the structural element is transformed into an electrical signal. The two most common approaches are *strain gage* and *capacitance* type transducers. A strain gage pressure transducer consists of a thin circular diaphragm on the bottom of which are bonded tiny strain gages wired as a Wheatstone bridge. When the diaphragm experiences a pressure on its exposed upper surface that is different from the pressure in a small cavity under the diaphragm it deflects, and the resulting bridge imbalance is a measure of the deflection. Calibration provides the constant of proportionality between bridge imbalance (interpreted as a voltage) and applied pressure. The voltage output of this type of transducer is usually in the millivolt (mV) range and requires amplification prior to measurement. Relatively inexpensive transducers can be made by using semiconductor materials. In this case, the semiconductor resistors are “written” as a bridge circuit directly onto a substrate (e.g., silicon) that acts as the diaphragm. The strain on the semiconductor results in a change in semiconductor resistance; this is known as the *piezoresistive effect*. The change in semiconductor resistance is analogous to the change in metal resistors, except in for metal resistors, the change in resistance is *primarily* due to the change in the resistor’s cross-sectional area as it is strained. For semiconductor materials, the resistance change is related to other changes in the internal structure of the semiconductor.

The capacitance-based pressure transducer has a stretched membrane clamped between two insulating discs, which also support capacitive electrodes. A difference in pressure across the diaphragm causes it to deflect, increasing one capacitor and decreasing the other. These capacitors are connected to an electrical, alternating-current (AC) bridge circuit, producing a high level of voltage output (usually 10 Volts full scale without amplification).

Strain gage transducers can be made small, hence they can be internally mounted in a wind tunnel model. Also, they have reasonably good frequency response because of the small mass of the diaphragm and the short distance between the pressure tap and the diaphragm face. Capacitance transducers usually are not well suited for internal mounting (too large) and such systems do not have a fast response. Both types of transducers can be calibrated using a primary pressure standard such as a dead-weight tester, which supplies a pressure of precisely known magnitude, or using another (already) calibrated pressure transducer. In this lab, you will use both *capacitance* type and semi-conductor *strain gage* transducers to measure pressure.

---

*A common pressure transducer for *rapidly changing* conditions, based on the piezoelectric effect, will be introduced in later labs.

Baratron – This is a capacitance-based transducer (of a specific brand name) to measure freestream dynamic pressure. The Baratron has internal signal conditioning electronics, with an output of 10 Volts at its maximum differential pressure, e.g., 10 Torr, which you can usually find by inspecting the Baratron's label. For this device, the differential pressure Δp is assumed to be related to the transducer voltage V by the relation

$$\Delta p = R \times V \qquad (1)$$

where R is the responsivity of the transducer, e.g., 1 Torr/V.

Barocel – You will use a second capacitance transducer of a slightly different design (see Figure 2) for converting the pressure from the traversing Pitot probe. The Barocel has signal conditioning electronics that also provide an approximately 10 V full-scale signal at some maximum differential pressure. However, this maximum pressure can, in essence, be adjusted with a range switch located on the front-panel of the transducer power supply unit. The range switch, which actually controls the signal amplification, can decrease the **full-scale** differential pressure by a factor of 10,000 over the maximum pressure setting. Thus smaller pressure readings can be made to produce the full 10 V signal. Other controls on the power supply unit allow you to determine the full-scale output voltage range, ΔV (not exactly 10 V), that corresponds to the full-scale pressure range, and to adjust the voltage output at a zero differential pressure, i.e., adjust the **zero offset** of the transducer $V_{p=0}$. For this transducer, we must recognize that

$$\Delta p = R \times \left(V - V_{p=0}\right) . \qquad (2)$$

Scanivalve – This is a bank of piezoresistive pressure transducers you will used to simultaneously measure the 24 pressures on the airfoil surface. The Scanivalve system (Model DSA 3217/16PX) is composed of two units (see Figure 3), each having 16 differential pressure transducers with a maximum pressure range of 0.18 psi (or 5" H_2O). The average linearity error for the pressure transducers, as determined by the manufacturer, is ±0.03% of full-scale. Each unit has its own analog-to-digital converter and controller that converts the measured voltages into pressures based on a stored set of calibrations. The units are connected to our data acquisition computer via ethernet.

iii) **Traverse** - The Pitot probe is clamped onto a traveling nut that moves along a lead screw mounted vertically on the top of the wind tunnel test section (see Figure 4). The lead screw is driven by a stepper motor, which is a pulsed direct current (DC) motor capable of shaft rotation in either direction. Each pulse sent from a controller to the motor causes the motor to rotate 1.8 degrees (this value is specific to the stepper motor used in this lab) and stop. It is held at the new position with a holding torque. Upon command, the computer sends a signal to an interface card that then instructs the controller to send a pulse to the motor. The stepper motor used here can be pulsed at a maximum rate of 2000 steps (or equivalently, 10 revolutions) per second. The pitch of the lead screw, i.e., the number of revolutions of the lead screw needed to advance the traveling nut precisely one inch, is known. Thus, a simple calculation indicates the number of pulses needed to move the probe a required distance.

iv) **Smoke Tunnel** - This is a two-dimensional wind tunnel (see Figure 5) with a test section that is 48 inches high, 36 inches long, and 2.5 inches deep. The sides of the wind tunnel are made of glass. Air is pulled through the test section at a low velocity (maximum 29 ft/sec) by means of a small blower at the exhaust end of the tunnel. The test section is lit with floodlamps from the top and bottom. Smoke is generated in a reservoir, which is located in a compartment beneath the wind tunnel. Oil in the reservoir saturates a wick wrapped around a wire heating element that vaporizes the oil. An air tube, which originates from the downstream end of the blower, forces air through the reservoir and picks up the oil producing a fine smoke. The reservoir is connected to a streamlined feeder pipe that stands vertically in the middle of the flow at the upstream end of the wind tunnel test section. This feeder pipe spans the height of the test section and includes 25 small tubes spaced 3/4 inch apart that protrude from the downstream side of the feeder pipe. Smoke emerges from these small tubes and enters the main airstream, so that at the test section entrance an observer sees the flow streamlines as discrete narrow bands of white smoke. Various models may be mounted in the test section and the resulting flow patterns formed by the streaklines can be observed (or recorded by a camera). The flow velocity is kept low so that the smoke particles in the freestream will stay in layers or lamina and maintain their identity; smoke in turbulent flow tends to dissipate and makes observation difficult.

c) The Wind Tunnel

A wind tunnel is a duct or pipe through which air is drawn or blown.[**] The Wright brothers designed and built a wind tunnel in 1901. The basic principle upon which the wind tunnel is based is that the forces on an airplane moving through air at a particular speed are the same as the forces on a fixed airplane with air moving past it at the same speed. Of course, the model in the wind tunnel is usually smaller than (but geometrically similar to) the full size device, so that it is necessary to know and apply the scaling laws in order to interpret the wind tunnel data in terms of a full scale vehicle. The wind tunnel used in these experiments is of the open-return type (Figure 6). Air is drawn from the room into a large settling chamber (1)

[**] Anderson, p. 123

fitted with a honeycomb and several screens. The honeycomb is there to remove swirl imparted to the air by the fan. The screens break down large eddies in the flow and smooth the flow before it enters the test section. Following the settling chamber, the air accelerates through a contraction cone (2) where the area reduces (continuity requires that the velocity increase). The test (working) section (3) is of constant area (42" × 40"). The test section is fitted with one movable side wall so that small adjustments may be made to the area in order to account for boundary layer growth, thus keeping the streamwise velocity and static pressure distributions constant. The air exhausts into the room and recirculates. The maximum velocity of this wind tunnel is ~50 mph, and the turbulent fluctuations in the freestream are typically less than 0.5% of the freestream velocity. Thus, it is termed a “low turbulence wind tunnel.”

Preliminary

For the flow visualization experiments, no quantitative data will be taken; the emphasis is on observing the behavior of the flow and extracting conclusions from those observations. Each student should come prepared to make notes and draw rough sketches documenting what is observed; these sketches and notes will comprise the data from the experiments.

The following items in reference to the pressure measurement experiments must be turned in at the start of your lab session.

1. Develop a single equation that gives difference between the total (stagnation) and static pressure in the wind tunnel flow, which is known as dynamic pressure q, ***in units of mm Hg*** (also called Torr) as a function of:

   u, velocity of the flow (***in mph***),
   T_{room}, room temperature (***in °F***)
   p_{room}, room pressure (***in inches of Hg***),
   and ***two*** constants (i.e., numbers like “3.4”).

   This means your equation should have only two *numbers*, and three *variables* (u, T_{room} and p_{room}). You will measure T_{room} and p_{room} (in the units given) and use this equation to determine the wind tunnel q (in mm Hg) for a wind speed given in mph. Watch your units, this is part of your grade. **Turn in the equation and its development**.

2. A list of 16 measurement locations for determining the boundary layer velocity profile (see Procedure item 10). That is you need 16 points along a line perpendicular to the wall (not

downstream locations but across the boundary layer) where you will measure the velocity. In addition, include a sketch (which can be hand drawn, copied from a book, etc.) of a theoretical boundary layer profile and indicate the positions of your suggested measurement locations on the sketch.

3. A list of 3 angles of attack for the C_p measurements on our NACA 64-212 airfoil (one of which should be zero).

LOW SPEED WIND TUNNEL MEASUREMENTS

Procedure

For all the measurements with the wind tunnel operating, you will use the same wind tunnel speed. Use a value of 35 mph, unless the TA's suggest a different value. Make sure to ***record the pressure and temperature in the room*** so that you can convert the dynamic pressure recorded from the Baratron to a wind tunnel velocity.

Barocel Range Adjustment and Zeroing

1. Run the "calibration" procedure on the computer menu.
2. First, using the computer, you will determine the voltage range ("full-scale" minus "zero" voltage output) of the Barocel. The computer will instruct you to a knob on the front-panel of the Barocel's power supply unit (located in the equipment rack).
3. Then you will set the Barocel's amplifier (denoted "range") to the appropriate setting – typically ×0.3 for this experiment (ask the TA if this is still the correct setting). This lets you adjust the pressure range of the Barocel to the maximum pressure difference you expect to measure in the experiment. At a gain setting of ×1.0, the maximum voltage output from the amplifier corresponds to the maximum pressure range of the Barocel (usually recorded on the cover plate of the Barocel transducer).
4. Next you will adjust the zero offset, i.e., adjust the output voltage to be zero when the pressure difference across the Barocel is zero. To properly perform this procedure, you will **need to set up the system to produce a zero pressure difference across the Barocel input ports**. Then you can adjust the offset to zero using the needle gauge and record the value on the computer.

Surface Pressure Distribution

5. The airfoil used in this experiment will already be mounted in the wind tunnel, and the airfoil pressure taps will already be connected to the Scanivalve system. Make sure the

wall surface static pressure tap, which is on the ceiling of the tunnel and supplies the freestream pressure, p_∞, is connected to both Scanivalves.

6. Use the computer data acquisition system to perform the surface pressure measurements. (*Don't forget to turn the wind tunnel on before taking data!*) The computer will record the airfoil pressure differences a large number of times (the number of samples will be stored in the computer output file). Then the computer will calculate the average and root-mean-square (rms) of the values and store the result for a single pressure tap. You will manually set the airfoil at <u>three different geometric angles of attack,</u> one of which should be zero. (You may find it easier to change the airfoil angle with the wind tunnel off, though this is not required.) You may also wish to use observe the tufts on the airfoil to observe flow separation at the higher angles of attack – you can even use this to check whether your chosen angles of attack are "interesting."

<u>Pitot Probe Surveys</u>

7. Make sure someone has **connected the Pitot probe** and the wall surface static pressure tap to the Barocel.

   While the boundary layer survey is described first below, you may perform the wake survey first if the Pitot probe is already located in the wake region.

8. The Pitot probe, also already mounted in the tunnel, will be traversed from the ceiling of the wind tunnel out a distance of three inches in order to **<u>survey the ceiling boundary layer</u>**. The boundary layer is very thick at this location since it has been growing along a considerable length from the wind tunnel settling chamber through the converging section to the measuring station. Make sure you start by manually locating the Pitot probe tip at the edge of the wall. To do this, you will adjust the location of a mechanical stop on the lead screw/Pitot probe system. This is the location the computer denotes as "y=0".

9. Use the data acquisition program to traverse the probe and take data. After the probe has been moved to a new location away from the wall, denoted y, the software allows a short time for the pressure to settle out and then record a number of samples (storing the number of samples, the average and rms in the output file) to evaluate the Pitot pressure. In order to take a data point it is necessary to input the desired value of y. Start by taking data with the probe tip nearly at the edge of the wall, i.e., at y=0.

10. You need to make measurements at a total of 18 y values: 16 unique y's and 2 *repeats*. Your lab group should agree on these values. The first value, as noted above should be next to the wall and there should also be some values near 3.0 in., since this is known to correspond roughly to the edge of the boundary layer. As the data are being taken, the

computer screen will show a plot of the velocity and position that is updated every time a data point is taken. The two repeat values are taken so that you can observe the repeatability of the data. *Make the two repeat measurements at the end of the boundary layer survey*. One of the repeat points should be near the inner edge of the boundary layer (somewhere near, but not necessarily at, the wall) and one should be closer to the outer edge of the boundary layer.

11. The probe also will be traversed to **survey the wake region behind the airfoil**. First, manually set the airfoil at 8 degrees angle of attack. You will need to adjust the connection between the Pitot tube and lead screw/stepper motor in order to lower it (from its position near the wall) for the wake survey. When the probe is at its highest point, check that the probe is on a horizontal line that passes through the airfoil trailing edge when the airfoil is at an angle of attack of 8 degrees. This will be where the computer (arbitrarily) denotes y=0.
12. Use the data acquisition program to perform the wake survey. The required values of y are pre-programmed (16 points in all), starting at a y=0 and extending 3 inches. **Perform the complete wake survey a total of two times**, that is run the survey once, then go back and choose the wake survey option again. (Do not forget to check the starting position of the probe.)

Data to be Taken

1. **Surface Pressure Distribution -** The lab computer will record the measurements acquired by the Scanivalve systems, which will be measuring the differential pressure between each wing pressure tap and a freestream static pressure (in mm Hg). The pressure results are stored in a file versus the chordwise location of the pressure tap nondimensionalized by the airfoil chord length. The wind tunnel dynamic pressure (mm Hg) will also be recorded by the computer (remember to record the atmospheric pressure and temperature to convert this to a wind tunnel velocity).
2. **Pitot Probe Survey of a Boundary Layer -** The Barocel will measure the pressure difference between the Pitot probe pressure and the wall surface static pressure on the ceiling of the wind tunnel at the measurement station. The data acquisition program will output to disk the pressure difference (mm Hg) versus the distance (in.) from the surface. The survey begins with the probe (nearly) touching the ceiling. If it was just touching the wall, and since the Pitot probe is 0.063 inches in outside dimension, this first position (which the computer denotes as y=0) would actually correspond to the distance to the

middle of the probe. You will record 16 locations away from the wall, and then repeat two measurement locations.

3. **Pitot Probe Survey of a Wake** - The Barocel in this application will measure the pressure difference between the Pitot pressure in the wake and the wind tunnel freestream static pressure. The acquisition software will output the value of the streamwise component of the dynamic pressure (mm Hg) versus the vertical distance location (in.). You should record the wake profile twice.
4. **Tubing Schematic** - Make a sketch indicating how a typical airfoil pressure tap is connected to the pressure transducer. Also sketch the tubing hook-up to the transducer used during the boundary layer and wake surveys. Finally, sketch the tubing hook-up used in the measurement of wind tunnel dynamic pressure with the Pitot-static probe.

Data Reduction

1. **Surface Pressure Distribution** - Convert the measured pressure differences and free stream dynamic pressures to local pressure coefficients.
2. **Pitot Probe Surveys** - For the boundary layer results, apply the Bernoulli equation locally to convert the dynamic pressure to local streamwise velocity component. From the result, select a value of δ and u_{edge}, defined respectively as the height above the surface where the velocity becomes *essentially* constant and the value of that velocity. Then calculate the nondimensional quantities y/δ and u/u_{edge}. For the wake profile, again calculate the velocity from the pressure differences.

Results Needed for Report

1. Make a four-part tubing schematic figure showing all connections necessary for the measurement of (a) the airfoil static pressures, (b) the boundary layer velocity profile, (c) the wake velocity profile and (d) wind tunnel dynamic pressure. Indicate what each tube is connected to at both of its ends and label each tube as to what pressure it contains. The figure subtitles for each tubing hook-up should describe to which of the different experiments it corresponds.
2. Plot two figures showing the chordwise pressure coefficient distribution on the airfoil versus nondimensional chordwise position, x/c, where c is the airfoil chord. The standard aerodynamics format is to plot C_p as the ordinate, negative upward. On both figures plot the distribution at zero angle of attack as a standard. Then, plot one distribution at the

smaller angle of attack on the first figure and the other distribution at larger angle of attack on the second. Plot data points only; do **NOT** draw lines or smooth curves between them.

3. Plot a figure showing the shape of the nondimensional boundary layer profile u/u_{edge} versus y/δ with distance as ordinate. Again, plot data points only (not connected with curves).
4. Plot a figure showing the variation in streamwise velocity component u through the wake behind the airfoil with y as ordinate. Plot data points only.
5. Plot the normalized velocity profile, u/u_∞, where u_∞ is the wind tunnel velocity simultaneously recorded with each wake velocity measurement, again with vertical position as the ordinate.

SMOKE TUNNEL VISUALIZATIONS

Procedure

1. The room is supplied with a high quality CCD Foculus color camera. To use the camera, you need to run the FGControl software located on the computer's desktop.
2. On the front panel, turn the main power **on**, then turn **on** the power for the lights and smoke. Allow the smoke generator to start producing the smoke (~5-10 seconds), then turn the blower **on**.[*] To start, set the speed control about halfway - you will *not* need to know the air velocity, but it varies approximately linearly with the setting of the speed control with a maximum velocity of 29 ft/sec.
3. Before opening the front door/window of the test section, turn the smoke generator and blower **off**.[†] Open the front door of the test section and mount the following models in turn on the attachment disk. Observe the flow patterns in each case; take notes and draw rough sketches documenting what is observed; do **not** rely on your memory - keep a careful log as the laboratory progresses.
   a) a cylinder;
   b) a symmetrical airfoil without flap - at a minimum, vary the angle of attack from a small value through stall;

---

[*] If needed (if the smoke flow begins to disappear so much you can not see it), you can routinely turn the blower off to allow the smoke generator time to regenerate smoke. Only do this if the smoke flow is hard to see; otherwise, you will just end up filling the room with smoke.

[†] Again, if the smoke flow is hard to see, you can leave the smoke generator on when you turn the blower off.

c) an airfoil with flap (the flap angle is controlled by turning the knob marked *Aux 1* on the front panel) - at a minimum, set the airfoil at a moderate angle of attack and vary the flap angle from 0 to 45 degrees;

d) a finite wing - set at a moderate angle of attack before installation; and

e) a 3-D wing tip.

This is a flow visualization experiment. That means you should feel free to adjust the wind tunnel speed and geometry of the models in order to "see" what happens as you change conditions. **Please note**: make sure you make sufficient observations to address the issues listed below in the Results Needed for Report section.

4. When the observations have been completed, turn **off** the smoke first, then the lights. Allow the blower to run for about five minutes to clear the smoke out of the tunnel, then turn **off** the blower and the main power.

Data to be Taken

Just the sketches or digital images of the flowfields for the various models at the appropriate conditions.

Data Reduction

Since no quantitative data will be taken, no data reduction is required.

Results Needed for Report

You need to provide results that help answer the list of discussion questions below; you should address these questions in your report. This will, in part, require that certain flow features be observed during the experiments described in the Pressure Experiments. These questions are in addition to any that might be listed in the supplemental handout. Each answer to the questions below must be based on a figure (introduced in the appropriate part of the Results and Discussion section of your report). The figures should be digital images or sketches (free-hand is okay, but carefully done) of the flow patterns that were observed. Therefore, carefully observe the major flow features and take notes during the experiment.

Smoke Tunnel

1. **Cylinder** - Contrast what was observed as the airflow went around the cylinder with the potential flow prediction for the flow around a cylinder. Why is there a difference? What is the effect of this difference on the aerodynamic performance of a cylinder?
2. **Symmetrical airfoil without flap** - Describe the flow behavior you observe as the angle of attack is increased from a small value to a value above the stall point. Pay particular attention to the behavior of the streamlines nearest the body as a function of angle of attack.
3. **Airfoil with flap** - With the airfoil set at a moderate angle of attack, vary the flap angle from zero to 45 degrees and describe the changes in the flow around the airfoil/flap combination that are observed as a function of flap deflection angle.
4. **Finite wing at angle of attack and 3-D wing tip** - Describe the behavior of the streamlines near to tip of the wing and downstream of the wing. What does this behavior represent physically?

Figure 1. Two-dimensional wing showing pressure tap locations (light colored line at centerline of airfoil), red tufts used to visualize separation and tubing used to connect pressure taps to Scanivalve.

Figure 2. Picture of the Barocel transducer.

Figure 3. Picture of the two Scanivalve units.

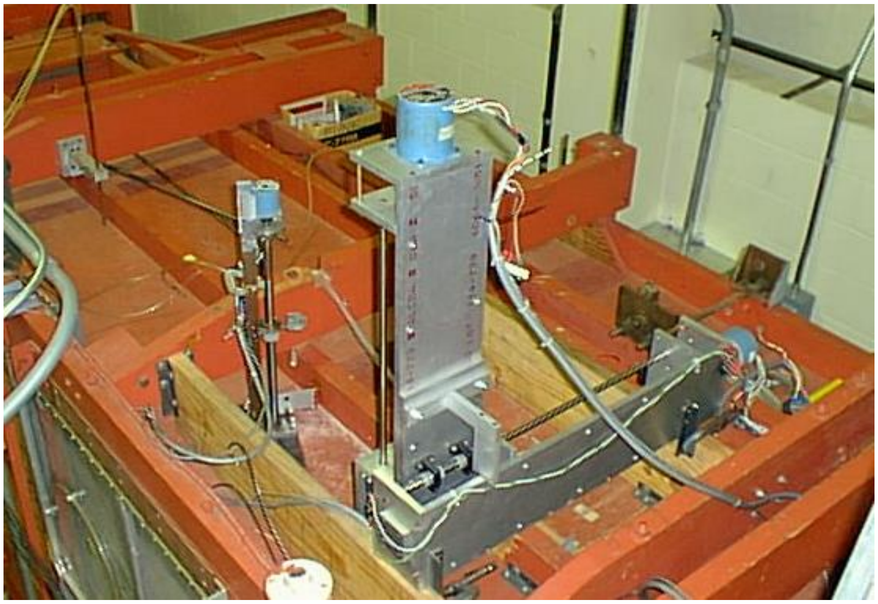

Figure 4. Traverse, located on top of windtunnel, used to move Pitot probe for boundary layer and wake surveys.

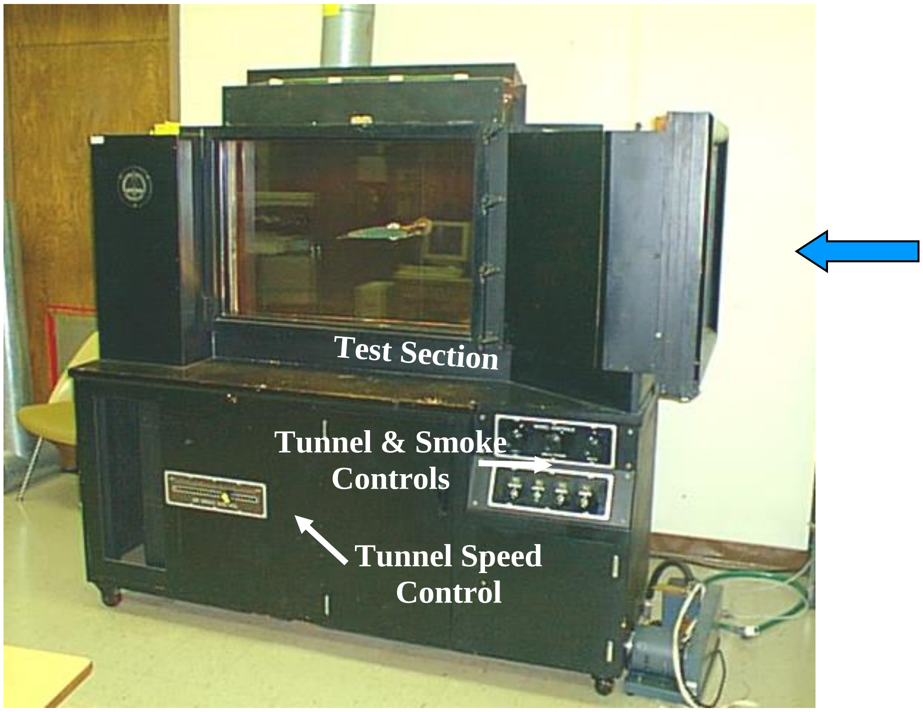

Figure 5. Smoke tunnel (flow is right to left).

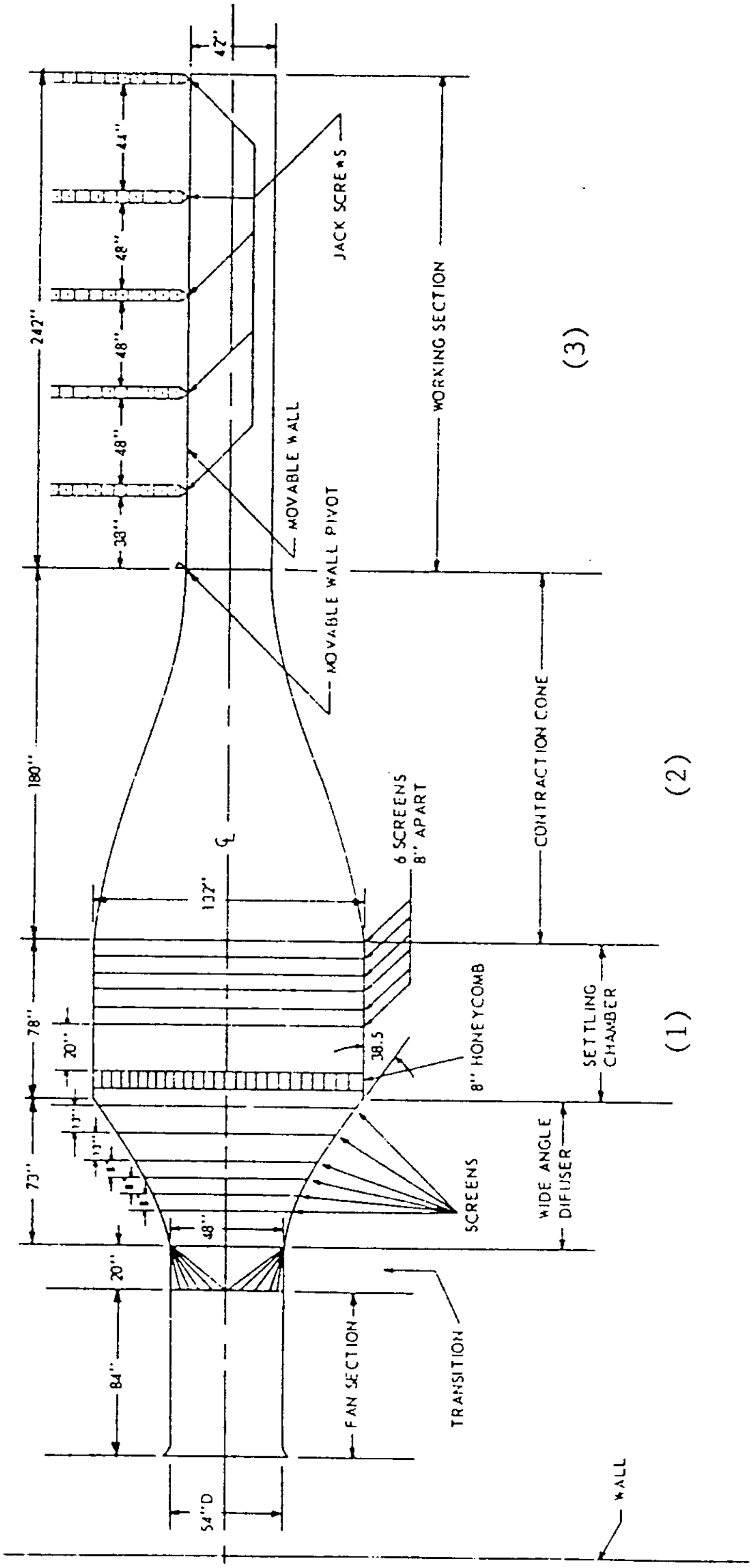

Figure 6. Georgia Tech low turbulence wind tunnel.